National Aeronautics and Space Administration

NASA Strategic Roadmap Committees

Final Roadmaps

May 22, 2005

Exploring our Planet for the Benefit of Society

NASA Earth Science and Applications from Space

Strategic Roadmap

Report of the Earth Science and Applications from Space Strategic Roadmap Committee

(Strategic Roadmap Committee Number 9)

May 2005

Table of Contents

Executive Summary

With the successful deployment of the Earth Observing System (EOS), a long-term plan for the future of Earth system science is needed. This Earth Science and Applications from Space roadmap provides a framework for such a plan spanning three decades.

The end goal (2035 and beyond) for this roadmap is a fully instrumented Earth system, networked to predictive models, serving science and decision-makers. This future program will realize the full benefits to society of our research, while opening up new science through discovery. To get there, we must build a foundation for comprehensive observing and modeling in the next decade (2005-2015), and work to expand our view of Earth and reach into society in the decade after (2015-2025). Throughout we must mature our measurement and modeling capabilities, and carefully manage our data - past, present and future.

Roadmap Objective

Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems.

The objective of this roadmap is directly traceable to the nation's objectives for NASA, and to NASA's mission and vision. The Earth Science and Applications from Space Strategic Roadmap is unique within NASA because it responds to multiple presidential directives and initiatives, including Climate Change Research Program, the U.S. Integrated Earth Observation System, the Ocean Action Plan, and the Vision for Space Exploration. Naturally, this roadmap will evolve over time with society's concerns, in response to discoveries about the Earth system, and in response to technology advances for both space and in situ observations.

Guiding Science Questions

The roadmap Committee developed a set of guiding science questions to frame the discussion on how to achieve the roadmap's objective:

How Does the Earth Support Abundant Life?

- How does the atmosphere protect and sustain us?
- How are our weather and climate evolving?
- What controls the availability of water on the planet?
- How does life influence and respond to changes in environmental processes on Earth?
- What causes changes to the Earth's surface and interior?
- What role do human systems play in driving changes in the Earth system?

Pursuing the answers to these questions will generate fundamental knowledge that enables us to address some of the most intellectually compelling problems humanity faces today. Applying this knowledge to society's practical needs will increase our prosperity and help us protect and enhance Earth's ability to support life.

Strategic Roadmap Scientific Objectives

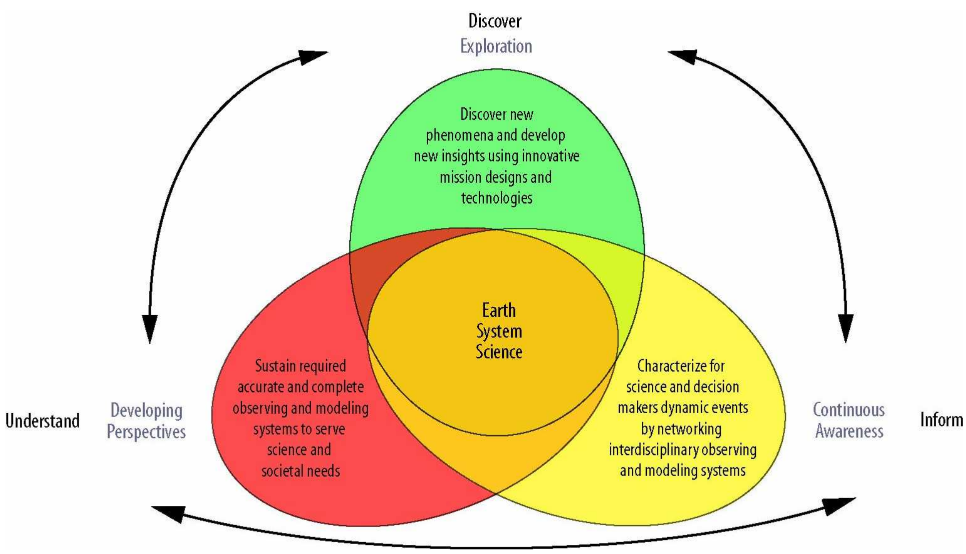
The strategic roadmap scientific objectives map to these questions and are as follows:

Understand the Earth as a system of interacting natural and human systems, including…

- Atmospheric Composition: the sources, sinks, and transformations of aerosols and atmospheric chemical species
- Climate and Weather: the present state and expected evolution
- Water: the storage, distribution, and transport of water in all its forms
- Life: biogeochemical cycles and the distribution and processes of life within the Earth's ecosystems
- Solid Earth: the processes that modify Earth's land surface and interior and contribute to natural hazards

Strategic Roadmap Integration Objectives

No individual measurement can answer these guiding questions, but they can be fully addressed through the integration of investigation systems. Because the capacity to answer guiding questions emerges through the combined results of multiple scientific investigations, this document identifies three **strategic roadmap integration objectives** to guide this integration. These are: Exploration and Discovery; Continuous Awareness; and Developing Perspectives. Each integration objective can be roughly mapped to a phase of a measurement's lifecycle, and the philosophy behind each objective helps to determine the best use of research and operational assets.



Achievements by Decade

Armed with the main roadmap objective for Earth science from space, and an approach based on the integration objectives, the next logical step is to ask what will be known, and by when? The following table maps these integration objectives to some of the important achievements identified for each decade.

	2005-2015: Building a foundation for comprehensive observing & modeling	2015-2025: Expanding our view of Earth & reach into society	2025-2035 & Beyond: Fully instrumented Earth system networked to predictive models serving science & decisions makers
Exploration & Discovery: Explore unknown aspects of the Earth system by implementing new investigations enabled by new insights, technologies, capabilities, & vantage points	• Global assessment of above-ground carbon biomass • Time-dependent deformation maps of fault zones, volcanoes, slopes & ice sheets • Comprehensive assessment of changes in ice cover	• Characterize water distribution in root zone; improved weather & climate prediction • Upper ocean profiling to understand ocean biosphere	• Pursuing answers to new questions, enabled by: distributed autonomy, bio- & nano technology, very large apertures, etc.
Continuous Awareness: Develop new scientific understanding of dynamic processes & demonstrate capabilities useful for decision support by providing prompt recognition & adaptive observation of dynamic events through the networking of distributed observing & modeling systems	• Improved understanding of natural & anthropogenic aerosols & their effects on climate • Ice sheets changes & ocean circulation tied to predictive climate models • Quantified snow deposition & water equivalent • CO2 flux to constrain global sources & sinks	• Quantified dynamics of major ice sheet motion • Tropospheric winds over land & ocean for weather & ocean circulation models • Quantified dynamics of water vapor, clouds, rainfall, surface & subsurface water storage, run-off, & fresh water availability • Vegetation/algal type & land/ ocean carbon sequestration • Surface deformation dynamics & surface beneath ice • Improved understanding of Earth's time-varying magnetic field	• Assessment of plant and algal physiological status and productivity • Improved global topography -- in conjunction with SRTM data first global measurement of topographic change • Detection of volcanic/ tectonic & land-use changes • Fully integrated Earth System model and assimilation system with data distribution portals for simple high speed access to all aspects of the Earth System
Developing Perspectives: Enable new scientific understanding of long-term Earth processes & trends by sustaining & integrating comprehensive global observing & modeling systems	• Operational observations calibrated for climate science • Framework to couple Earth system model modules deployed nationally	• Reduced uncertainties in global & regional climate models through accurate models of cloud feedback & aerosol forcing • Models and data assimilation systems integral to the observing system and decision support systems, including future mission design	• Global water cycle, including soil moisture, precipitation, linked to climate & weather models • Networked observations, models, & knowledge systems for science & operational systems

Prioritization Criteria

Prioritizing investigations is at the heart of the roadmap, and was done with considerable thought and a defined, logical process. At the core of the roadmap is the time-ordering of activities based on an assessment of scientific and societal relevance, and technical maturity with an emphasis on maximizing efficiency of related measurements. This is the idea of “awareness clusters” that springs from the Continuous Awareness integration objective. *Awareness clusters focus efforts on answering particular science questions in a given line of inquiry by coordinating and connecting information from multiple space and airborne observations, in situ sensors, and modeling systems during the focus time period*.

The prioritization criteria are listed below:

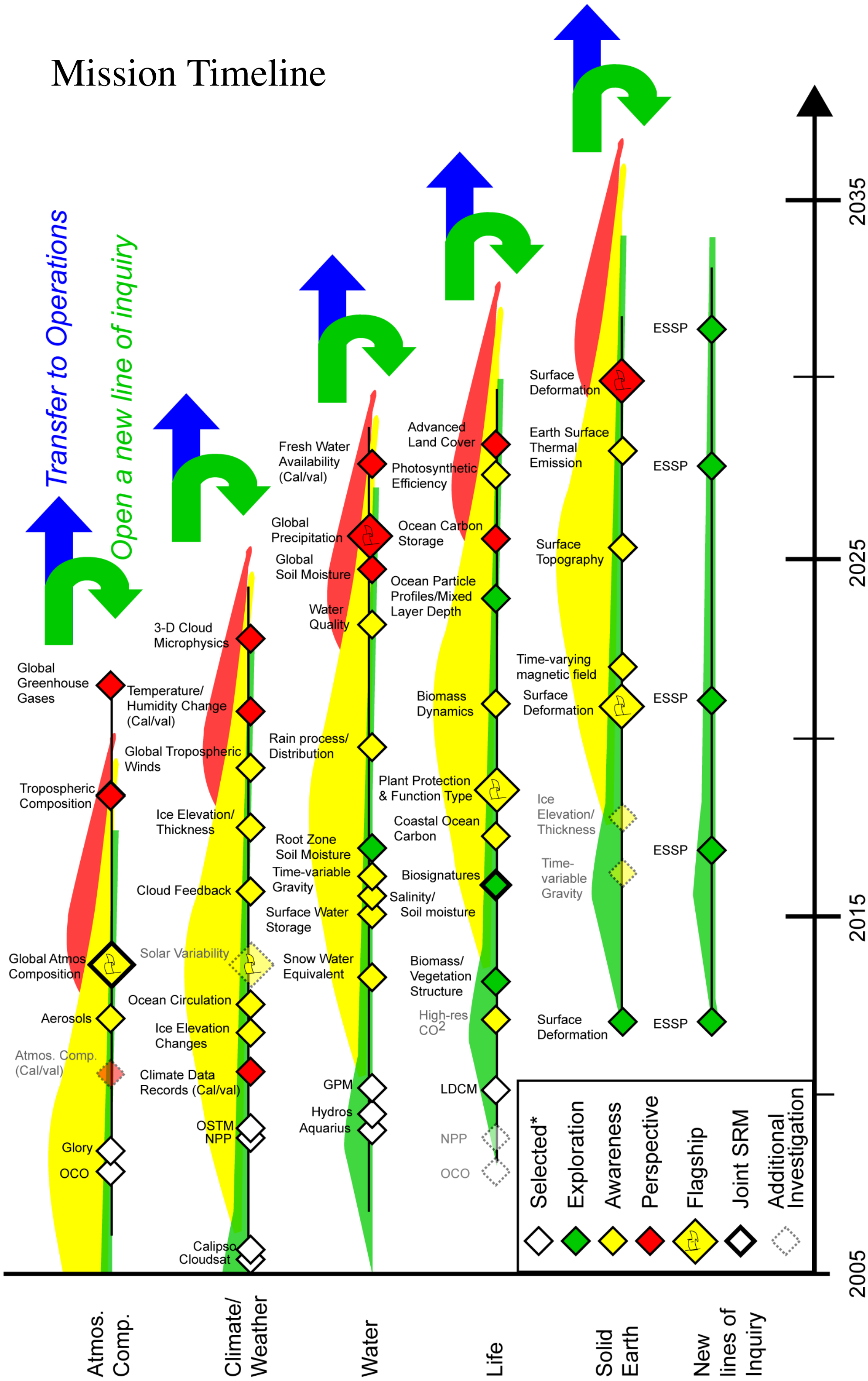
- ***Does the investigation advance science?***
- ***Does the investigation support decision-makers?***
- ***Does the investigation benefit society?***
- ***Is the investigation consistent with recommendations of national priorities?***

To determine the current state of each line of inquiry the Committee developed the concept of the measurement maturity index (MMI) for space-based measurements. MMI was also used to help prioritize investigations.

Mission Timeline

For each line of science inquiry derived from the strategic roadmap scientific objectives, investigations have been prioritized and arranged on a timeline. These missions (shown as diamonds) will realize the achievements laid out for each decade. Blue and green arrows on the timeline indicate planned transitions from research to operations and the opening of new lines of inquiry, respectively.

Mission Timeline



This strategic roadmap includes currently funded NASA investigations for information purposes only. To avoid even the perception of financial conflicts of interest, the Committee did not prioritize or make recommendations concerning any currently funded activities. NASA asked the Committee to assume that NASA will complete currently funded missions in the first decade of the roadmap, including missions in implementation that NASA has committed to complete, as well as missions in formulation that have yet to pass their Mission Confirmation Review. NASA asked the Committee to assume that NASA will find a flight opportunity for the Glory instrumentation.

To determine the recommended order of the awareness clusters linked to each scientific objective, we evaluated the current state of each line of inquiry, based on the current mission set and NASA's near-term plans. In addition, we examined the maturity of all of the measurements addressing each scientific objective using the Measurement Maturity Index.

Modeling and Data Management

Modeling is critical to all three roadmap integration objectives. Simulation and prediction are fundamental to improved Earth System understanding, reducing uncertainty and providing societal benefit. The grand challenge is to have an observational system that observes all key Earth system variables and assimilates that information into a system of integrated, interacting models that include each of the major subsystems: oceans, atmosphere, cryosphere, biosphere and solid Earth.

The Committee envisions a future with high bandwidth, universal access to Earth system information that is available via an easily queried Earth system portal. Imagine the usefulness of a map or globe-based query system where scientists, educators, and policy-makers can obtain up-to-the-minute information about specific locations or regions of the planet.

Links to Other Strategic and Capability Roadmaps

The Earth science roadmap's primary linkages are with the Sun-Solar System roadmap, and concern a shared desire for joint investigations of the effects of solar variability on the Earth's climate and upper atmospheric chemistry dynamics. The roadmap also shares interests with all three Exploration roadmaps (Lunar, Mars, and Solar System), Earth-like planets, and Aeronautics.

There are several technological advances needed to complete the integration objectives. These needs provide linkages to several capability roadmaps, including Telescopes; Autonomous Systems and Robotics; Instruments and Sensors; Modeling, Simulation, and Analysis; and Nanotechnology.

Conclusions and Near-term Recommendations

This roadmap outlines a vigorous, robust, yet likely affordable program of investigations for the nation that, if implemented, will give NASA's Earth science program a glorious future that builds upon the successes of the past program. That future is integral to NASA's quest to explore our solar system, yet responsive to society's needs here on Earth.

We recommend four near-term actions that NASA can begin work on immediately, as well as longer-term steps for which NASA should begin planning.

Near-term recommendations:

1. ***Complete the approved program*** in a timely fashion, including the next Earth System Science Pathfinder Announcement of Opportunity. This roadmap was built on the assumption that the NASA missions currently in formulation and implementation would be completed as planned, and these missions are the foundation of this roadmap.

2. ***Add advanced planning funding for future Earth Science and Applications missions*** from Space. The following near-term missions and our first flagship mission (listed in order of launch dates) need to be studied immediately to accomplish our recommended timeline:
   - Cal/Val Mission
   - Ice Elevation Changes
   - Surface Deformation
   - Ocean Surface Topography
   - Aerosols and high resolution CO2
   - First Flagship Mission – L1 Atmospheric Composition/Solar influence on Climate

3. ***Fund advanced planning for the first awareness investigation focus:*** atmospheric chemistry, including technology, missions, models, networks, educational opportunities, and international cooperation.

4. ***Fund at least one new start*** for the missions above in FY'07 or FY '08 and the others as soon as possible after that.

Introduction

Exploration – The Delicate Balance of Cosmos and Earth

Our human need to explore is never exhausted. From our home on Earth, we reach ever outward. Each successful exploration is rapidly superseded by the irresistible desire to pursue new vistas.

The compass that today guides this timeless endeavor is scientific inquiry. It is science that gazes outward, providing the grand questions that challenge us to journey farther and farther from home. But it is also science that peers inward, exploring previously inaccessible areas of the Earth, and asking the practical questions that help us to make Earth safer, protect our citizens, and expand our economy.

The NASA scientific program must be carefully constructed to address an underlying reality: knowledge of the Earth drives the economic growth and environmental security that allow us to be an exploring nation. This program must devote equal attention to both *inspirational questions* that underpin our outward desires, and practical questions that support our inward needs. A *sustainable* exploration program depends critically on this delicate balance of Cosmos and Earth.

1.1 National Objectives for Space Exploration

NASA's overarching Agency objective is the fundamental goal of the Vision for Space Exploration – "…to advance U.S. scientific, security, and economic interests through a robust space exploration program." NASA will direct its efforts towards five National Objectives. These National Objectives are:

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond.
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.
- Study the Earth system from space and develop new space-based and related capabilities for this purpose.

The first four objectives come directly from the *Vision for Space Exploration*. The fifth National Objective affirms NASA's continued commitment to understand and protect our home planet, Earth. This objective was added in *The New Age of Exploration* to address other Presidential initiatives and directives not covered in the Vision for Space Exploration.

1.2 NASA Strategic Objective for this Roadmap

The objective for this roadmap is one of 18 NASA strategic objectives for 2005 and beyond derived from the five guiding national objectives for NASA (2005). All of NASA's programs and resources will be tied to these NASA objectives.

Advance scientific knowledge of the Earth system through space-based observation, assimilation of new observations, and development and deployment of enabling technologies, systems, and capabilities, including those with the potential to improve future operational systems.

This strategic roadmap is unique within NASA in that it responds to multiple presidential directives/initiatives. NASA has a critical role in implementing several recent major Presidential directives or initiatives, including:

- Climate Change Research;
- The U.S. Integrated Earth Observation System;
- The Ocean Action Plan; and
- The Vision for Space Exploration.

NASA's programs addressing Earth science and applications from space are *essential* to the success of the first three presidential initiatives listed above, and will surely prove to be so to the fourth. NASA's contributions to the Earth sciences are unique, numerous, and critically important to future efforts to protect life and property, facilitate responsible environmental stewardship, and understand and predict the dynamic Earth system. For more information on these initiatives (see Appendix B).

1.3 Ties to the NASA Mission and Vision

The NASA vision seeks "To improve life here, to extend life to there, and to find life beyond." The NASA mission is "To understand and protect our home planet, to explore the universe and search for life, and to inspire the next generation of explorers…as only NASA can." The Earth system roadmap addresses several aspects of these important guidelines for NASA's role. It primarily address the aspect of the vision that attempts to "improve life here," but also address the other aspects of the vision and mission. Because humanity is a part of the Earth system, understanding the Earth system scientifically can lead to profound improvements in life on Earth, and can help us protect the Earth. Understanding the way the Earth functions is also a critical foundation for exploring the universe. The Earth, our "home-base," serves as a reference by which we observe and judge the rest of the universe, as well as by which we understand life along with its limitations. Advancements in Earth science can inspire exploration in the next generation in a unique way. Exploration of the Earth is an endeavor that is unique in that we live here, and many more modes of exploration are currently possible than for exploration elsewhere.

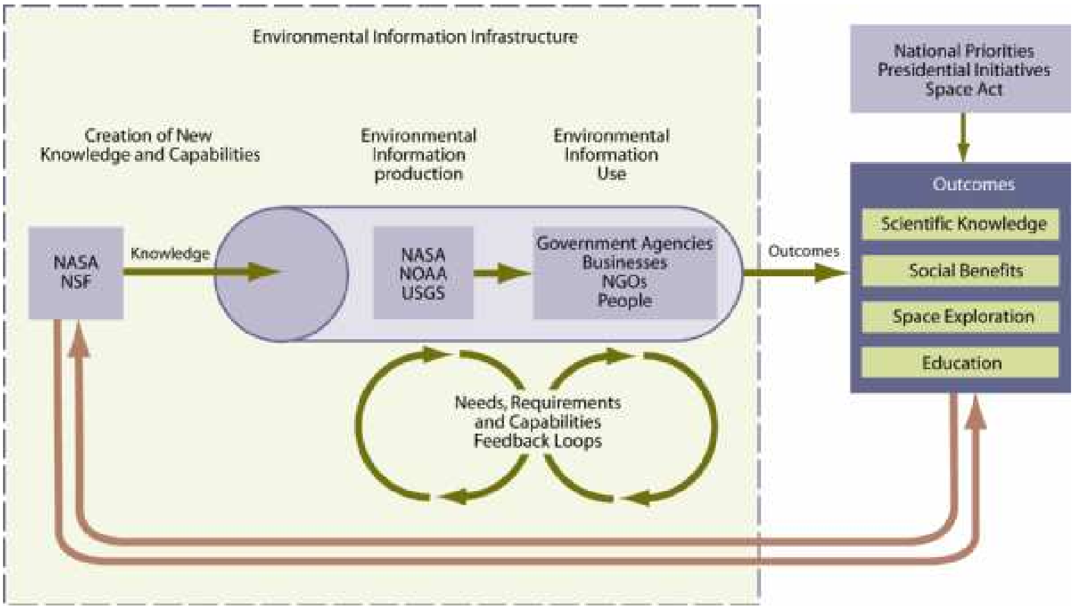
1.4 NASA’s Vital Role: Front-End Research to Enable National Priorities & Societal Benefits

In addition to making fundamental discoveries that lead to societal benefits directly and through spin-offs, an active program that bridges basic and applied science makes it possible for NASA to take leadership in addressing some of the most pressing problems facing humanity in the coming decades, including food security, human health, clean water, and economic development and poverty. Over the next two decades the pressures of human actions on the biosphere will stress its ability to provide natural capital and ecosystem services and this will require a concerted effort by NASA to study the ramifications, indeed to support sound management solutions. Working in partnership with other agencies, NASA Earth science is well positioned to find answers to questions such as “how will future agriculture systems under stress from climate change and land degradation feed a growing population?”

Given NASA's central role in the pursuit of new Earth science knowledge, it is important that NASA also take a leadership role in developing a robust and sustainable mechanism for determining the needs of the nation for Earth science information. This will allow this knowledge to be applied to ensure that we are achieving the greatest benefit of our scientific investments for society, and will help NASA maintain an appropriate balance between curiosity-driven and practical scientific pursuits.

We see the environmental information infrastructure as a pipeline from the creation of new knowledge and capabilities (e.g., through exploration, discovery, and development activities by NASA and NSF), to environmental information production (e.g., by NASA, NOAA, and the USGS), to environmental information use by government agencies, businesses, non-governmental organizations, and individuals. The outcomes of these activities include new scientific knowledge, societal benefits, education, and space exploration, which are national priorities identified through Presidential initiatives and the Space Act. On-going feedback loops of needs, requirements, and capabilities connect the production and use of environmental information. Feedback loops connect national priorities for future outcomes with the research priorities for the creation of new knowledge.

The Committee believes:
1) That it is important to keep the pipeline filled by investing in the creation of new knowledge in order to ensure future outcomes vital to the interests of our nation, and
2) That it is important to formally support feedback mechanisms to ensure that new knowledge is being created that can ultimately satisfy national priorities.
3) That NASA has a unique role in education to excite and inspire the public through its fascinating science results from Earth and space, and better prepare the younger generation for the society of the future.



Societal Benefits of Environmental Information -- Effective Feedback Keeps the Pipeline Filled and Flowing

It is possible to plan and prioritize fundamental (or curiosity-driven) science based almost entirely on needs identified by the science community itself. In contrast, the pursuit of practical science having benefits to society carries the obligation to assess societal needs and determine how best to fulfill them. This is a task that is far more complex and time-consuming than most people realize. The user base for Earth information is large and diverse, ranging from local governments to multinational corporations to individuals. With the rapid spread of information technology, this community and its needs evolve ever more rapidly. How do we know what Earth information will be most needed by governments, businesses, and individuals ten to thirty years from now? Our ability to answer this question accurately is critical if we are to spend NASA budgets wisely. Doing so will require us to explore many new avenues of academic and practical inquiry regarding how people use information and what methods can be used to assess their needs. A dedicated program addressing this issue must be implemented and used to continuously improve our "awareness" of the societal needs that NASA science meets.

The end goal (2035 and beyond) for this roadmap is a fully instrumented Earth system, networked to predictive models, serving science and decision-makers. This future program will realize the full benefits to society of our research, while opening up new science through discovery. To get there, we must build a foundation for comprehensive observing and modeling in the next decade (2005-2015), and work to expand our view of Earth and reach into society in the decade after (2015-2025). Throughout we must mature our measurement and modeling capabilities, and carefully manage our data - past, present and future.

The objective of this roadmap is directly traceable to the nation's objectives for NASA, and to NASA's mission and vision. It will evolve over time with society's concerns in response to discoveries about the Earth system, and in response to technology advances for both space and in situ observations.

2 Flowdown to Roadmap Objectives

2.1 Architecture

A key feature of this roadmap is the flowdown within a pathways and stages framework from presidential initiatives through the roadmap objective to science questions to achievements by decade to investigations and missions (Table 1).

Direction of flow

Hierarchy	Report reference
Presidential Initiatives	Appendix B.1.1
NASA Objective for 2005 and Beyond - Earth Science & Applications Roadmap	Section 1
Guiding Science Questions	Section 2.2
Scientific Objectives:	Section 2.3
Integration Objectives	Section 2.4
Pathways/Stages	Section 3.3
Achievements by decade	Section 4.2
Investigations by decade	Section 4.2
Missions by decade	Section 4.5

Table 1: Flowdown from Presidential Initiatives to missions within the pathways/stages framework

The roadmap objective contains a key phrase: "*advance scientific knowledge of the Earth system*," which the Committee took as its primary focus in executing the flowdown to next-level objectives.

2.2 Science Questions

Guiding Questions: Within the framework of our objectives any line of scientific inquiry will have a gradual progression through phases of Exploration, Continuous Awareness and Developing Perspectives. Our level of knowledge about the Earth system is currently at different stages, depending on what questions we ask. The desired outcome of this roadmap is to advance our scientific knowledge of the Earth system. We will do this through a steady progression of activities that answer guiding questions and provide fundamental scientific knowledge of the Earth. Addressing these questions will lead to results that NASA can pursue with its partners to transform this basic knowledge into the practical science that underlies critical societal benefits. This balance between fundamental and applied knowledge is a hallmark of the Earth sciences, and a key reason for its central importance in NASA.

***Fundamental* Scientific Knowledge:**

How Does the Earth Support Abundant Life?

- How does the atmosphere protect and sustain us?
- How are our weather and climate evolving?
- What controls the availability of water on the planet?
- How does life influence and respond to changes in environmental processes on Earth?
- What causes changes to the Earth's surface and interior?
- What role do human systems play in driving changes in the Earth system?

We are committed to strengthening the practical scientific knowledge that follows from addressing these questions. As we do so, we will better able to support decisions that will help to protect and enhance Earth's ability to support life:

- We will better understand how to ensure that the atmosphere continues to protect and sustain us.
- We will better understand how changes in weather and climate impact us, and what can be done to respond.
- We will better understand what we can do to protect and improve the availability of water.
- We will better understand how to positively influence the interaction of life with environmental processes.
- We will better understand how to use our understanding of the solid Earth to mitigate natural hazards.

The guiding questions lead directly to **strategic roadmap scientific objectives** and are linked to the **strategic roadmap integration objectives**.

2.3 Strategic Roadmap Scientific Objectives:

Progress towards answering these questions will come from implementing investigations, including observing systems and modeling systems, with requirements directly traceable to the following **strategic roadmap scientific objectives**:

Understand the Earth as a system of interacting natural and human systems, including:

- Atmospheric Composition: the sources, sinks, transport, and transformations of aerosols and atmospheric chemical species
- Climate and Weather: the present state and expected evolution
- Water: the storage, distribution, and transport of water in all its forms

- Life: biogeochemical cycles and the distribution and processes of life within Earth's ecosystems
- Solid Earth: the processes that modify Earth's land surface and interior and contribute to natural hazards.

2.3.1 Atmospheric Composition.

NASA's atmospheric composition program is geared to providing an improved prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation in the context of changing climate, the evolution of greenhouse gases and their impacts on climate, and the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality.

Atmospheric chemistry and associated composition are a central aspect of Earth system dynamics. Exchanges with the atmosphere link terrestrial and oceanic pools within the carbon cycle and other biogeochemical cycles. Solar radiation affects atmospheric chemistry and thus its composition. The ability of the atmosphere to integrate surface emissions globally on time scales from a week to years couples several environmental issues including global ozone depletion and recovery and its impact on surface ultraviolet radiation, climate forcing by radiatively active gases and aerosols, and global air quality. Aerosols are critical to cloud formation and indirectly to precipitation (Water); cloud feedbacks are among the most critical unknowns in climate models (Climate). CO2 is a greenhouse gas released by both burning of fossil fuel and respiring organisms, and removed from the atmosphere by photosynthesis (Life).

The levels of ozone in the stratosphere and troposphere, respectively, determine the amount of solar ultraviolet radiation reaching the Earth's surface and air quality at the surface. Both can affect human health; increases in the former are helpful, increases in the latter are harmful. NASA currently assesses the state of the stratospheric ozone layer as mandated by the Clean Air Act. According to the Montreal Protocol and it's amendments, as chlorine abundances decline, stratospheric ozone should rise. But will it? Changes in transport and temperature complicate this "expected" recovery. The research program is focused on assessing how the ozone layer recovers in the future.

Greenhouse gases are those that partially trap outgoing infrared radiation. Increases in these gases are widely expected to increase the greenhouse effect, leading to a warming atmosphere and surface; complicating feedbacks are also involved. Carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and chlorofluorocarbons (CFCs) account for most of the forcing, with a small part derived from ozone and water vapor in the stratosphere. NASA's program also measures the detailed distribution and the evolution of these greenhouse gases.

NASA's atmospheric composition research program emphasizes space-borne measurements of tropospheric ozone, aerosols, and gaseous ozone precursors needed to define how emissions in one region affect air quality in other regions. It also looks at possible links between air quality and climate change. Atmospheric winds transport pollutants (such as aerosols and ozone precursors) over vast distances, even across oceans. Space-borne measurements are essential to define the impact of long-range transport of pollutants on air quality. Production of tropospheric ozone is highly sensitive to temperature and winds; stagnation of warm air promotes ozone formation. Model calculations have shown this process may be sensitive to climate change. The research program should focus on obtaining measurements to test these models.

NASA's atmospheric composition research program also requires essential suborbital and laboratory measurements, as well as a vigorous modeling effort. Suborbital observations, obtained by instruments on board balloons, manned aircraft, and unmanned aerial vehicles (UAVs), provide validation of satellite measurements as well as definition of processes occurring on spatial and temporal scales that are challenging to observe from space. Laboratory measurements of the kinetics of both gaseous and gas–aerosols interactions provide crucial information for models; laboratory observations of spectroscopy provide critical information needed to obtain many of the space-borne measurements. Modeling efforts should span the range from chemical data assimilation, focused on interpreting specific observations, to global, three dimensional models that quantify the links between atmospheric composition, global biogeochemical cycles, oceanic processes, and climate change.

While the measurements of atmospheric composition from low Earth orbit using passive remote sensing is fairly mature, scientists have yet to demonstrate the measurement of atmospheric gas phase species with high temporal resolution enabled by sentinel orbits (e.g., geostationary, Lagrange points). The passive LEO measurements carried out today are sufficiently mature that some (most notably ozone column and profile, and water vapor profile) can be transitioned to an operational agency; others remain to be done for the first time. Exploring the sun's effects on atmospheric chemistry and composition is an example of a needed new measurement. Earth's climate is controlled by the solar radiation incident upon the Earth and the associated feedbacks within the Earth system. Solar-driven ionization of the upper atmosphere modifies the ozone levels and the dynamics of the stratosphere. Ion penetration to the troposphere may affect aerosol nucleation and hence cloud formation. None of these effects are well understood, but all are expected to be highly sensitive to variations in the solar power spectrum, in particular UV radiation. However, our understanding of the spectral variability of solar radiation is very poor. A Sun-Earth Mission at the L1 Lagrange Point will advance considerably our understanding of the above processes by providing continuous measurements of atmospheric composition from the surface to outer space, together with measurements of solar activity and of the solar wind. It will enable considerable improvement of Sun-Earth connections in the next generation of Earth climate forecasts.

2.3.2 Climate and Weather

NASA's activities in climate and weather are targeted toward the long and short-term processes generally associated with the fluid parts of the Earth system - i.e. the atmosphere and the ocean, and, in the case of climate, the ice cover that can significantly influence the behavior of each of these.

Weather processes, which occur on scales of hours to weeks, are primarily atmospheric in nature, and can have profound economic and social implications. Weather is commonly thought of in terms of temperature, humidity, precipitation, cloudiness, visibility, and wind. But one of the most critical weather variable is precipitation (rain or snow), as it can have important implications for vegetation health, natural disasters such as hurricanes, floods and landslides, significantly disrupt transportation, or profoundly impact the economic success or failure of the agriculture industry. In addition, precipitation ties in directly to other key considerations within NASA's Earth science program, such as the water and energy cycles. As a result, much of the weather-related mission planning has to date been closely linked to observing precipitation and understanding its underlying processes, such as cloud microphysics. Additional parameters observed to understand weather include surface temperatures, cloud distributions, ocean wind characteristics, etc. The main objectives in the area of weather related investigations are to enable accurate forecasts of precipitation, hurricane landfall, and severe storms.

Since the launch of the earliest satellites 45 years ago, NASA has invested heavily and successfully in weather-related space-based observations, and a robust operational capability for many of the key parameters has been developed. Current and near-term efforts continue to be targeted toward improved precipitation measurement capabilities and cloud microphysics, as well as the three-dimensional distribution of clouds. Given the demonstrated capability of a number of measurements pioneered over previous decades, and the technological challenges associated with meeting some of the highest priority needs for weather, the hardware part of NASA's investment in weather research has recently been limited, with increasing emphasis on assuring the use of NASA-produced data to improve weather forecasting. A critical future investment, however, is in direct observations of global winds, as can be achieved with doppler lidar, to fill important gaps in our understanding of global atmospheric circulation, and the associated implications for the energy cycle and the transport of water and aerosols. Development of additional capabilities, such as high-resolution temperature and humidity profiling is needed to acquire near-surface information, definitions of fronts, and determination of cloud layers in order to interface with finer-scale models. These will likely require active sounding techniques, as we are approaching the limit of passive capabilities.

Climate is typically characterized in terms of probability distribution functions averaged over months and longer, but for the purposes of mission planning, we do not consider periods much longer than several decades. While this research focus benefits considerably from investments in other areas, such as atmospheric composition, specific climate related activities are targeted towards (a) improving multi-decadal climate projection, (b) seasonal-to-interannual prediction of temperatures, precipitation, and drought, and (c) understanding and predicting sea level rise. These are achieved by advancing our understanding of the interactions among the oceans, atmosphere, and cryosphere. Ocean processes are both the driver and the memory of climate variability and change, and as such, many of the efforts in this area are related to understanding ocean circulation processes through the observation and modeling of parameters that affect circulation. These include sea surface height, ocean salinity, surface winds, temperature characteristics, etc. Observations that support our ability to monitor these characteristics and understand their interactions with the rest of the Earth system are of high priority.

The most dramatically changing element of the climate system is the Earth's ice cover that part of the Earth system that helps keep the planet cool by reflecting most of the incoming solar energy and is believed to have been responsible for past abrupt climate changes. Sea ice has a significant impact on ocean circulation, through its direct exchanges of energy, mass, and salt with the ocean. It also influences atmospheric processes by modulating the moisture and energy exchanges between the atmosphere and the ocean. As a result, observations of sea ice thickness are needed to complement the currently routine spatial measurements, especially in the Arctic where the ice cover is shrinking dramatically. Similarly, ice on land is of critical importance and is an observational priority, not just in terms of climate processes, but also sea level.

Apart from ocean thermal expansion, the most dramatic effects on sea level, which is estimated to be rising at nearly 2 mm/yr, are likely to come from the Earth's glaciers and ice sheets. These ice masses store the equivalent nearly 70 meters of sea level, and were the likely source of rapid sea level rise (5 mm/yr) at the end of the last ice age. Observations to date show remarkable changes in parts of the Earth's vast ice sheets and suggest potential instability; consequently, the need to monitor these changes and understand the underlying mechanisms is critical, if we are to understand the potential impacts in coastal regions. This can be achieved by building on the current ice elevation and mass change measurements and determining the amount and nature of discharge by measuring velocities and ice sheet thickness, as well as time-variable gravity measurements.

Ocean observation capabilities for sea level are fairly mature, but current sampling with nadir-only altimetry leaves wide gaps between tracks, which diminishes its ability to measure both turbulent transports in the open ocean and coastal sea level. Sea level rise is not spatially uniform: different coastal areas will be affected differently. In order to maximize societal benefits, consistent high-accuracy measurements are needed at significantly increased spatial density. Also needed are improved technologies for observations in coastal regions, where sea level is affected by the intense winds of storms and there are strong ties to marine life. In the same sense, there is a need to tie the ocean vector winds to be measured by NPOESS to the accurate time series developed during the 1990s and early 2000s with scatterometry.

Climate is very sensitive to cloud processes, through their ability to change the Earth's radiative energy balance. Current climate models have such large uncertainties in unresolved cloud physics that their feedbacks are not well understood. Key properties include cloud cover, height, thickness, ice/water phase, and particle size. Several missions will contribute to improving cloud physics in climate models, as well as to observing the small decadal changes in cloud properties that are sufficient to change climate sensitivity. These missions include the Cal/Val mission to assure sufficient measurement stability, aerosol missions, and active lidar and radar cloud 2-D and 3-D profiling missions.

Crucial to the long time series with extremely high accuracy needed to study a changing climate is the need for providing 'benchmark measurements', a satellite system with very high accuracy to which all orbiting weather and research satellites are tied. The transfer radiometers should cover the full solar and infrared spectrum to calibrate radiometers, spectrometers, and interferometers from 0.3 to 100 µm, the full earth spectrum that drives climate change from solar scattering/absorption through thermal emission/absorption.

The relationship between climate, Sun, and atmospheric composition was addressed in the previous section.

Climate and weather, though they operate on different time scales, both involve the distribution of energy and mass within the fluid elements of the Earth system. As such, the observing and modeling capabilities offer an important complement to one another, and a coordinated investment in these activities, coupled with those in atmospheric composition and water will have significant payoffs.

2.3.3 Water

Water is both a key resource in environmental sustainability as well as a primary component in the Earth's energy budget. Yet, uncertainties remain large. While the global mean rainfall is projected to increase, climate forecast models differ on the expected change in precipitation at regional scales. Of great concern is the uncertainty of projected rainfall in semi-arid regions such as southwest US. The important role that extreme weather events play in these regions is currently difficult to forecast at any time scales. Before useful predictions of precipitation and snowfall can be made, it is imperative that we fully understand the movement of water, and the causes for the apparent variability of the global water cycle—from evaporation, to condensation, to precipitation, to storage terms of snow, ice, soil moisture and underground aquifers, to runoff, and ultimately back to evaporation. Only if the entire process is fully understood can we confidently predict changes that are necessary to guide societal use of water resources. To that end, one must first formulate a number of questions that deal with the closure of the whole water cycle:

1) Is the global water cycle accelerating?

- Can we observe the evaporation, precipitation, and storage well enough to close the atmospheric water cycle and understand the root causes for any changes?
- Can we observe the storage of water in terms of snow, soil moisture, surface water and aquifers, and river runoff to fully understand the transfer of water from one reservoir to another? Is this water balance consistent with the atmospheric branch of the water cycle?

2) How do natural and anthropogenic processes and factors affect water quality?

It's important to link the study of the water cycle to the rest of the Earth system. These include the role of aerosols in affecting cloud properties (which affect regional precipitation and the partitioning of energy between the surface and the atmosphere. Biology also plays a role in partitioning water between the surface terrestrial biosphere and the atmosphere.

The atmospheric water cycle (evaporation, precipitation, and storage) can be addressed today only in part. Rain has been measured successfully from satellites with a combination of radars and microwave radiometers, but measuring falling snow remains a challenge. Over large regions where snow and ice storage is not an issue, soil moisture is the largest storage term. It can be measured with low frequency active and passive microwave sensors. Evaporation rate is inferred from other sufficiently comprehensive measurements. The Global Precipitation Mission (GPM) and the soil moisture mission Hydros will make important progress in this branch of the hydrologic cycle. Both precipitation and soil moisture have significant application components of their own. Before a true closure experiment can be carried out, better evaporation measurements will have to be made.

The terrestrial water cycle is equally challenging. Precipitation must balance evaporation plus surface storage. Here soil moisture, snow, ice and surface water storage, including lakes, rivers and wetlands, plus underground aquifer storage, and the transport between them must be considered. Snow and ice can both be measured through combinations of active and passive microwave sensors, while water storage in lakes and rivers can be obtained through interferometric radar techniques and laser altimetry. Changes in ground water can be derived from detailed gravitational measurements. When flown in conjunction, such missions will help close the terrestrial water cycle. Like the atmospheric water cycle, this component also has significant and immediate practical applications in terms of fresh water availability and river runoff projections.

Water quality, important for both environmental and economic health, is perhaps the most difficult parameter to measure from space, requiring measurements of dissolved oxygen, turbidity, and chlorophyll. A combination of space-based and in-situ observations offers the greatest opportunity for progress in this area.

Together, these experiments are critical to gain confidence in our description of the water cycle that is required before useful forecasts can be made. Significant societal benefits can be derived from the individual measurements. Knowing the global and regional amount of precipitation has great social value even if the entire global water cycle is not yet fully understood. The same is true for soil moisture, for snow accumulations, and for surface water and river discharges. Some of these parameters should be measured individually in preparation for a great experiment in which all of the parameters are measured simultaneously from different vantage points.

2.3.4 Life

As far as we know, Earth is the only planetary body that is home to life. Life is evolved, organized, dynamic and abundant and these complexities are revealed on a global scale in the Earth's biosphere. Earth science provides the opportunity to understand our planet and at the same time explore the dynamics and functions of a fully evolved and developed life system. The functioning of life on Earth helps regulate climate through the emission of trace gases and it provides important ecosystem services upon which economic systems and human health depend. However, our understanding of life and its interaction with the Earth system is far from complete.

The approach to the Life line of inquiry is to discover fundamental dynamics of the biosphere, answer key questions related to the carbon cycle and the functioning of ecosystems in natural and disturbed states, and integrate this understanding into the larger Earth System framework. Life on Earth helps regulate climate through emission of trace gases,. Carefully planned missions can move the science from our current indirect assessments of biomass stocks to direct determinations of biosphere dynamics directly coupled with the other elements of the Earth system. In this way, we endeavor to develop a predictive understanding of the living Earth and its role in the Earth System.

The Life program has a focused scientific strategy to guide the development and deployment of measurements, based on five general challenges:

1) *Observe global changes in biomass and stocks:* observe ecosystem function and process and its role on the global carbon cycle; improve direct measurements of carbon stocks and biomass, and the fluxes of carbon, beginning with assessments of global distribution through characterization of change, dynamics, and processes

2) *Mechanics of ecosystems:* gain a broad, process-level understanding of all facets of the biosphere as a life-support system, including biodiversity and ecosystem function.

3) *Influence of the dominant species on Earth:* observe and predict how human activities affect the Earth system.

4) *Connections:* understand the role of the biosphere in the Earth system and its interaction with and influence upon climate, atmospheric composition, water, solid Earth, and solar input. Collaborative missions with other disciplines will enable synergy across the Earth sciences and with the Sun-Solar Connection Roadmap.

5) *Life here and beyond:* synthesize our measurements to identify the key signatures of Life to complement and support discovery missions; aid in the development of exploration observers such as the Terrestrial Planet Finder.

One clear focus for the Life roadmap is to gain a predictive understanding of the global carbon cycle, with particular reference to its dynamics, controls, and influence from and on human activities. The carbon cycle is both regulated by climate and is influenced by it. Using the carbon cycle as an emphasis provides a strategic focus for measurement missions. A predictive knowledge of the carbon cycle is fundamental to understanding all biogeochemical cycles on Earth and its role in climate. An assessment of the carbon cycle requires measurement of all pools of carbon and the fluxes among them. Knowledge of how ecosystem metabolism provides sources and sinks of carbon is absolutely critical. Several key measurement categories can be identified:

- *High-resolution CO_2.* Measurements of atmospheric concentrations and profiles of CO_2, CH_4, and other greenhouse gases with sufficient accuracy to characterize sub-regional carbon emissions and sequestration are a priority.
- *Vegetation Structure, Biomass, and Disturbance.* Vegetation height profiles over Earth's land surface are needed to quantify land biomass and carbon stocks, quantify ecosystem recovery following disturbance, and characterize habitats.
- *Plant Physiology and Functional Types.* Observations of plant functional types and physiological function are required for both land and ocean. Current understanding is limited by a lack of quantitative information on the variety, distribution, abundance, and variability of plant groups with important ecological functions.
- *Coastal and Open Ocean Carbon. Coastal and Open Ocean Carbon.* Measurements of carbon stocks in the coastal and global ocean are required beyond the present capability of determining chlorophyll concentrations.

Near-term missions focus on basic measurements of changes in carbon storage on land and in the oceans. The NPP mission will enable measurements of changes in the biosphere, including land and ocean productivity, vegetation phenology, fires, and other important variables at kilometer spatial scales. These measurements would continue operationally on NPOESS (VIIRS and LCDM/OLI) The Climate program's Cal/Val mission will help insure the quality of the VIIRS data on NPP and NPOESS. While these missions focus on carbon storage, OCO will make atmospheric column measurements of CO_2 which will be used to assess the variability of carbon sources and sinks and their causes (shared with Atmospheric Composition).

The next phase of missions should provide better quantification of both storage and flux parameters, as well as forcing parameters. A High-resolution CO_2 mission in tandem with an Aerosol mission will provide CO_2 profiles in the atmosphere, allowing increased analysis of sources and sinks. A proof-of-concept Biomass mission can focus on providing global, mapped estimates of above ground vegetation biomass. A flagship mission in the 2020 timeframe should focus on plant physiology and functional types both on land and in the ocean. This mission can provide high-spectral-resolution imagery for quantifying plant abundances, distributions, and carbon fluxes on appropriate space/time scales. Integrating with this flagship mission should be a Biomass dynamics follow-on mission, which will directly measure changes in above-ground carbon stocks. A Photosynthetic Efficiency mission can directly assess plant and algal physiological status using pulsed lidar technology. An Advanced Land Cover measurement mission would measure land cover and use change measured at high spatial resolution with the ability to discriminate plant functional types and human created land cover features.

Three missions are needed to assess the ocean biosphere and its role in the carbon cycle. The first is a Coastal / Global Ocean Carbon mission, which will quantify dissolved organic carbon pools in open ocean and coastal environments. This mission should be followed by Ocean Particle Profile and Ocean Carbon Storage missions, which are aimed at assessing vertical profiles of particle abundances in the upper ocean and all pools of carbon, respectively. These missions will all contribute to understanding the ocean ecosystem dynamics and its role in the carbon cycle.

The Life program can contribute to supporting other Strategic Roadmap areas. For instance the suite of Life observing platforms recommended here can be marshaled to gain a better indicator signature for life where it may occur. The development of a special mission to quantify and test a *bio-signature for life* using high-resolution spectral imagery would be an important experimental contribution to other exploration and discovery missions. Finally, solar processes influence the biosphere, and the biosphere can influence the climate impacts of solar variations. Hence, there are strong links between the Life program and the objectives of the Sun-Solar Connection roadmap (SRM10).

2.3.5 Solid Earth

In 2002 NASA’s Solid Earth Science Working Group identified the six scientific challenges of highest priority for the agency’s Solid Earth Science Program for the next quarter century. Those challenges, still unmet, are to answer the following questions:

(1) What is the nature of deformation at plate boundaries, and what are the implications for earthquake hazards?
(2) How do tectonics and climate interact to shape the Earth's surface and create natural hazards?
(3) What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea level change?
(4) How do magmatic systems evolve, and under what conditions do volcanoes erupt?
(5) What are the dynamics of the mantle and crust, and how does the Earth's surface respond?
(6) What are the dynamics of the Earth’s magnetic field and its interactions with the Earth system?

To address the factors that control the spatial and temporal patterns of earthquakes and earthquake-generated tsunamis, space-based observations are needed for synoptic measurements of the strain field through the entire earthquake cycle, including episodes of aseismic accumulation of strain. Such measurements will provide insights into how stress is transferred between faults, the fraction of strain that is accommodated seismically, and ultimately how faults fail. Diverse temporal and spatial scales for the governing processes dictate a variety of specific observational approaches. Satellites devoted to Interferometric Synthetic Aperture Radar (InSAR) measurements together with Global Positional System (GPS) networks are needed to provide dense, frequent sampling and high-accuracy observations of changes at the Earth's surface. Existing and planned seismic networks and borehole sensors operated by other agencies will complement space-based low-frequency sounders, and highly accurate gravity measurements can help to characterize subsurface regions subject to seismic hazards. One or more satellites dedicated to InSAR measurements will provide, for North America, an essential component of the EarthScope Program, other elements of which have recently been initiated with funding from the U.S. National Science Foundation.

The land surface evolves both by the actions of man and by such natural forces as tectonic deformation and transient hydrologic and biologic influences on erosion and deposition. During severe storms, how floods progress and landslides are generated depends on topography, soil characteristics, vegetation, and rainfall intensity. Similar interactions determine how flood waves migrate through a catchment and how much sediment is eroded, transported, and deposited during a storm. Remotely sensed data play an integral role in reconstructing the recent history of the land surface and in predicting hazards due to events such as floods and landslides. Information needed to address this challenge includes surface, subsurface, and hydrologic characteristics. These categories have a range of observational requirements. Quantities that change rapidly, such as river stage or precipitation, call for hourly measurements, whereas others might require only seasonal measurements (e.g., vegetation) or occasional (5–10 yr) quantification (for example, soil composition and thickness). The ability to acquire such data in real- or near-real time and to integrate that information with quantitative models are requisite to the development of a capability to predict the timing and magnitude of floods and the heightened risk of landslides during storms, particularly in remote, poorly monitored areas.

Paleo-environmental and historical data have clearly documented sea-level changes in the past, and new scientific information on the nature and causes of sea-level change and the development of a quantitative predictive capability are therefore of utmost importance for the future. The solid Earth plays an important role in this issue, because of the time-varying response of the solid Earth to changes in surface loading by oceans and ice masses. More generally, this topic — addressed above in the Climate section — is inherently an interdisciplinary scientific problem impacted by many programs within NASA as well as the efforts of other federal and international agencies.

The eruptive power and often-long intervals of quiet dormancy render volcanoes both difficult objects of study and dangerous geographic neighbors to population centers. The threat of eruption is always there, but because eruptions are episodic, the fastest route to general understanding is to take advantage of observations of volcanic activity on a global scale. Including remote terrestrial and undersea volcanoes, there are thousands of volcanic centers whose level of activity is poorly known. Indicators of activity include surface deformation, seismicity, changes in gravity, fluxes of gasses, and actual eruptions. Little is known, however, of how these phenomena are interrelated. The physical mechanisms that cause surface deformation and those that control the rates and styles of eruptions are similarly poorly understood. An ability to predict the timing, magnitude, and style of volcanic eruptions should be achievable with improved global observations and physical models.

Mantle convection is the engine responsible for plate motions, seismicity, volcanism, and mountain building. The deformation of the Earth's surface required to accommodate plate tectonics occurs primarily along plate boundary faults and relatively broad zones of deformation adjacent to the plate boundaries in the continents. The forces that drive the motions of the plates, however, are not well quantified. The global gravity field and long-wavelength topography provide key integrative measures of density anomalies associated with mantle convection, although their interpretation requires information on the structure of the tectonic plates and the variation of viscosity within the mantle. Improved information on plate characteristics and mantle viscosity can come, in turn, from measurements of the time-dependent response of global gravity, topography, and Earth rotation to loading and unloading by glaciers, oceans, and other forcings.

Although it is widely recognized that a dynamo operating in the fluid outer core generates the Earth's magnetic field, the details of how that dynamo works remain far from understood. Over the past 150 years, the main (axial dipole) component of the Earth's magnetic field has decayed by nearly 10%, a rate 10 times faster than if the dynamo were simply switched off. Intriguingly, this decay rate is characteristic of magnetic reversals, which paleomagnetic observations have shown occur on average, though with great variability, about once every half million years. The recent dipole decay is due largely to changes in the field in the vicinity of the South Atlantic Ocean. This pattern is connected to the growth of the South Atlantic Magnetic Anomaly, an area in which the field at the Earth's surface is now about 35% weaker than would be expected. This hole in the field impacts the radiation dosage of satellites in low-altitude orbits. Addressing such questions as how the South Atlantic Magnetic Anomaly will evolve and whether the main field is reversing requires long-term observations by constellations of satellites combined with numerical modeling of the Earth’s core dynamo.

The interconnected nature of Earth science means that the most challenging issues in the field today bridge several disciplines. As such, defining the measurement requirements to address these challenges is best done through a unified observational strategy. Such a broad strategy incorporates diverse methodologies (including space-borne and ground measurements), technological advances, and complementarity among observations. NASA’s Solid Earth Science Working Group in 2002 recommended the following observational strategies to address the fundamental challenges to solid Earth science and society: (1) Surface deformation; (2) high-resolution topography; (3) variability of Earth's magnetic field; (4) variability of Earth's gravity field; and (5) imaging spectroscopy of Earth's changing surface. Continued development of space geodetic networks and the International Terrestrial Reference Frame, as well as investment in promising techniques and observations, such as subsurface imaging using low-frequency sounders, are important components of an overall program.

2.3.6 Human Interactions

We have not identified a separate activity for the role of humans in the Earth system. This is considered a crosscutting line of inquiry, to which each of the other lines of inquiry contribute. Human activities are changing the biosphere and can place the life support system of this planet at risk. As we enter the 21st century, we face significant scientific and engineering challenges as environmental changes occur at an accelerating rate. We are experiencing rapid climate and ecological shifts, the degradation of freshwater resources, the globalization of disease, the threat of biological and chemical warfare and terrorism, and the more complex question of long-term environmental security. We are seeing the impact of multiple stressors on environmental systems, yielding changes that require new science and innovation to understand. These developments present enormous intellectual challenges in the need to address combinations of factors, such as the interactions between human activity and natural cycles, to address environmental challenges. In response to these challenges, scientists have begun conceptualizing new approaches to problems, reaching across traditional disciplinary boundaries to study complex environmental systems *in toto*. Researchers are also creating new linkages between basic and applied scientific endeavors.

It is important to understand the complex interactions between human systems and natural systems, and this understanding will come from measurements tied to models. Observations of land cover and land use change and other actions of humans will aid in the development of prognostic models of human disturbance to the Earth system that can link to the other Earth science areas.

2.4 Strategic Roadmap Integration Objectives

No individual measurement, mission, or model can answer the set of guiding questions identified in Section 2.2. They can be fully addressed only through the integration of investigation systems into national (and international) observation systems, such as the Integrated Earth Observation System (IEOS) or the Global Earth Observation System of Systems (GEOSS). Because the capacity to answer guiding questions emerges through the integrated results of multiple scientific investigations, this document also identifies three **strategic roadmap integration objectives**. These are: Exploration and Discovery; Continuous Awareness; and Developing Perspectives (Fig. 1).

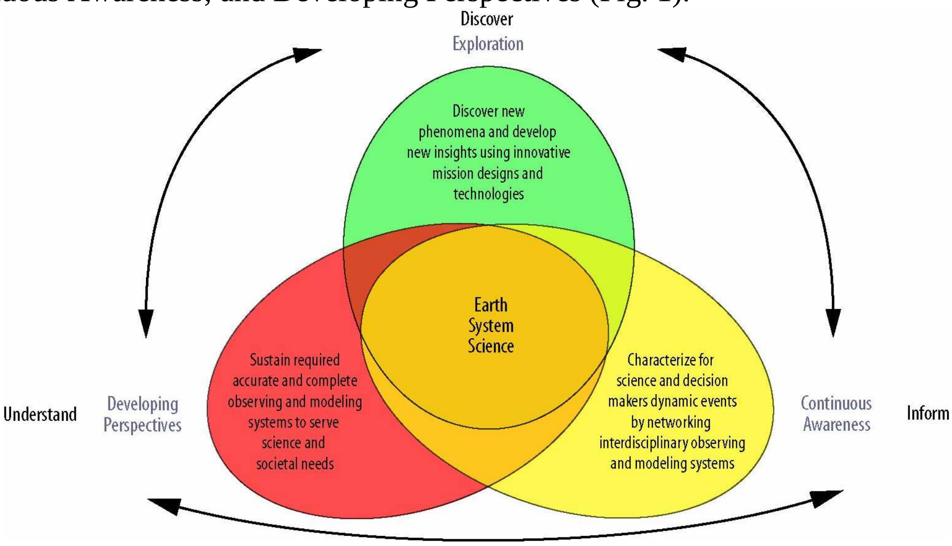


Figure 1: Our three strategic roadmap integration objectives represent different approaches to understanding the Earth system that converge to represent the whole of Earth system science.

2.4.1 Exploration and Discovery

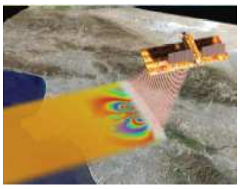
Explore unknown aspects of the Earth system by implementing new investigations enabled by new insights, technologies, capabilities, and vantage points.

This objective focuses on the idea of exploration for the sake of uncovering new and exciting aspects of the Earth system, including exploring phenomena we cannot yet sample, places we've never seen, and processes we don't yet understand; such as the Earth's interior, or the bottom of the ice sheets and the oceans. It traces to the NASA strategic objective for this roadmap in several ways. It contributes to all three elements: space-based observations, assimilation of new measurements, and the development of new technology and capabilities. In order to explore the frontiers of Earth science, a global perspective only available from space, is required. In order to interpret guiding measurement data from space-based observations, the results must be assimilated into existing infrastructure. Resulting models must be run and results analyzed in order to understand the findings. Thus, implicit in this objective is the need for new technology and capabilities; these are included as part of the objective itself.

Exploration and Discovery of Surface Change with InSAR

EXAMPLE

NASA has always pioneered technical and scientific breakthroughs, and the use of Interferometric Synthetic Aperture Radar for studying how the surface of a planet changes is an ideal example of an exploratory mission for discovering insights on surface topographic change me. Clearly rated the highest priority measurement of the solid Earth science community, mm-level deformation measurements of the surface due to plate tectonics, subsidence, magma injection and other phenomena may lead to revolutionary forecasting of – and mitigation from – natural hazards like earthquakes and volcanoes.



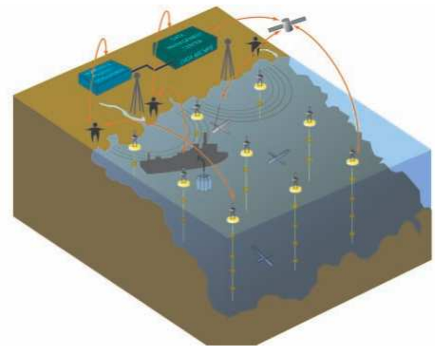
2.4.2 Continuous Awareness

Develop new scientific understanding of dynamic processes and demonstrate capabilities useful for decision support by providing prompt recognition and adaptive observation of dynamic events through the networking of distributed observing and modeling systems.

This objective focuses on understanding the short-term variability in the Earth system. Understanding will be gained by combining measurements from multiple space platforms, ground-based and in situ observations, with modeling and validation efforts, in an intelligent fashion. The continuous awareness integration objective touches on all three elements of the NASA strategic objective for this roadmap. In order to achieve this objective, not only must the global perspective of space be used, but a broad variety of vantage points and observing techniques. This will help characterize the Earth's behavior over a range of vertical, horizontal, and temporal resolutions. The real-time assimilation of new measurements into the science and policy-making communities is an implicit part of the objective, and presents a unique challenge. The development of new technology and capabilities for this objective takes the form of a systems push rather than a technology push. The idealized end state—to view all possible phenomena on all parts of the globe continually—is a challenge, and requires development of new system concepts and advanced data processing methods to handle the massive influx of incoming data.

Continuous Awareness of Coastal Zones
EXAMPLE

The coasts are where we live and play, set sail for trade routes and harvest for their rich marine life. The coasts are also a unique interface between the land and sea and atmosphere. The only way to truly understand the complex interactions of diverse natural phenomena and human influence is to use a continuous awareness approach of simultaneous, independent measurements. The addition of satellite measurements of ocean color (Sea Surface Reflectance) at high temporal and spatial resolution, in conjunction with ocean surface currents, winds, and topography, to already-existing in situ measurements would be able to link the bio-geophysical parameters to phenomena like harmful algal blooms, sea level rise, ecosystem health, storm water runoff – and their consequences for humans. The greatest scientific and societal benefits accrue when continuous awareness clusters are used to make sure the system is greater than the sum of its parts.



A coastal continuous awareness system could consist of:

- In situ arrays
- Hyperspectral imagers
- Along-track interferometers
- Scatterometers

Cable arrays of in situ sensors and floating buoys are making measurements and expanding in regions like Monterey and Los Angeles, California: MARS, MOOS, SCCOOS programs

2.4.3 *Developing Perspectives*

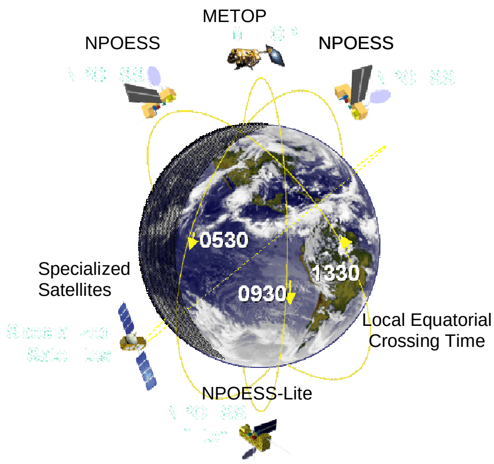
Enable new scientific understanding of long-term Earth processes and trends by sustaining and integrating comprehensive global observing and modeling systems.

This objective is focused on identifying key parameters of the Earth system that will help understand its long-term variability. To do this, NASA must develop technologies, and then implement initial observing systems capable of measuring these parameters to the required exquisite accuracy and consistency over long time scales, particularly important for long-term climate studies. It is expected that partner agencies will continue the measurements over such timescales, as part of the Integrated Earth Observation System. NASA must engage with these partner agencies to execute a smooth transition from research to operations. We envision "climate calibration observatories," launched and maintained by NASA, charged with making climate-quality "benchmark" radiometric observations, with stringent calibration and stability requirements (typically down to the 0.1% level). NASA must also ensure the existence, accessibility, and frequent improvement of long time series of data, through a combination of active data management and active research. To extract the most societal benefit from this information, we need a vigorous numerical modeling capability, focused on long-term climate trends (and quite different from the modeling capability required by the continuous awareness integration objective.)

Developing Perspectives traces to the NASA strategic objective for this roadmap. First, space-based observations are necessary in order to achieve the global perspective this integration objective aims to accomplish. Also, there is a need for new technologies to be developed to provide the capabilities required for this objective, such as very-long-term consistent observations. For example, a mission pushing the technological limits of absolute accuracy, designed to tie data from less accurate missions (which add space-time coverage) is a challenge uniquely suited for NASA.

Developing Perspectives with Atmospheric Chemistry Cal/Val Mission
EXAMPLE

Investigative missions (such as Aura, OCO and Glory) will provide essential information regarding atmospheric chemistry. As these missions provide a preliminary understanding of atmospheric issues, ***their observations will serve as the beginning of environmental data records*** that can provide critical information on patterns of the changing climate.



NPOESS (right) is a tri-agency (NASA, NOAA, DoD) effort to leverage and combine environmental satellite activities; its mission is to provide a national, operational, polar-orbiting remote-sensing capability, incorporating new technologies from NASA. NPOESS will monitor several elements of the Earth system, ***creating 55 environmental data records***. NOAA will maintain a long-term archive and provide the data to the worldwide community.

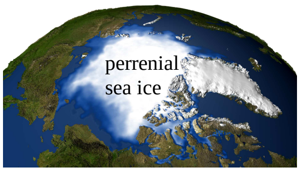
NPOESS data will provide societal benefits:

- Weather observations and predictions
- Ozone measurements
- Climate monitoring and prediction

For a smooth transition between investigative missions and NPOESS measurements, and thus ***to generate the quality of climate data needed a mission designated for calibration and validation is critical.***

A Walk through Exploration, Awareness, and Perspective: Sea Ice

EXAMPLE



In many cases, we learn about elements of the Earth system and their interactions with the rest of the system first through discovery, by just observing, then through awareness, when we have enough information to develop an understanding of the processes and how they work, and finally through perspective when we understand the long-term changes, and the roles of these elements in the larger system. Our past present and future observations of sea ice offer clear examples of each of these stages.

Exploration

The launch of the first visible imaging polar orbiting satellites, allowed the first comprehensive view of the Earth's sea ice cover under cloud-free conditions during polar day. In the years and decades that followed, we were able to use multi-channel microwave instruments to observe continuously under all weather conditions ice extent (1973: single-channel radiometer), ice concentration and type (1978: multi-channel radiometer), ice deformation (1995: synthetic aperture radar), and most recently ice thickness (1991: Radar altimetry, and 2003: laser altimetry, with ongoing developments in VHF sounding). Each of these advances enabled the development, validation, and utilization of the first large-scale models of polar sea ice cover. Ice thickness remains a new area for new discoveries, as it has not been well sampled yet, and the thickness distribution and changes in ice cover, remain largely unknown.

Continuous Awareness

These new discoveries, when coupled with models and other observations, allow scientists to address important issues in Earth system science such as understanding the interactions between the ocean, ice cover, and atmosphere. These interactions have significant implications for atmospheric and oceanic circulation, and thus weather and climate. Achieving a clear understanding of how these processes work has been enabled by observations of: ice margin changes (passive microwave radiometry), details of lead formation (synthetic aperture radar), surface temperatures (infrared, and passive microwave), ice thickness, (altimetry, VHF sounding), snow depth on sea ice (passive microwave), ice motion (visible, scatterometry, passive microwave), surface reflectance (visible), and surface irradiance (combinations of solar irradiance and atmospheric optical measurements) This suite of observations and associated process models allows the development of a comprehensive understanding of sea ice behavior, its interactions with the ocean and atmosphere, and its influence on climate and weather.

Developing Perspectives

To understand the long-term behavior of sea ice, the different characteristics between Arctic and Antarctic sea ice cover, and the role of sea ice within the larger Earth system, following the knowledge gained through the awareness efforts, ongoing monitoring is needed of the spatial characteristics of the ice cover (its spatial extent, and the size and locations of openings within the ice cover), its movement, and its spatially variable thickness. These are the parameters for which a long-term observing capability should be implemented to appropriately "develop perspectives" and flow from past, present, and future observational capabilities.

Guiding science questions lead to fundamental scientific objectives with practical applications, which link to the integration objectives of the roadmap.

3 Formulating the Roadmap

3.1 Context

In the early years of space exploration (1960's to 1980's), NASA Earth science was focused on demonstrating the feasibility of remote sensing of the Earth from space. This was followed by the EOS era (1980's to early 2000's), during which the concept of investigating the Earth as a system from space matured. The strategic implementation stages for Earth Science and Applications link to this history and trace to the strategic roadmap objective and the national goal for space exploration (Figure 2). The next decade (2005 – 2015) will begin building a foundation for comprehensive observing and modeling by focusing on atmospheric composition, climate and weather. The following decade (2015-2025) will expand our view of Earth and reach into society by shifting focus to water, life and solid Earth characteristics of the system. The decade after will result in an integrated, comprehensive and sustained "information web" for Planet Earth, which is the fully developed U.S. Integrated Earth Observation System (IEOS). NASA's role within that system will be to continue to pursue new science questions and to investigate aspects of the Earth system that we have not yet explored.

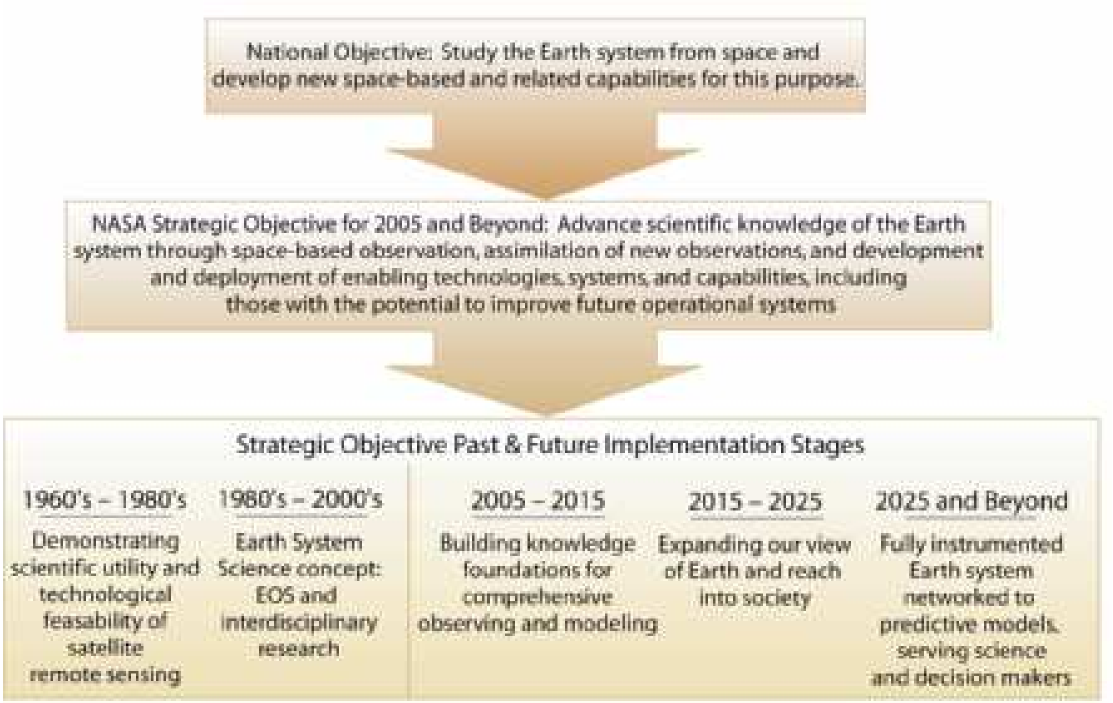


Figure 2: Flowdown from national goal for space exploration to the objective of this roadmap and its relationship to the past, present and future of NASA Earth Science.

3.2 Developing the investigation timeline

In developing our investigation timeline, we envisioned a series of linked, overlapping 'lines of inquiry', each spanning an approximate 25-year interval (Figure 3). Initial investigations along each line of inquiry would tend to be exploratory in nature. This would be followed by the start of a period of "awareness clusters" of investigations. Next comes a period of perspectives investigations, as key parameters are identified and preparations are made to sustain them over the long term. Exploratory missions may continue throughout most of the timeline, as our scientific knowledge and/or technology advances.

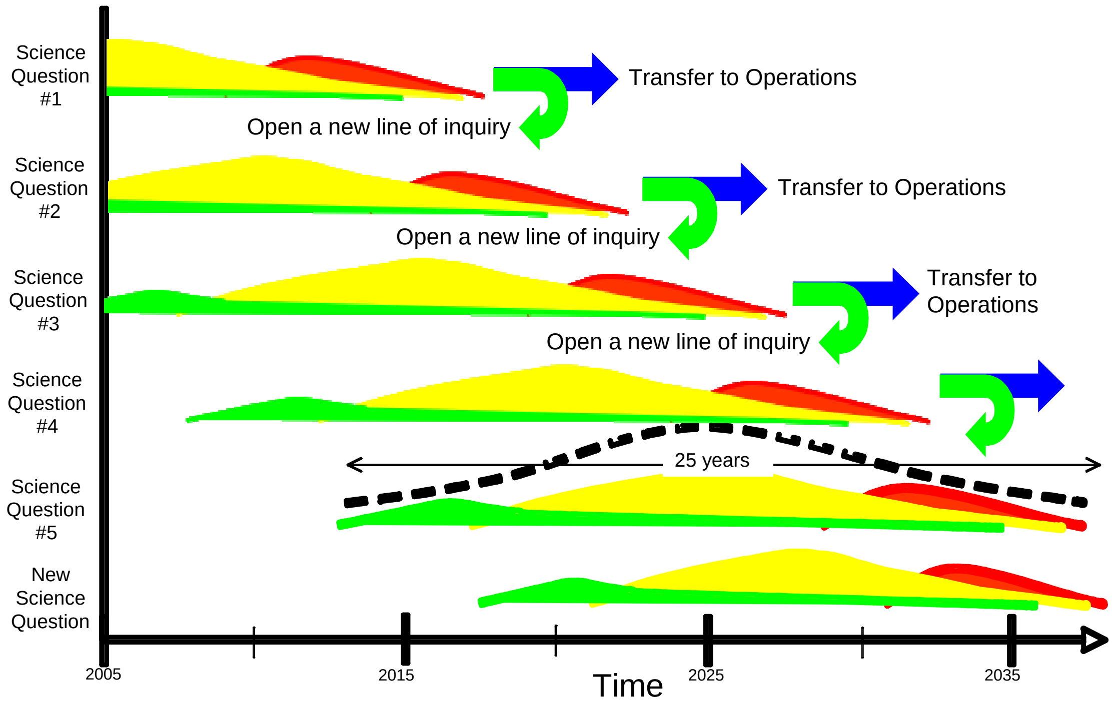


Figure 3: Notional timeline showing exploratory investigations (green), awareness investigations (yellow), and perspectives investigations (red).

> *Awareness clusters focus efforts on answering particular science questions in a given line of inquiry by coordinating and connecting information from multiple space and airborne observations, in situ sensors, and modeling systems during the focus time period.*

Each line of inquiry is targeted at one of the 5 guiding science questions discussed in Section 2.2. Investigations laid out along the line of inquiry are designed to address the achievements set out for each guiding question. Towards the end of each line of inquiry, two outcomes are illustrated. The first is a transfer to operations, i.e., measurements are sustained over the long term by an operational agency. The second outcome is the opening of a new line of inquiry, which enters an exploratory phase. Both may be possible – as they mature, some (but not all) key measurements are transferred to operations, while a breakthrough in technology or scientific discovery may bring to the surface new questions.

To determine the recommended order of the awareness clusters linked to each scientific objective, we evaluated the current state of each line of inquiry, based on the current mission set and NASA's near-term plans. As confirmation, we examined the maturity of all of the measurements in each science area using the Measurement Maturity Index, as described in section 3.4.2.

Investigations were prioritized by the Committee based on the criteria set out in section 2.4, then laid out in sequence on the timeline. To implement the roadmap, we assumed that a balanced portfolio of mission classes, including small, medium, large and flagship missions, would be available. Consideration was given to producing an affordable mission set, which led to spacing out the investigations.

3.3 <u>Pathways and Stages</u>

Figure 4 illustrates the pathways and stages for NASA Earth science over the next three decades, shown in three tiers. The first is designed to open up new areas of science inquiry through exploratory investigations that target the unknown characteristics of the Earth system. The second tier is designed to address the scientific objectives in sequence, with the order of the sequence and activities within each dependent on the overall scientific maturity of that line of inquiry. In each case, the initial activities are discovery-oriented (green), followed by a period of continuous awareness (yellow), then the development of a long-term perspective (red). The third tier (shown as blue boxes) matures our ability to manage information about the Earth system over the three decades.

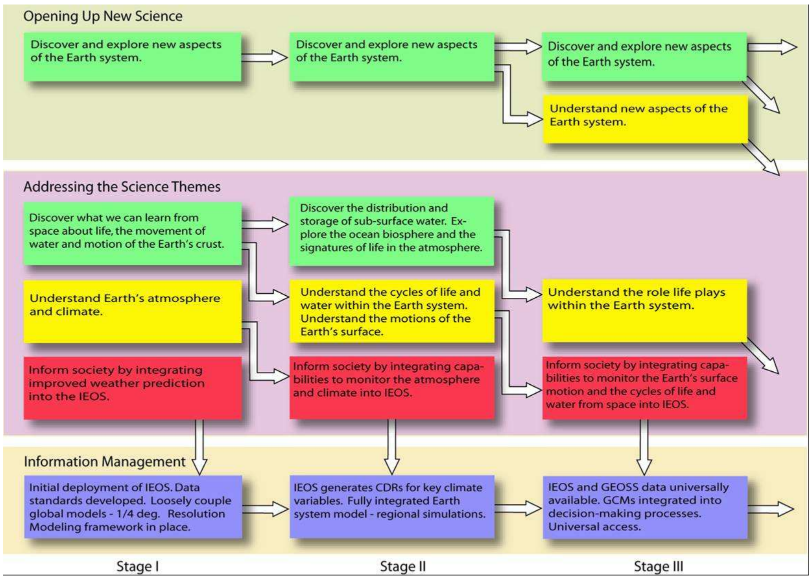


Figure 4. Pathways and stages for NASA Earth science over the next three decades.

3.3.1 Stage I: Building a foundation for comprehensive observing and modeling

In Stage I (2005-2015), we will begin building a foundation for comprehensive observing and modeling by focusing on atmospheric composition, climate, and weather. Through collaboration with NOAA, we expect that by the end of this stage we should be exploiting new NASA observing capabilities and research to improve operational environmental satellites and weather forecasting models. Exploratory activities are planned for the water, life and solid earth lines of inquiry, in preparation for a more intensive look at these questions in the following decade. We expect that data standards for long-term monitoring will be developed as the IEOS is initially deployed, and that fully integrated global Earth System models will be available by 2015, with higher resolution regional simulations in various disciplines by that timeframe. The coupling technology (Earth System Modeling Framework) will simplify the swapping of model components.

3.3.2 Stage II: Expanding our view of Earth and reach into society

In Stage II (2015-2025), we expand our view of Earth and reach into society by focusing on water, life, and solid Earth lines of inquiry. Towards the start of this stage we anticipate handing off responsibility for monitoring aspects of atmospheric composition and climate to NPOESS. Critical to this handoff are some core NASA activities that will enhance the value of NPOESS for science, such as calibration/validation, and funding of science data analysis from NPOESS data streams. Exploratory activities continue to round out our knowledge of the cycles of life and water, and to look for unknown aspects of the Earth system. We expect that our partners in the US IEOS will be producing 'gold standard' climate data records by the end of this decade, and that Global Climate Models will be fully integrated together, with some regional level simulations under way.

3.3.3 Stage III: Fully instrumented Earth system networked to predictive models, serving science and decision makers

In Stage III (2025-2035) we will integrate a comprehensive and sustained "information web" for Planet Earth and open up new lines of science inquiry through discovery. During this stage we should be able to hand off responsibility for monitoring aspects of life, water, and solid Earth to the appropriate operational partners in the US IEOS. Exploratory activities continue to look for unknown aspects of the Earth system. We expect that information derived from IEOS and GEOSS will be universally available and accessible by the end of this decade (much like weather forecasts today), and that Global Climate Models will be firmly embedded in decision-making processes. We envision a fully integrated Earth system model at this stage with universal, high-speed access to the information it provides. As society moves towards sustained management of the Earth system, we expect NASA to be at the forefront in providing the science-based information that policy and decision-makers will need.

3.4 Prioritization Criteria

3.4.1 Criteria used

Prioritizing investigations is at the heart of the roadmap, and was done with considerable thought and a defined, logical process. At the core of the roadmap is the time-ordering of activities based on scoring of scientific, technical, and societal relevance with an emphasis on maximizing efficiency of related measurements. This is the idea of 'awareness clusters,' a time period during which activity is focused on answering particular science questions in a given line of inquiry by coordinating and connecting information from multiple space and airborne observations, in situ sensors, modeling systems, and validation efforts.

An investigation list was created starting from the Earth Science Technology Office (ESTO) database of investigations and mission concepts, and continuing with science community documents like the Solid Earth Science Working Group report, the Earth-Sun System: Potential Roadmap and Mission Development Activities Document (Dec. 23, 2004), the Committee on Earth Observation Satellites handbook, EOS data record lists, and NOAA climate and weather measurement requirements. These measurements and missions were then evaluated against our prioritization criteria, listed below:

- ***Does the investigation advance science?***
- ***Does the investigation support decision-makers?***
- ***Does the investigation benefit society?***
- ***Is the investigation consistent with recommendations of national priorities?***

In terms of the potential to advance science, we considered whether there was significant potential to make a major scientific breakthrough, and whether a particular investigation supported NASA's overall mission. With respect to decision support, consideration was given to NASA's responsibilities to the Climate Change Science Program (CCSP) and IEOS, and whether a particular investigation addressed nationally important applications. We also weighed the potential to reduce uncertainty in predictions, and the social importance of the science question addressed. In examining the benefits to society, we looked at the extent to which an investigation might help protect vital needs (such as water and clean air), or lead to reductions in disruptions to daily life (e.g. through disaster mitigation and warning). We asked ourselves whether an investigation would have a high likelihood of educating the public. Does it have linkages to multiple disciplines?

This prioritization is subject to reasonable constraints on the available budget, the technological readiness of a given measurement, and the maturity of the measurement within a given line of science inquiry. Naturally, broader community input and the results of the NRC Decadal Study will augment the detail and appropriateness of this prioritization system and resulting timeline.

3.4.2 The Measurement Maturity Index

To determine the current state of each line of inquiry the Committee developed the concept of the measurement maturity index (MMI) for space-based measurements. The MMI encapsulates both the scientific maturity of a measurement and its readiness to transition to operational use. It is a subjective maturity descriptor of a specific measurement by a specific technique to be used with other considerations, not as a stand-alone number for decision-making. Carefully applied, it can be used to help decide how to progress with a measurement. As an aggregate measure the distribution of measurement maturity values within a given line of inquiry could be used as an indicator of a well-balanced program that includes new as well as maturing measurement capabilities. The Committee believes that the measurement maturity index could be a valuable tool, and that it could be generalized beyond space measurement to all measurement types (for example, in situ, airborne, etc.). The Committee discussed but did not have time to explore the concept of a complementary measure of model maturity and the need to plan and manage the matching of future observation outputs with future model inputs.

There are eight MMI levels (Table 2). MMI-1 refers to a parameter that is thought to be significant, for example, as a driver or indicator of climate change that has not been measured yet. An example of MMI-1 is ocean mixed-layer depth, which may be critical for understanding the ocean biosphere, but has not yet been measured or derived from remote sensing data. MMI-8 refers to a measurement for which the transition from research to operations is complete, that is routinely used in decision support systems. An example of MMI-8 is the capability to monitor day-to-day weather patterns, which has already successfully transitioned from NASA to NOAA.

Measurement Maturity Index	Definition for Space-based Measurements	Example Measurement Technique	
MMI-1	Parameter thought to be significant. Not measured yet.	Ocean Mixed Layer Depth	
MMI-2	Measurement feasibility demonstrated. Parameter shown to be significant in one or more Earth system models.	Ice thickness	Discovery
MMI-3	Measurement from space demonstrated in a pathfinder mission. Parameter shown to be significant across multiple Earth system models. Pilot program for decision support initiated	Sea Ice Thickness	
MMI-4	Measurement demonstrated in a pathfinder mission Parameter shown to be significant across multiple Earth system models. Pilot program for decision support ongoing.	Precipitation	
MMI-5	Measurement demonstrated over a sustained period. Parameter generally accepted to be a key measurement to be sustained over long periods.	Land Surface Temperature	Awareness
MMI-6	Measurement demonstrated over a sustained period. Parameter demonstrated to add value to an existing decision support tool or process.	Sea surface topography	
MMI-7	Measurement demonstrated over a sustained period. Measurement ready for transfer to operational use.	Stratospheric Ozone (high vert. resolution)	Perspective
MMI-8	Transition from research to operations complete. Parameter routinely used in an existing decision support tool or policy process.	Daily weather patterns	

Table 2: Definition of Measurement Maturity Index levels for space-based measurements. Approximate mapping to Integration Objectives is shown on the right-hand side.

As measurement maturity levels are advanced, clearly multiple activities will need to progress (Figure 5). Technology development and improvement will occur for lower levels of MMI (1-3). Somewhere between MMI-2 and MMI-3, a pathfinder spaceborne mission is launched, followed by an operational precursor mission between levels 4 and 5, and then an operational mission at level 6. At lower MMI-levels, the measurement will be incorporated into Earth system models in a rudimentary fashion, reaching demonstration of significance across multiple models by MMI-3. By MMI-5, the parameter is generally accepted as a key measurement that it is critical to sustain over long periods. Atmospheric CO_2 and sea level are examples of such key parameters. Embedding the measurement in decision support starts early in this process, with pilot programs beginning at level 4, and a completion of the handoff from research to operations by level 6.

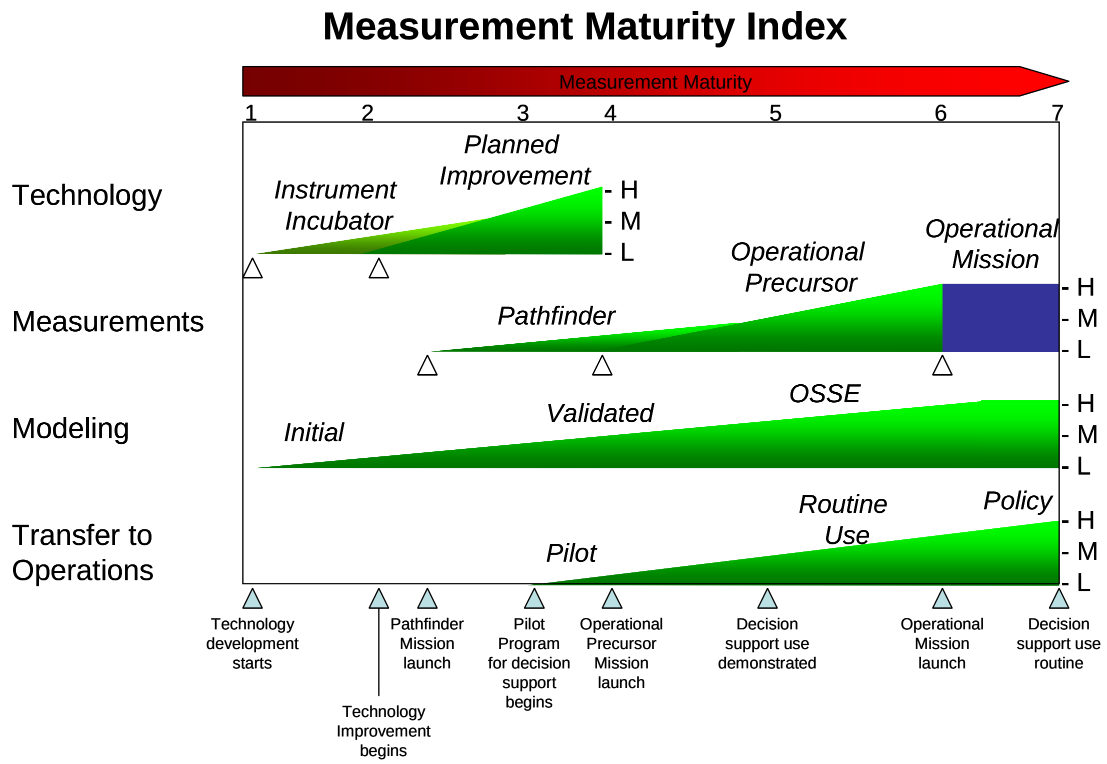


Figure 5: The Measurement Maturity Index and underlying activities that result in advancing maturity for a given measurement.

Note that not all measurements are expected to progress to MMI-level 8 – this will depend on the needs of operational agencies, and our improved understanding of its significance to either science or operational use as each measurement matures.

The Earth Science and Applications roadmap was formulated by defining pathways and stages across three decades. Careful thought was given to prioritization of investigations, and a new metric - the Measurement Maturity Index - was developed and used by the Committee.

4 Implementation Framework

4.1 Time-ordering based on Awareness Clusters

The sequence of the mission clusters is a fundamental aspect of our roadmap that will guide current and future investments. It includes missions throughout that address each of the science goals at any given time. The "cluster" structure is an indication of where NASA should place its organizational focus, but missions in any given science cluster often serve the interests of other science themes. The cluster sequence in our timeline will not be finalized until the National Research Council has completed its decadal survey, and appropriate vetting has been completed, but it was arrived at by examining recent, current, and approved near-term missions, maturity of various measurement concepts, and scientific needs.

The first cluster, Atmospheric Composition, results from the fact that there have been substantial investments recently in this area, suggesting we are already in the Awareness phase. The Climate/Weather follows second, because it flows logically from the atmospheric composition cluster, which will address key issues in the atmospheric aspects of climate and weather. Currently there are important climate missions in the queue. The third cluster, the distribution and transport of water is integrally linked to the atmospheric and climate processes, and there are several approved water-related missions are planned for the 2010 time frame that would catalyze the Water cluster. For these reasons, the ordering of the first three clusters has a clear and rational basis.

The remaining two science areas, Life and Solid Earth, are every bit as important, and the overall success of the Earth Applications from Space Strategic Roadmap would be greatly enhanced if these later clusters could be advanced to an earlier time period, as doing so would maximize the opportunity to examine cross-disciplinary processes and their interactions. However, this would require significantly more resources than the current Earth science budget affords *and* acceleration of the development of technology for active sensors (which both of these science areas rely heavily upon.) The Committee feels, however, that such up-front investments would be well worth making.

As discussed in section 2.2, we have not identified a separate cluster for the role of humans in the Earth system - this is considered a cross-cutting line of inquiry, to which each of the other lines of inquiry contributes.

As a check on our approach to time-ordering of the awareness clusters, the measurement maturity index was evaluated across the suite of measurements applicable to a given line of science inquiry (Table 3). This evaluation is subjective; a more careful examination of current MMI levels and their desired future states across measurement clusters deserves further study.

Measurements	MMI level (2005)
ATMOSPHERIC COMPOSITION AND CLIMATE	
Atm Temp Profile	5
Atm Moisture Profile	5
Total precipitable water	8
Cloud Cover & Layers	5
Cloud Opt Thick & Part Size	4
Cloud Liquid Water	3
Cloud Ice Water Path	3
Atm Wind Profile	
Stratosphere	1
Troposphere (using clouds/water vapor)	8
Troposphere (using aerosols/molec)	1
Lightning	5
Aerosols	
Total	5
Stratosphere	3
Troposphere	3
Ozone	
Stratosphere	7
Troposphere	8
Albedo	7
Solar Irradiance	7
Solar UV Irradiance	7
Energy Balance	5
Atmospheric Chemistry	
Stratospheric Chemistry	6
Tropospheric Chemistry	3
Sea Ice Cover	8
Ice Surface Topography	4
Sea Ice Thickness	3

Measurements	MMI level (2005)
WATER	
Sea Surface Wind	
Open Ocean	6
Coastal	2
Sea Surface Temp	8
Sea Surface Topography	7
Ocean wave height	
Open Ocean	5
Coastal	2
Net Heat Flux	3
Ocean Salinity	3
Ocean Currents & Circulation	
Open Ocean	2
Coastal	2
Snow Cover	6
Snow Depth, Water Eq, ...	3
Freeze/Thaw Transition	3
River Discharge/Stage Ht	2
Fresh water availability	2
Fresh water quality	2
Precipitation	5
Soil Moisture	3

Measurements	MMI level (2005)
LIFE	
Vegetation Index	5
Primary Productivity	4
Land Cover/Land Use	5
Top & Sub Canopy Biomass	
Biomass	3
Vegetation Structure	3
Photosynthetic Efficiency	1
Plant Physiology & Function types	1
Ocean Color	
Open Ocean	5
Coastal	5
Ocean Mixed Layer Depth	
Open Ocean	1
Coastal	1
Ocean Particulate Organics	3
SOLID EARTH	
Land Surface Deformation	3
Land Surface Topography	4
Land Surface Composition	5
Land Surface Temp	5
Gravity Field	4
Earth's Magnetic Field	6
Land Ice Cover & Topography	
Ice sheet thickness	2
Ice mass balance	4
Ice sheet internal layering	2
Fires	3

Table 3: MMI evaluations for measurements associated with each line of inquiry; shaded boxes indicate environmental data records (EDRs) which may be produced by NPOESS.

Our interpretation of the results in Tables 3 is that they appear to confirm that we are already in the awareness clusters for atmospheric composition and climate/weather, while we are still in the exploratory stage for life, water and solid earth. Based on the notional timeline we set up in Figure 3, this means that the gap between the land surface deformation and atmospheric temperature profile measurements, for example, is about fifteen years.

4.2 Scientific Investigations and Anticipated Achievements by Stage

Table 4 summarizes the anticipated achievements by decadal stage, across all of the science questions. The sections that follow describe the decadal stages and indicate the investigation and notional mission that correspond to the achievements, summarized in the achievement table in the Executive Summary.

4.2.1 Stage I: Building a foundation for comprehensive observing and modeling -- Focus on atmospheric composition, climate and weather

For each of line of science inquiry we have identified a set of achievements arranged by decade. Table 5 shows the relationship between the expected achievements for the first stage, the investigations needed to realize each achievement and the (notional) missions we expect will implement those investigations. Missions are designated by the instrument suite expected to meet the measurement objective and the vantage point (orbit) for the platform. In some cases, we can already anticipate that a mission is expected to make

	2005-2015	2015-2025	2025-2035 & Beyond
Exploration & Discovery	• Accurate assessment of carbon sequestration on land • Time-dependent deformation maps of fault zones, volcanoes, slopes and ice sheets • Comprehensive assessment of changes in ice cover • New opportunities for exploration & discovery	• Characterize water distribution in root zone; improved weather and climate prediction • Major contribution to understanding ocean biosphere • Pathfinder measurement to complement the Terrestrial Planet Finder mission; characterize signatures of life in IR spectra • Quantify the dynamics of Greenland and Antarctic ice sheet motion • New opportunities for exploration & discovery	• Pursuing answers to questions we don't yet know to ask in 2005, enabled by: – Robust, distributed autonomy, – Bio- & nano-technology sensors, – Very large microwave/optical apertures, etc.
Continuous Awareness	• Distinguishing anthropogenic and natural aerosols and their effects on climate • Improved understanding of sources of aerosols, long-range transport, ozone variability, & sun-atmosphere interactions. • Comparison with Icesat results; determine ice sheet contribution to sea level to within 0.05 mm/yr • Determine contribution of mesoscale ocean eddies to global energy budget • Understand feedback processes in the Earth's atmosphere consistent with observed time scales of solar variability of total and spectral irradiance • Quantify snow water equivalent, areal extent; water resources planning; links to biogeochemistry • Quantify CO2 flux at all levels in the atmosphere	• Comparison with Icesat results; improve assessments of ice sheet contributions to sea level; determine nature and causes of rapid changes in sea ice • Measurements of tropospheric winds over land & ocean directly for weather forecasts; improve ocean circulation models with wind and surface currents in coastal and open ocean • Quantify cloud feedback in the climate system; enable verification of improved cloud/climate models • Quantify dynamics of surface water storage & availability at monthly and longer timescales; freshwater and flood monitoring and prediction; derived global discharge • Combined with temperatures and models to estimate thermal expansion of the ocean to within 0.05 mm/yr; assess potential for shut-down of dominant circulation patterns; quantify near-surface water storage • Quantify dynamics of subsurface storage; role of groundwater variations in climate; water availability; estimate sea level equivalent stored on land to 0.05 mm/yr • Quantify H2O content of clouds • Quantify 3-D structure of rainfall • Quantify variations in freshwater quality, links to anthropogenic activities, land use and biogeochemistry • Accurate assessment of carbon sequestration, and CO2 drawdown in coastal zones and over global scales • Functional grouping of vegetation on land and algal groups in ocean, to improve estimates of carbon flux • Estimate decadal and interannual carbon flux in vegetation on land • Understanding governing processes of deformation at high spatial/temporal resolution • Detection of volcanic and tectonic activity, land use change • Determine topography and conditions beneath the ice sheet • Improved understanding of the contribution of solid Earth, oceanographic, and hydrological process to gravity field • Improved understanding of short-period variation in the main field, crustal remnant fields, and mantle current-induced fields	• Assessment of plant and algal physiological status and productivity • Linking volcanic and tectonic activity, land use change • Improved global topography and in conjunction with SRTM data first global measurement of topographic change
Developing Perspectives	• Insure smooth handoff of operational measurements and accurate calibration of NPOESS observations for science use	• Understanding of "fast" processes like convection and cloud evolution • First daily 3-D global measurements of the Earth's atmosphere and trace gasses • Successful hand-off to operational agency of capability to monitor and predict water vapor and temperature change • Narrow the uncertainties in climate sensitivity for both regional and global climate change. Includes regional cloud feedback and both direct and indirect aerosol forcing	• Soil moisture in forested areas; improved weather and climate prediction; understanding of links with ecology, biogeochemistry • Continuous, global monitoring of rainfall; direct input to climate models and weather tracking/forecasting • Successful hand-off to operational agency of capability to monitor and predict water availability • Short repeat from GEO will provide decision support users knowledge of coastal zone changes in carbon, algal blooms, water quality • Land cover use and change measured at high resolution, relationship to society, natural changes • Rapid access to deforming area of interest globally for forecasting outcomes
	• Fully integrated Earth System model to synthesize (assimilate) all observations of the Earth system and predict the evolution of interacting components • Global mesoscale weather models • Climate models resolving weather • Earth System Modeling Framework implemented nationally	• Models and data assimilation systems integral to the observing system and decision support systems, including future mission design • Evolve technologies, observations, models, & knowledge systems for science & operational systems	• Fully integrated Earth System model and assimilation system with data distribution portals for simple high speed access to all aspects of the Earth System • Continue to evolve technologies, observations, models, & knowledge systems for science & operational systems

Table 4: Roadmap achievements arranged by decade and by integration objectives

more than one measurement. Such missions are indicated by a number of blue dots in the mission column entry in Table 5. The aerosols mission, for example, is expected to achieve both aerosol objectives while also measuring high-resolution CO_2. Whether the investigation addresses an exploration, awareness, or perspective achievement is indicated by the background color in each row.

Table 5 lists the *known* achievements we can expect in this decade. We also want to leave room for the *unknown*: exploratory missions that address new areas of science or are enabled by breakthroughs in technology. We believe this was the original intent behind the ESSP program and recommend NASA return to that intent.

Line of inquiry	**Investigation**	**Notional Mission**	**Achievement**
	Aerosols impact on climate through clouds, anthropogenic additions	Multi-angle spectropolarimetric imaging; 3-D aerosol profiling (LEO) •	Distinguishing anthropogenic and natural aerosols and their effects on climate
Atmos. Comp.	Global atmospheric composition	UV/Vis/NIR imaging (Sentinel Orbit, L1 or GEO) • •	Improved understanding of sources of aerosols, long-range transport, ozone variability, & sun-atmosphere interactions.
	Atmospheric composition (Cal/Val)	Cal/Val Free-flyer (LEO)	Insure smooth handoff of operational measurements and accurate calibration of NPOESS observations for science use
	Ice elevation changes / sea-ice thickness	High-resolution ice altimetry (LEO)	Comparison with Icesat results; determine ice sheet contributions to sea level to within 0.05 mm/yr
	Ocean circulation	3-D ocean altimetry (LEO)	Determine contribution of mesoscale ocean eddies to global energy budget
Climate/ Weather	Solar influence on climate	Hyperspectral imaging instrument for solar UV, EUV, X-rays (L1) • •	Understand feedback processes in the Earth's atmosphere consistent with observed time scales of solar variability of total and spectral irradiance
	Climate Data Records (Cal/Val)	Cal/Val Free-flyer (LEO)	Insure smooth handoff of operational measurements and accurate calibration of NPOESS observations for science use
Water	Snow-water distribution	SAR and/or passive microwave (LEO)	Quantify snow water equivalent, areal extent; water resources planning; links to biogeochemistry
Life	Biomass and Vegetation Structure	Combined 3-D structure and multispectral imaging (e.g., radar, lidar & multispectral Visible imager) (LEO) • • •	First accurate assessment of carbon sequestration on land
	High-resolution CO2	3-D laser profiling (LEO) •	Quantify CO_2 flux at all levels in the atmosphere
Solid Earth	Rates of change of surface positions and strains	Precision geodetic imaging (e.g., L-band InSAR) (LEO)	Time-dependent deformation maps of fault zones, volcanoes, slopes and ice sheets; comprehensive assessment of changes in ice cover

Table 5: Stage I achievements for each line of inquiry mapped to scientific investigations and missions for the first decade. Background color indicates whether the investigation objective is predominantly exploration (green), awareness (yellow), or perspective (red). Blue dots indicate dual-purpose missions.

Line of inquiry	Investigation	Notional Mission	Achievement
Atmos. Comp.	Behavior of water vapor, clouds, aerosols, and ozone in the upper troposphere	Wide-swatch microwave 3-D sounding (e.g., nadir and limb) (MEO)	Understanding of "fast" processes like convection and cloud evolution
	Global greenhouse gas distribution and change	Continuous, spectrally resolved Solar occultation (L2)	First daily 3-D global measurements of the Earth's atmosphere and trace gasses
Climate/ Weather	Ice Elevation Changes/Sea Ice Thickness	High-resolution ice altimetry (LEO) •	Comparison with Icesat results; improve assessments of ice sheet contributions to sea level; determine nature and causes of rapid changes in sea ice
	Ice Sheet Thickness/Bottom Topography	Ice penetrating radar (LEO) •	Quantify the dynamics of Greenland and Antarctic ice sheet motion
	Global tropospheric winds	Combined ocean surface/ lower atmosphere winds (LEO)	Measurements of tropospheric winds over land & ocean directly for weather forecasts; improve ocean circulation models with wind and surface currents in coastal and open ocean
	Cloud Feedback	3-D clouds -- Cloudsat-Calipso follow-on (LEO)	Quantify cloud feedback in the climate system; enable verification of improved cloud/climate models.
	Temperature/Humidity Change	Cal/Val instruments for NPOESS follow-on (LEO)	Successful hand-off to operational agency of capability to monitor and predict water vapor and temperature change
	3-D cloud microphysics and aerosol distribution	Wide-swath 3-D cloud and aerosol profiling (LEO)	Narrow the uncertainties in climate sensitivity for both regional and global climate change. Includes regional cloud feedback and both direct and indirect aerosol forcing
Water	Rivers, wetlands, surface water storage	Precision/ interferometric altimetry (LEO)	Quantify dynamics of surface water storage and availability at monthly and longer timescales; freshwater, flood monitoring, and prediction; derived global discharge
	Ocean salinity/soil moisture	Microwave radar/ radiometry - Aquarius/ Hydros follow-on (LEO)	Combined with temperatures and models to estimate thermal expansion of the ocean to within 0.05 mm/yr; assess potential for shut-down of dominant circulation patterns; quantify near-surface water storage
	Groundwater storage	Time-variable gravity – GRACE follow-on (LEO) ••	Quantify dynamics of subsurface storage; role of groundwater variations in climate; water availability; estimate sea level equivalent stored on land to 0.05 mm/yr
	Cloud water, ice content and distribution	3-D profiling -- Cloudsat-Calipso follow-on (LEO)	Quantify H2O content of clouds
	Rain process/ distribution	3-D rain profiling (LEO)	Quantify 3-D structure of rainfall
	Water quality	Hyperpectral imaging (LEO)	Quantify variations in freshwater quality, links to anthropogenic activities, land use and biogeochemistry
	Root zone soil moisture	Ground penetrating active microwave (LEO)	characterize water distribution in root zone; improved weather and climate prediction
Life	Changes in dissolved organic and inorganic carbon pools for long-term storage of ocean carbon	High performance ocean color imaging (UV/Vis/NIR) (LEO or GEO), supporting sea surface temperature and salinity measurements.	Accurate assessment of carbon sequestration, and CO2 drawdown in coastal zones and over global scales
	Ocean particle profile and mixed layer depth	Upper ocean profiling (e.g., via blue/green lidar) (LEO)	Major contribution to understanding ocean biosphere
	Biosignatures of life	Hyperspectral imager (GEO or L1)	Pathfinder measurement to complement the Terrestrial Planet Finder mission; characterize signatures of life in IR spectra
	Plant functional groups on land and in ocean	High performance hyperspectral UV/Vis/NIR imaging (LEO or GEO)	Functional grouping of vegetation on land and algal groups in ocean, to improve model estimates of carbon flux
	Biomass Dynamics	Combined 3-D structure and multispectral imaging (e.g., radar, lidar, & multispectral Visible imaging) (LEO)	Estimate decadal and interannual carbon flux in vegetation on land
Solid Earth	Rates of change of surface positions and strains	Frequent, precision geodetic imaging (MEO constellation)	Understanding governing processes of deformation at high spatial/temporal resolution
	Ice Elevation/Thickness	Ice penetrating radar (LEO) •	Determine topography and conditions beneath the ice sheet
	Time-varying global gravity field	Time-variable gravity – GRACE follow-on (LEO) ••	Improved understanding of the contribution of solid Earth, oceanographic, and hydrological process to gravity field
	Time-varying global magnetic field	Distributed magnetometry (e.g., 12-sat constellation, LEO, 300-800 km, low-inclination & polar orbits)	Improved understanding of short-period variation in the main field, crustal remnant fields, and mantle current-induced fields

Table 6: Stage II achievements for each line of inquiry mapped to scientific investigations and missions for the second decade. Background color indicates whether the investigation objective is predominantly exploration (green), awareness (yellow), or perspective (red). Blue dots indicate dual-purpose missions.

4.2.2 *Stage II: Extending our view of Earth and reach into society -- Focus on water, life and solid earth*

Table 6 shows the relationship between the expected achievements for this second stage, the investigations needed to realize each achievement, and the missions we expect will implement those investigations. Whether the investigation addresses an exploration, awareness or perspective achievement is again indicated by the background color in each row. We will also leave room for true exploratory missions in this decade to open up new areas of science or take advantage of breakthroughs in technology.

4.2.3 Stage III: Fully instrumented Earth system networked to predictive models serving science and decision makers – Focus on new science questions and lines of inquiry

Stage III will result in an integrated, comprehensive and sustained "information web" for Planet Earth, the U.S. Integrated Earth Observation System (IEOS). NASA's role within the IEOS will be to continue to pursue new science questions and to investigate aspects of the Earth system that we have not yet explored. Table 7 shows the relationship between the expected achievements for this third stage, the investigations needed to realize each achievement and the missions we expect will implement those investigations. Whether the investigation addresses an exploration, awareness, or perspective achievement is indicated by the background color in each row. We will also leave room for true exploratory missions in this decade to open up new areas of science or take advantage of breakthroughs in technology. Although this table lists no entries for atmospheric composition or climate and weather lines of inquiry, we fully expect that new technologies and new science questions will open up new investigations, missions, and achievements for these areas, as well as lead to new lines of inquiry.

	Investigation	**Notional Mission**	**Achievement**
Water	Global soil moisture	Passive/ active microwave (MEO)	Soil moisture in forested areas; improved weather and climate prediction; understanding of links with ecology, biogeochemistry
	Global precipitation	Active/ passive microwave (3 GEO)	Continuous, global monitoring of rainfall; direct input to climate models and weather tracking/forecasting
	Fresh Water Availability (Cal/Val mission)	Cal/Val instruments for NPOESS follow-on	Successful hand-off to operational agency of capability to monitor and predict water availability
Life	Changes in dissolved organic and inorganic carbon pools for long-term storage of ocean carbon	High performance ocean color imager (UV/Vis/NIR) (GEO); supporting sea surface temperature and salinity measurements.	Short repeat from GEO will provide decision support users knowledge of coastal zone changes in carbon, algal blooms, water quality
	Advanced land cover changes	Hyperspectral UVVis/NIR imaging (LEO)	Land cover use and change measured at high resolution, relationship to society, natural changes
	Photosynthetic efficiency	Combined 3-D structure and multispectral imaging (e.g., lidar and multispectral Vis imaging) (LEO)	Assessment of plant and algal physiological status and productivity
Solid Earth	Rates of change of surface positions and strains	High temporal resolution geodetic imaging (GEO)	Rapid access to deforming area of interest globally for forecasting outcomes
	Earth's surface thermal changes	Multispectral imaging in thermal IR (LEO)	Linking volcanic and tectonic activity, land use change
	High resolution global land topography	3-D land structure (e.g., Lidar and/or InSAR) (LEO)	Improved global topography and in conjunction with SRTM data first global measurement of topographic change

Table 7: Stage III achievements for each line of inquiry mapped to scientific investigations and missions for the third decade. Background color indicates whether the investigation objective is predominantly exploration (green), awareness (yellow), or perspective (red).

4.3 Modeling & Data Management

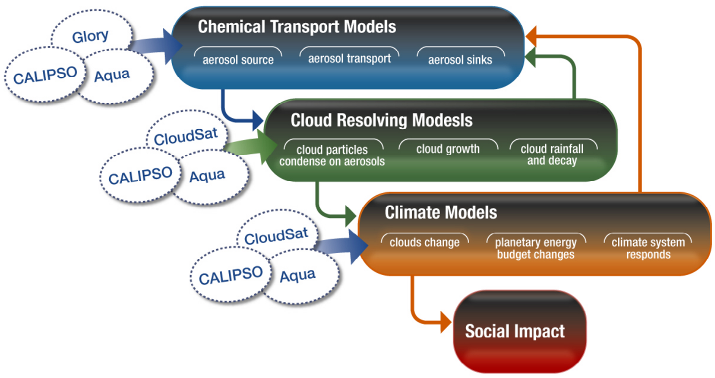
4.3.1 Modeling

A recent Nature editorial (Nature, 5 May 2005, v. 435) posed the question: "What is the difference between a live cat and a dead one? A dead cat is a collection of its component parts. A live cat is the emergent behavior of the system incorporating those parts." The editorial was describing the pursuit of systems biology, but the same analogy can be applied to Earth System Science. While it is important to understand the individual components or disciplines, it is the interaction of those disciplines that determines the functioning of the complete Earth System. "The technical wizardry of the *Earth Observations* and the attendant vast data sets obtained are only part of the *Earth* system approach – a system is not fully understood until a quantitative model can be built."

NASA makes space based and ancillary observations not simply to demonstrate technology, but to address specific gaps in our knowledge and to reduce uncertainty. The modeling system, which assimilates the disparate observations, provides the critical link between the raw measurements and the ability make the complex information readily available to the community and to improve decision support tools used by the operational agencies. Those tools in turn inform policy and management decisions. Easy, intuitive access to the data and model output allow "what if" type queries to inspire both the general public and the next generation of scientists and engineers.

Assimilation is fundamental to the Earth System modeling effort. Because there will be completely new and novel observations, and increasing amounts and frequency of data, assimilation will be one of the major challenges and it will require a focused research effort.

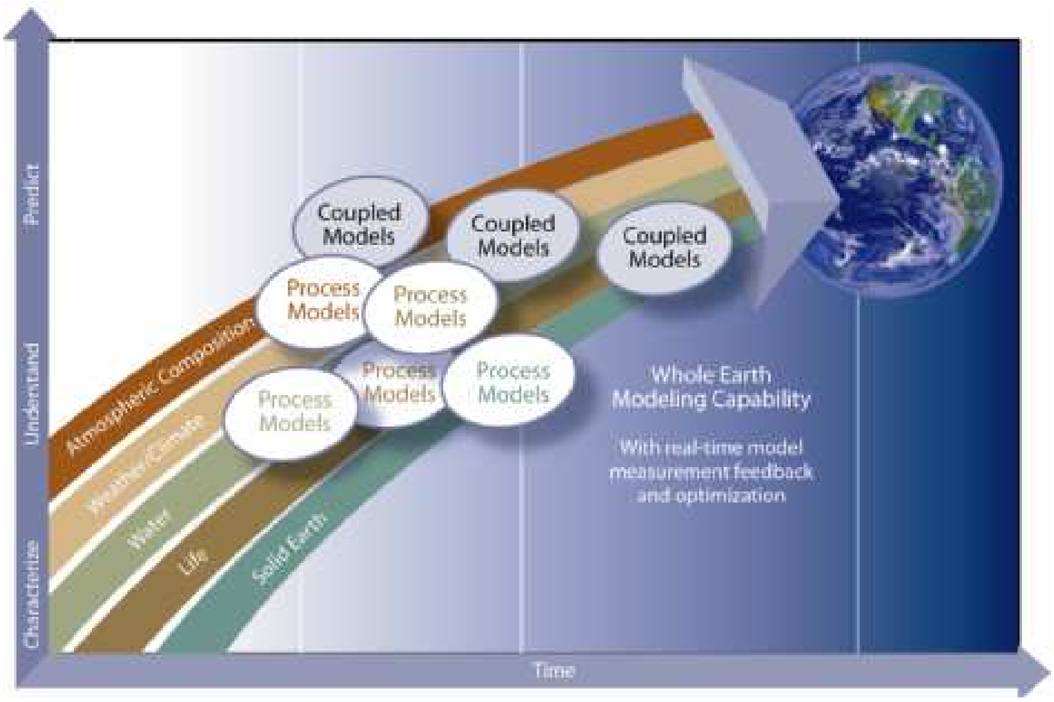
Once a model is developed and verified against observations, it should be used in the first step of identifying and prioritizing new observation systems. The model in turn, through the use of simulated observations using OSSE's (Observation System Simulation Experiments), can be used to determine the impact of a particular observation on improving model predictions. Determining the sensitivity of the prediction to the simulated measurement can help prioritize the technology investments for new space missions.



New approaches using multi-scale and multi-discipline modeling solve key climate challenges (those with largest climate uncertainty)

The idealized end-state for Earth System Science is to have a systems approach that observes all key Earth system variables and assimilate that information into a framework of integrated, interacting models that include each of the major subsystems: oceans, atmosphere, cryosphere, biosphere and solid Earth. This system will provide quantitative predictive capability that will continually be evaluated against the observations. Together with their partners, NASA will enable a robust Earth system predictive capability that represents the community consensus of current knowledge.

New discovery observations will illuminate completely new processes, which will continually provide a challenge to the modelers to understand and assimilate. Continuous awareness will provide data on time scales and comprehensiveness never before seen that will challenge the ability of the modelers to keep pace with the physics, mathematics and assimilation techniques required. For developing perspectives a key will be rigorously defining the observation requirements for absolute accuracy, long-term stability and precision as a function of the observation variable, time scale and space scale. Included in such a requirement is the ability to prioritize the impact of an observable on constraining the accuracy of the desired prediction.



Accomplishing this end-state of a fully integrated Earth system model will require the infrastructure with the necessary high end computing capability and software engineering and visualization environments. This is more fully discussed in the Advanced Modeling, Simulation and Analysis Capability Roadmap 14. Also critical is the concept of an Earth System Modeling Framework (ESMF) that will allow the necessary multi-agency, multi-national effort. Each building block of the integrated model must be built and tested in a community-modeling environment in which multiple models operate and ‘learn’ from each other. Based on this, a consensus model will emerge, representing the mean state of the model space. The competing models will continue to evolve, based on the stream of observations and model evaluations; the consensus model will be periodically updated, based on these evaluations. There will still be a spectrum of effort from pure research to “operational” prediction. In such a community-modeling environment, paradoxes and unexplained phenomena will emerge, focusing research efforts on the highest payoff questions. An ESMF, such as described here, can only be developed by a large consortium of international partners, US agencies and academic partners.

Because such large, complex model and data assimilation systems are much larger and more expensive than what a single researcher, or even a handful can do, they should be considered as ‘missions’ in themselves, including technology development (for example, the Earth System Modeling Framework, software to couple models developed by different groups or multiprocessor hardware with extremely fast communications among processors), system engineering to ensure that components provided by commercial vendors and different scientists work well together, data management to ensure that many outsiders can study the results, etc. It is estimated that the required infrastructure support will be equivalent on an annual basis to that of a small satellite mission. The goal cannot be accomplished by simply stripping off a portion of the satellite mission budgets as has been done in the past.

The Capability Roadmap 14 describes 3 levels of investment. Level 1 is a minimal, but expanded investment, where MS&A (modeling, simulation and analysis) capabilities are developed on a highly focused and near-term schedule to expand the applications base. Level 2 represents the lowest level of investment in which integration is fostered and developed for use across the agency. Level 3 represents the highest investment level over the longest time period having the greatest benefit. Significant MS&A systems are developed in which distinctions among science, engineering and operations are diminished and involves outside agencies beyond NASA. The recommendation of the Capability Roadmap team varies between 0.5% of the program (in this case Earth Science) budget for a minimal, “Level 1” investment to 2% to satisfy up to the “Level 3” investment.

Accomplishments			
2005	2015	2025	2035
• Coupled global climate models – 1 deg resolution • Earth System Modeling Framework implemented • Global mesoscale weather models • Weather forecasts improved by use of satellite data (AIRS, MODIS)	• Fully integrated Earth System model to synthesize (assimilate) all observations of the Earth system and predict the evolution of interacting components • Climate models resolving weather • Earth System Modeling Framework implemented nationally	• Models and data assimilation systems integral to the observing system and decision support systems, including future mission design	• Fully integrated Earth System model and assimilation system with data distribution portals for simple high speed access to all aspects of the Earth System
Required Infrastructure			
Dedicated Network (1 Gb/s sustained) Performance (1-50 TeraFLOPS) Memory (40 GB)	Dedicated Network (100’s Gb/s sustained) Performance (PetaFLOPS) Memory (5 TB)	Dedicated Network (10 Tb/s sustained) Performance (100’s of PetaFLOPS) Memory (1 PB)	Dedicated Network (100’s Tb to Pb/s sustained) Performance (1000 PetaFLOPS) Memory (100’s PB)

Modeling accomplishments and required infrastructure by decade

4.3.2 Data Management and Data Stewardship

The goal of data management for an Earth Information System is to get the fruits of the NASA and international investments in Earth observations and modeling into forms that can readily be used by scientists, decision makers, and the general public. With easy, high speed access to the wide range of Earth Science information, users should be inspired to ask their own "what if" types of questions. There is a significant effort in the basic needs for defining data formats, storage media, long term storage plans, etc. But the real utility in data management is getting the appropriate Earth System information into the hands of those that need it.

Earth observation and model results will be developed by a diverse set of national and international systems. Observations will be acquired by international constellations of satellites, such as the currently operating "A-Train." Key considerations will be the capability to access information from non-NASA observing and modeling systems, and the national and international investments in the capacity to move large volumes of data, such as the National Lambda-Rail, a major initiative of U.S. research universities and private sector technology companies to provide a national scale infrastructure for research and experimentation in networking technologies and applications.

Observations must be organized in appropriate data format so that they can be used by models. Each data set must be vetted in the issues of data stewardship, data formatting, and data management.

Data stewardship consists of the application of rigorous analyses and oversight to ensure that data sets meet the needs of users. Data stewardship can be categorized into two primary areas: observing system performance monitoring and the development of homogeneous time series, where the adjective homogeneous is used to indicate the removal of changes in the time series that may have arisen for reasons unrelated to Earth system changes. These are important steps for creating Climate Data Records (CDR) which are used to perform detection and attribution studies of changes in the earth systems. This is particularly important in the context of long-term changes since most measurement missions last for several years while information is needed to detect changes in the multi-decade to century time scales.

Data management also includes data services, data access and visualization, data collection, long term data archiving, and data inventories. It is important to plan the strategy keeping in mind the goal of developing the system of systems. The ultimate goal is to have an integrated system, but at the same time, people should be able to query the system and get the answer they need.

There should be a clearly defined path whereby the NASA research and development observation and model results would get to the operational agencies with responsibilities for specific Earth system aspects and national applications. The key is the difficult and complex interface between the raw observations and model output and the information that can be useful to decision makers, from major national and international policy decisions, to casual decisions by the general public. Models and data visualization tools are important components in extracting the information into useful forms.

4.3.3 Relation to Objectives/Stages/Pathways

Models and measurements must be at matching levels of maturity if the clustering approach recommended in this roadmap is to succeed. Requirements for modeling and data management for each stage need further definition, so NASA can allocate appropriate levels of resources to these activities.

4.3.4 Transition to operations.

Given its role as a research and development agency, NASA will facilitate integration by operational agencies through merging and coordinating the Earth System modeling objectives from many organizations. The result will ensure that validated Earth system predictions are delivered in a timely manner and in a usable form. Through its systems analysis, engineering, and international leadership NASA can provide the breakthrough scientific missions and modeling efforts that, through partnerships, can be transitioned to Operational agencies at the appropriate time.

The ultimate goal is to have high bandwidth, universal access to Earth System information that is available via an easily queried Earth System portal, Imagine a map- or globe-based query system where scientists, educators and policy-makers can obtain up-to-the-minute information about specific locations or regions of the planet, and can compare it to information from the past.

4.4 <u>Decision Criteria</u>

The decision points for this roadmap will be determined at decadal reviews of the program by the National Research Council. We expect that our successors will have to answer tough questions about the current and future program at each decision point. At the transition points between stages (both I to II, and II to III), there will be common evaluations to make.

Typical decision questions may be:

- What new lines of inquiry have been opened up by the discoveries we have made?
- Are each of the themes currently categorized appropriately in their phases of Exploration, Continuous Awareness, and Perspectives?
  - Have the current clusters made the expected scientific and technical progress?
  - When appropriate, have the partnerships and planning for the transition from research to operations made the expected progress?
  - Have society’s priorities shifted, and what are the implications for the ordering of our clusters?
- What missions have slipped in our projected timeline and how does that affect our clustering and future mission choices?

- Have technologies evolved that enable unanticipated yet much needed measurement capabilities?
- What other opportunities/partnerships have arisen that may modify priority or alter implementation constraints?

At the transition point between stages I and II the specific questions we might anticipate asking may focus on specific mission status and scientific justification. For example, by around 2015, will the atmospheric chemistry flagship mission have been launched and preparing measurements for handover to NOAA? A corollary is then to ask, if that mission is successful, what other missions must be flown to calibrate for/handoff to the NPOESS follow-on in 2025? NASA will also need to prioritize based on technological and scientific maturity. When entering Stage II, is the Water cycle (the next planned cluster) prepared to enter the multimission continuous awareness decade?

As our knowledge of the Earth system advances, we expect that the maturity of our questions will also. At the transition point between stages II and III the kind of questions we might anticipate asking include whether it is possible to handoff or plan handoff of Water cycle, Life cycle and/or Solid Earth measurements to an operational partner? If during Stage II many atmospheric composition measurements are being maintained by NOAA, what are the next generation exploration measurements? Society will have changed in the next two decades and may expect NASA to take a more active role in monitoring efforts to mitigate climate change. Given the strong program emphasis for solid Earth surface deformation, by the beginning of Stage III have we shown predictive capability for earthquakes, volcanoes, and other events with InSAR data?

The results of answering these questions will result in an evolving program and mission timelines, as illustrated in section 4.6.

4.5 The Roadmap Timeline

The timeline developed for this roadmap (Figure 6) shows the five lines of science inquiry with investigations laid out on each, shown as diamonds on the line. Each diamond represents the launch of a mission designed to implement that investigation. To relate an investigation to a specific mission, refer to Tables 5-7. To develop the roadmap, we assumed a balanced portfolio of missions, including small, medium, large and flagship classes. Larger diamonds are intended to represent investigations so challenging or critical to a given line of inquiry that they warrant a flagship mission. Missions already selected for flight before 2010 are indicated as white diamonds on the timeline. A sixth track shows the line of exploratory investigations to open up new lines of science inquiry or to take advantage of breakthroughs in technology.

Overlaid on top of each line of inquiry is a representation of the Exploration, Awareness, and Perspectives mission timeline. This is intended to indicate time periods when spaceborne measurements take place, mapped against each of our three strategic integration objectives. The diamond representing each investigation is also colored to distinguish whether it corresponds to an Exploration, Awareness or Perspectives activity.

[Note that other activities critical to the success of this roadmap, such as technology development, modeling, data management, and research and analysis, are not depicted on Figure 6.] Thus Exploration investigations (green) occur most frequently at the beginning of a line of inquiry, but may continue almost to the end if important discoveries are made. Awareness investigations (yellow) start at the beginning of an "awareness cluster" on each line of inquiry and are concentrated in the middle of the timeline. Perspectives investigations (red) occur relatively late on the timeline, and are targeted at handing off from research to operations.

One mission in 2013 serves a dual role in meeting the investigation needs of both the atmospheric composition line and the climate/weather line. It is also tagged as a joint mission on the SRM 10 (Sun-Earth System) timeline. In the 2010 – 2020 timeframe, we have identified several other instances where it is already clear that more than one investigation can be served by a single mission, as indicated by the blue dots in Tables 5 and 6. The secondary investigation(s) appear in Figure 6 as "ghosted" diamond symbols with gray text. To identify other examples of dual-purpose missions, and partnership arrangements, so that this roadmap can be implemented in the most cost-effective way, requires that a vigorous and continuous Earth science advanced studies activity be reinstated without delay.

Figure 6 does not try to represent the connections to specific launch dates of relevant missions by NASA's operational partners [with a few near-term exceptions, such as the white diamond representing the launch of the Operational Land Imager (OLI) on the National Polar Orbiting Environmental Satellite System (NPOESS) to fulfill the requirements of the Landsat Data Continuity Mission (LDCM)]. The transition of research capabilities to operational missions that are off this timeline is represented by blue arrows. Placement is not intended to indicate that these transitions only occur at the end of a focused investigation. Green arrows along each line of inquiry indicate that a new line of inquiry has opened up through discovery; again, this could occur at any point along the timeline, not just at the end.

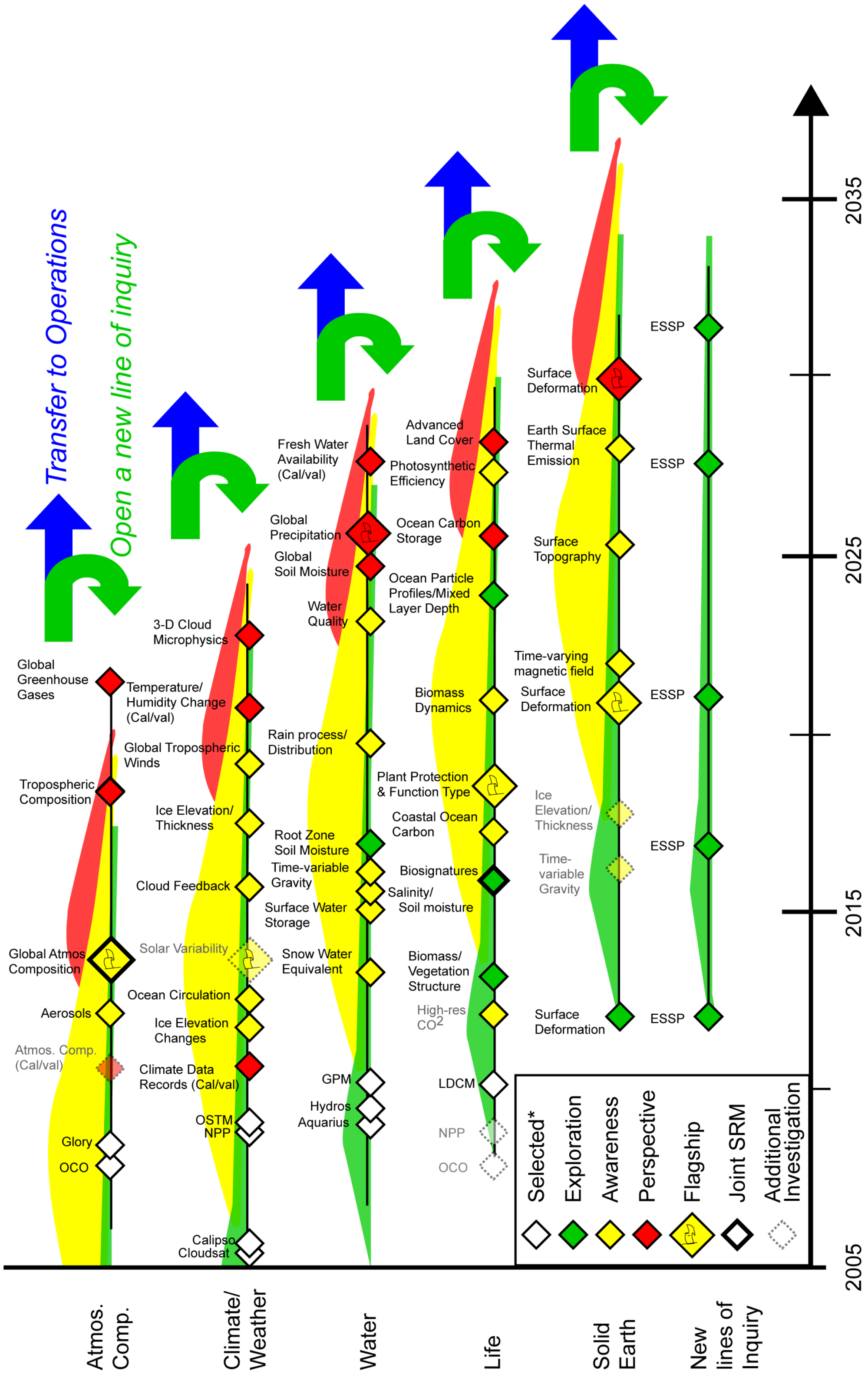


Figure 6: The Earth Science and Applications Roadmap, showing missions laid out along each line of science inquiry in priority order.

4.6 Summary of Key Program Milestones, Options, & Decision Points

Flexibility is a critical component of this roadmap. As expected with any visionary roadmap over a 30-year timeframe, changes are expected, especially in the out years. The overall goal of the roadmap is to develop a logical framework for evaluating programmatic and mission-oriented decision, and then to present the current scenario and best-estimate projections over the next three decades. Built into the roadmap is the opportunity for change due to natural evolution of the program or unexpected developments

NASA may reevaluate the entire program, a science theme, or a specific mission at any time. These decision points may include Decadal Reviews and impacting events, such as a scientific discovery, funding changes, or new programmatic direction. As illustrated in various scenarios in Figure 7, decision point changes may result in new lines of scientific inquiry, extended program lifetimes, reordering of mission launches or clusters, refocused missions and research.

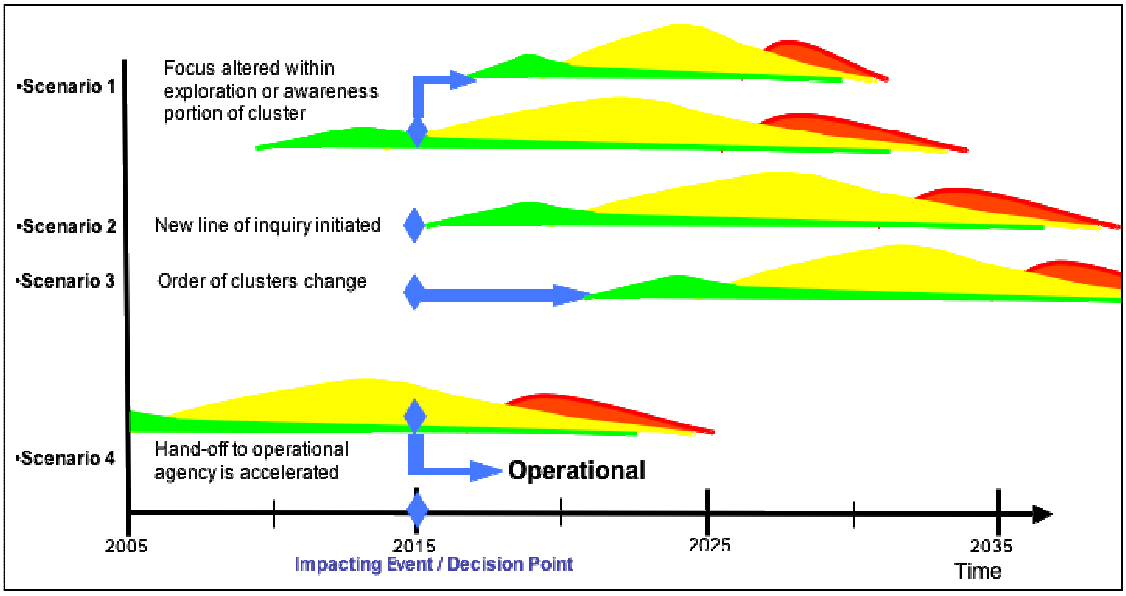


Figure 7: Roadmap timeline flexibility is illustrated with sample scenarios of changes that impact the emphasis, timing, and priority of science clusters.

Key program milestones are the Decadal Reviews between Stages I and II (in 2015), and Stages II and III (2025). As discussed in section 3.4, NASA and the broader Earth science community will need to evaluate the effectiveness of all aspects of the program to date. Have transition to operation goals been met? How have new discoveries changed the prioritization criteria previously defined? At each of these Decadal reviews, NASA has many options to reconfigure the program while still maintaining the long-term structural goals. The Decadal Reviews will have many similar judgments to evaluate on the program, as well as timeline-specific evaluations: in 2015 is the Water Cycle Continuous Awareness cluster ready to be implemented? In 2025 has Life and Carbon Cycle measurements reached a high enough maturity level to transition to operations? Decadal Reviews will also be the appropriate time to adjust the roadmap to reflect evolution of non-NASA agencies. If NOAA or another operational agency has realized the usefulness of a particular NASA measurement for decision support, the program may accelerate mission launches to enable a swifter transition to operations (Scenario 4, Figure 7)

The Earth Science program must be responsive on shorter timescales than decadal reviews as well, particularly to radical changes in scientific knowledge or technological capability, both within the Earth sciences as well as outside their direct fields, but which may impact national interests.

As science clusters progress through an estimated 25-year lifecycle and the emphasis shifts from primarily exploration to transitional operations and long-term perspectives on processes, it is likely that exciting and unpredicted discoveries will revolutionize our understanding and demand major changes in the 30-year plan. New lines of inquiry can be initiated at any time to refocus resources on these opportunities.

Successful implementation of any science roadmap will include evaluation as to whether specific science goals have been met. One scenario is that the measurement maturity index (MMI) level be used as a metric for planning scientific progress and assessing the balance of a portfolio of investigations. For specific missions there should be an MMI goal to be achieved. In this way, we can evaluate the effectiveness of a mission and the balance of the program. For example, in the Climate/Weather line of inquiry, a mission to study Cloud structure and feedbacks in 2016 will be an evolution from the “exploratory” Cloudsat and Calipso missions (MMI 3). The mission and related “awareness cluster” activities should realize an increase in MMI level to 6. Then, a requirement of the ‘perspectives’ 3-D Cloud Microphysics mission in 2022 should be to reach MMI-7, which indicates proven usefulness for decision support systems and readiness for transfer to of the capability to an operational agency.

In order to keep the roadmap as current and responsive as possible, it is recommended that NASA work with the Earth science community to implement highly-focused roadmapping activities every three years to stay abreast of changes between NRC Decadal Reviews.

Nearly all of NASA’s Earth science and applications from space missions have substantial international participation, ranging from simple data sharing arrangements to ground validation to provision of instruments, satellite buses and launch services for space missions. Careful consideration should be given to this within the context of the GEOSS as this roadmap is implemented.

Successful implementation of this roadmap will require a balanced, carefully planned program of missions of several classes, research, modeling and data management.

5 Most Critical Inter-Roadmap Dependencies, Technical Capabilities and Infrastructure

In this section we summarize linkages between this roadmap and other strategic and capability roadmaps. We also address the infrastructure needs to implement the roadmap.

5.1 Strategic Linkages

Perhaps the ***strongest links*** to other strategic roadmaps ***are those objectives shared with the Sun-Solar System Connection Roadmap (SRM 10)***. Determining the cause of changes in Earth's climate through joint investigation of the effects of solar variability on Earth's climate and upper atmospheric chemistry dynamics is a high priority objective for both roadmaps. In addition, joint efforts to predict solar variability and local space weather in order to mitigate impacts on society are highly desired.

Other synergistic linkages exist in the area of planetary models (e.g. geophysical models, atmospheric models, etc.), understanding the signatures of life in the spectra of life-sustaining planets (SRM 4), and in studying extreme environments with the Mars and Solar System Exploration Roadmaps (SRMs 2 and 3, respectively). ***Understanding the shared geology and formation of the Earth-Moon system*** is another synergistic research area between this roadmap and the lunar roadmap (SRM 1).

Finally, aerospace innovation for a new generation of platforms in support of NASA's Earth science related measurements is highly desirable and provides a natural link to the Aeronautics technology roadmap (SRM 11).

The following table and Figure 8 summarize the linkages to other strategic roadmaps.

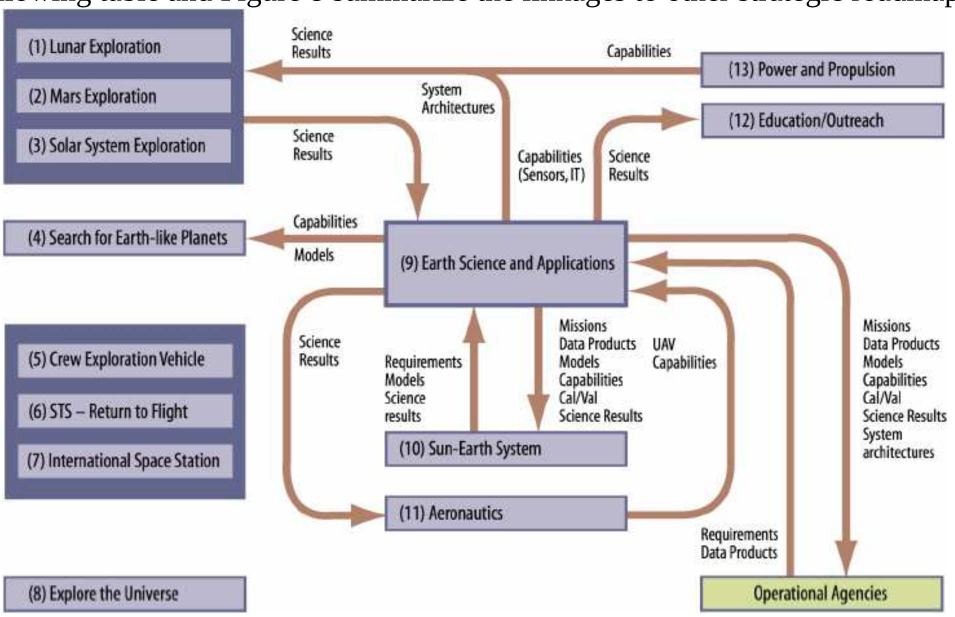


Figure 8: The Earth science roadmap shares common interests with several others.

Strategic Roadmap	Title	Linkage Type	Description	Related Roadmap Events	Timeline
1. Lunar Exploration	Understanding the shared geology and formation of the Earth and the Moon	Enhancing	Earth/Moon formation, early history (esp. before the oldest rocks found on Earth), bombardment record, and other shared events. The moon is a "witness plate" to the environment in which life on the Earth arose and evolved.	TBD - RM interim report not available	TBD - RM interim report not available
2. Mars Exploration	Planetary Models	Synergistic	Models developed for Earth have application to those developed for Mars and other terrestrial planets. This would include seismic models, geophysical models, meteorological models, atmospheric models, climate models, etc.	Earth and Mars investigations in the first time frame of both roadmaps	2005-2015
2. Mars Exploration	Understanding extreme environments	Synergistic	Mars has spectacular features that offer extremes compared to Earth, such as topography and dust storms. Analog sites on Earth can provide remote sensing opportunities for understanding images from Mars.	Related to investigations in the "Discovery" objective of Earth roadmap	2005-2015
1. Lunar Exploration &2. Mars Exploration & 3. Solar System Exploration	Common Remote Sensing Instrumentation, Modeling and Data Analysis Infrastructure	Enhancing	Earth science approaches and capabilities for measurement, processing of scientific data, and advanced modeling techniques related to data interoperability, can benefit Lunar, Mars and other planetary sciences, and increase scientific return and discovery, prediction, and decision making process.	Missions in Sr 9 centered on Solid Earth, Life, Climate/Weather, Atmosphere	All
4. Earth-Like Planet	Understanding Earth as example of terrestrial planet	Synergistic	Enhanced understanding of biomakers - detecting signature of life in the spectra of life sustaining planets	Related to Life missions in the Earth roadmap and Planet Characterization missions in the Earth-like planet roadmap	2015-2025
10. Sun-Solar System Connection	Understanding changes in Earth's climate	Enhancing	Joint investigation of the effects of solar variability on Earth's climate and upper atmospheric chemistry dynamics include understanding of radiative forcing processes, energy input from dynamic magnetosphere, and solar energetic particle input	Complementary or joint upper atmospheric missions (e.g. joint mission at L1)	2015-2025; 2025-2035
10. Sun-Solar System Connection	Understanding ozone depletion	Enhancing	Joint efforts to understand ozone depletion in the polar winter night as a result of energetic particle precipitation	Complementary or joint upper atmospheric missions	2015-2025
10. Sun-Solar System Connection	Understanding and Mitigating societal impacts of solar variability	Enhancing	Joint efforts to predict solar variability and local space weather in order to mitigate impacts on society (e.g. communications, power grids, and air traffic routing). Specification aides in evaluating and correlating identified impacts with space weather, while future prediction capabilities will enable impact avoidance and/or mitigation.	Complementary or joint modeling and assimilation programs for end-to-end integration of Earth-Sun system	All
11. Aeronautics Technology	Uninhabited Aerial Vehicle (UAV) Development	Enhancing	Aerospace innovation for a new generation of platforms in support of NASA's end-to-end science strategy	Related to Atmospheric measurements in the Earth roadmap	2005-2015

5.2 Capability Roadmaps

The implementation of this strategic roadmap's scientific and integration objectives is closely coupled to key technological innovations in the future. Here, we summarize the key technology capabilities needed to implement the objectives outlined in this roadmap and the links to the capability roadmaps.

This roadmap has articulated the objectives of discovery and awareness. Numerous coordinated observing sensors and real-time modeling and assimilation capabilities are required to achieve these objectives. As a result***, sensor web/ model web autonomy capability development*** is of high priority and has ***direct linkage to the autonomous systems and robotics roadmap (CRM 9)***.

Related to the above, ***the capacity to connect multiple observing and modeling systems into synergistic networks or system of systems*** is required. To achieve the awareness and perspective objectives of this roadmap, intensive modeling and analysis is required. This provides a direct ***link to the modeling, simulation, and analysis roadmap (CRM 13)***.

Furthermore, key technologies in the area of ***telescopes, instruments and sensors*** are required to perform key measurement goals of this roadmap. Several technological achievements in the area of ***nanotechnology*** significantly enhance our measurement capabilities.

The following table summarizes linkages to the capability roadmaps.

SR 9 (Earth) Linkages to Capability Roadmaps					
Capability Roadmap	**Capability**	**Linkage Type**	**Description**	**Related Roadmap Events**	**Timeframe**
3. Telescopes	2-5 m deployable collectors	Enabling	active and passive optical measurements from low- to high-Earth orbit. Areal cost <$1K/m2, areal density <0.5 kg/m2.	Climate/Weather; Life	2015-2025
3. Telescopes	50-m deformable deployable RF reflectors	Enabling	Coherent active radiofrequency measurements require closed-loop dynamic wavefront correction in order to optimize system response.	Solid Earth	2015-2020
9. Autonomous systems and robotics	Sensor web autonomy	Enabling	Automating the sensorweb/ modelweb to observe dynamic phenomena and accelerate the pace of discovery and awareness	All -integration across themes	All
11. Instruments & Sensors	Interferometric SAR	Enabling	Large (400-700 m^2), deployable antennas, high efficiency rad-rad T/R modules, digital beam formation (DFB) rad-hard processor	Solid Earth; water	2005-2015; 2015-2025
11. Instruments & Sensors	Millimeter wave RAR, SAR, and Interferometry	Enabling	Large deployable antenna, electronic beam formation, high freq. T/R modules	Climater/Weather	2015-2025
11. Instruments & Sensors	Passive synthetic aperture microwave imagers	Enabling	Low power MMIC receiver, massively parallel digital correlator, rad-hard processor	Atmosphere; climate/weather; water	2015-2020
11. Instruments & Sensors	Visible and IR detector arrays and readouts	Enabling	Rad-hard large format arrays	Life; atmosphere	2005-2015; 2015-2025
11. Instruments & Sensors	Doppler Wind profilers	Enabling	energy, +/- 5 GHz, 10 msec tunability and frequency lock settling time	Climater/Weather	2005-2015
13. Modeling, Simulation, Analysis	Capacity to connect multiple observing and modeling systems into synergistic networks/ system of systems	Enabling	Sensorweb/modelweb simulators and systems analysis capacity to advance the state-of-the-art in distributed collaborative observing and modeling	All -integration across themes	All
15. Nanotechnology	Ultra-high strength, lighter, and multi-functional materials (100x stronger than steel), i.e., large lightweight antenna	Enhancing	materials will enhance mission success while also saving on overall costs of missions due to less mass, longer durability	All	All
15. Nanotechnology	High efficiency power generation and storage	Enhancing	greatly enhance any space based mission by requiring less mass and fewer complex "power capture" systems that could potentially be "single point failure nodes"	All	All
15. Nanotechnology	High miniaturized spacecraft systems and instruments	Enhancing	High miniaturized spacecraft systems, instruments (including lasers), smaller, radiation tolerant and less power consuming electronics would mean less mass and less power required to meet mission goals	All	All

Priorities in advanced technologies needed for future Earth Science missions can be broadly categorized into two areas: Observing Technology Needs, and Information and Computing Technology Needs. These areas included technologies summarized in the following.

<u>Observing Technology Needs</u>

Passive optical imaging systems for measurement of land surface, vegetation, ocean, and atmosphere will need improved optical and spectral separation systems to allow reductions in mass and cost; detectors with high pixels counts; and on-board processing to reduce data transmission requirements.

Passive microwave systems for measurements of atmospheric characteristics, precipitation, soil moisture, and ice and snow will need large, lightweight antenna with multiple-frequency capability; low cost and mass microwave integrated circuits; and low-noise, high-frequency receivers.

Active optical systems for measuring atmospheric composition will need lightweight, high power, conductively cooled, high efficiency reliable laser systems.

Active microwave systems for measurements of precipitation, clouds, land surface topography, and ice and snow will need large, lightweight, deployable antenna systems; and radio frequency capability and digital subsystems with reduced mass and cost.

Formation flying to form large, multi-spacecraft antennas will need precision ranging, precision station-keeping, and autonomous operation.

Information and Computing Technology Needs
On-board data processing will adapt commercial technology to achieve fault-tolerant, high-performance space processors, networks, and storage. Advances in space communications are needed to enable adaptable communications by developing high speed networks and protocols for dynamic space links

In the area of Mission Automation development is needed in real-time event detection and image recognition, self-tending spacecraft and instruments, and high-level command language for sensor re-targeting.

High-performance computing improves Earth-process models by developing next generation computer modeling techniques, optimizing performance, and developing architectural frameworks to promote model integration

The area of Information Synthesis (e.g., deriving data information from extremely large complex discovery, visualization, and multi-mission data sets; provide tools to assist scientific access to knowledge) requires further developments in analysis including real-time science processing and distribution.

The Earth science roadmap's primary linkages are with the Sun-Solar System roadmap, and concern a shared desire for joint investigations of the effects of solar variability on the Earth's climate and upper atmospheric chemistry dynamics. The roadmap also shares interests with all three exploration roadmaps, Earth-like planets, and Aeronautics.

There are several technological advances needed to complete the integration objectives of Discovery & Exploration, Continuous Awareness, and Developing Perspectives. These needs provide linkages to several capability roadmaps, including: Telescopes; Autonomous Systems and Robotics; Instruments and Sensors; Modeling, Simulation, and Analysis; and Nanotechnology.

Collaboration with each of these groups is the recommended next step in the development of the Earth science roadmap timeline.

5.3 Infrastructure Needs

NASA and US Aerospace industry are very well equipped to implement this roadmap. NASA Centers such as GSFC and JPL have an excellent record of success in managing the development and operation of most of NASA's Earth science missions. With the right level of investment in technology the NASA centers, combined with industry can provide the advanced instrumentation required to fulfill the measurement needs. The US aerospace industry, provided its base is not eroded, can easily meet the projected spacecraft and launch vehicle needs. The Earth science community has become increasingly sophisticated in analysis of Earth science data and modeling. The EOSDIS distributes and archives terabytes of data from the current fleet of eighteen satellites, serving thousands of users.

The research and analysis budget will need to be sustained throughout the period of this roadmap so that new ideas and synergies across disciplines are given the support they need. Also needed are adequate and sustained investments in new instrument technologies along with opportunities to mature those technologies through flight demonstration. The maturation of new and existing instrument concepts will be crucial to the successful execution of this roadmap. NASA's end-to-end science relies upon the sustained capacity for airborne remote and in situ measurements from suborbital assets, as well as the world-wide ability to deploy ocean and ground-based systems.

The cost and complexity of integrated models of the Earth system are expected to increase to the point where major modeling systems and their support infrastructure will need to be managed in a manner similar to space missions. These systems will require sustained management and the investment in operations and regular upgrades or replacements over the decades so that NASA has access to the necessary computational capacity to achieve its predictive objectives. The network of commercial and NASA ground stations will probably have to support a significant expansion in data volume over the next couple of decades – the network's suitability for that task needs further study. NASA's requirements for modeling the Earth system, data management, and assimilation, will need to be re-evaluated as the awareness clusters are realized. Further, there are concerns over the need for a policy for managing our data over the long term, and the need for a coherent strategy and adequate support for the transfer of capability from research (NASA) to operations (NOAA or other agencies).

We are positioned for success in implementing this roadmap, but some areas of investment in technology and infrastructure require urgent attention.

6 Conclusions and Near-term Recommendations

Earth science and applications from space has come a long way since the 1960 launch of the first Earth observing satellites. The field of Earth system science that emerged in the 1980's and the subsequent era of the Earth Observing Satellites have shown us many of the key connections and helped us understand how much more we could learn over the coming decades.

This roadmap outlines a vigorous, robust, yet likely affordable program of investigations for the nation that, if implemented, would give NASA's Earth science program a glorious future, to exceed its glorious past. That future is integral to NASA's quest to explore our solar system, yet responsive to society's needs here on Earth.

This roadmap offers a structured approach to deciding which investigations to do and in what order. It addresses several of the concerns expressed in the NRC Decadal survey's interim report (April, 2005). We have proposed a new metric, the measurement maturity index, which can be used to assess and help plan the progress of measurements within a given line of science inquiry. The roadmap identifies potential off-ramps for current and future activities, which can be handed off to operational agencies. Further, this is done over timescales that allow NASA and its partners within U.S. Integrated Earth Observation System (IEOS) to plan accordingly. The roadmap recognizes NASA's leading role in research and development for the IEOS. It reasserts NASA Earth science as an exciting avenue for exploration and discovery, attracting the brightest and best to our field.

We recommend four near-term actions that NASA can begin work on immediately, as well as longer-term steps for which NASA should begin planning.

This roadmap was built on the assumption that the NASA missions currently in formulation and implementation would be completed as planned, and these missions are the foundation of this roadmap. The next step must be to work with the science community through working groups aligned with each line of inquiry and with the broader community through the NRC Decadal survey. NASA Earth science needs a vigorous and ongoing advanced studies program, to assess mission costs and technology readiness, to work out the most cost-effective ways to achieve our goals, and to start pre-formulation studies for new missions prior to 2007. *NASA should review its investment in Earth system modeling in light of our recommendations and work with NOAA to ensure the longevity of the climate data records collected thus far and their continuity into the future.* Lastly, to avoid a potential gap in the US Earth observation program, the Committee recommends that NASA allocate funds to start formulation of several new missions as soon as possible.

Near-term recommendations:

1. ***Complete the approved program*** in a timely fashion, including the next Earth System Science Pathfinder Announcement of Opportunity. This roadmap was built on the assumption that the NASA missions currently in formulation and implementation would be completed as planned, and these missions are the foundation of this roadmap.

2. ***Add advanced planning funding for future Earth Science and Applications missions*** from Space. The following near-term missions and our first flagship mission (listed in order of launch dates) need to be studied immediately to accomplish our recommended timeline:
   - Cal/Val Mission
   - Ice Elevation Changes
   - Surface Deformation
   - Ocean Surface Topography
   - Aerosols and high resolution CO2
   - First Flagship Mission – L1 Atmospheric Composition/Solar influence on Climate

3. ***Fund the advanced planning for the first awareness investigation focus:*** atmospheric chemistry, including technology, missions, models, networks, educational opportunities, and international cooperation.

4. ***Fund at least one new start*** for the missions above in FY'07 or FY '08 and the others as soon as possible after that.

Appendices

A Roadmap Background and Team Members

Roadmap Background

This ***Strategic Roadmap*** **(SRM)** is one of a set of high-level national roadmaps that form the foundation of National Aeronautics and Space Administration's (NASA's) strategic plan for the next 30 years (2005 to 2035). These roadmaps explore options and establish pathways for achievement of NASA's strategic objectives, which in turn articulate how NASA will fulfill its vision and mission for the nation. A companion set of ***Capability Roadmaps*** recommends approaches for providing technical capabilities judged to be critical to NASA's future programs.

Each roadmap was developed by a committee of nationally-recognized scientists, engineers, educators, visionaries, and managers. Committees were co-chaired by senior individuals from NASA Headquarters, a NASA Center, and outside NASA. Committee membership consisted of individuals from NASA/JPL/ other government agencies, academia, and industry, in approximately equal proportions.

The roadmaps provide NASA with high-level guidance and recommendations for the achievement of Agency requirements. The roadmap Committees considered and incorporated the reports and priorities of NASA advisory committees, including legacy theme roadmapping activities, National Research Council (NRC) "decadal surveys," and other strategic guidance.

Earth Science and Applications from Space Strategic Roadmap Committee Participants

Roadmap Committee Members

Orlando Figueroa, NASA Science Mission Directorate, co-chair
Diane Evans, Jet Propulsion Laboratory, co-chair
Charles Kennel, Scripps Institution of Oceanography, co-chair
Waleed Abdalati, Goddard Space Flight Center
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Gordon Johnston, Mission Directorate Coordinator, Designated Federal Official
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Liaison Members:
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Richard (Ricky) Rood -- NASA GSFC (currently on sabbatical at LLNL)

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Victor Zlotnicki, JPL/NASA
John Bates, NOAA
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Pat Liggett, JPL/NASA
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SRM 9 Members of Joint 9/10 Subcommittee
Chris Kummerow
David Siegel

B National policy framework and External Constituencies

NASA's Earth science and applications from space responds to multiple presidential initiatives, National Space Policy, and current policies on broad access to information. NASA's science and innovation for Earth science and applications from space are relevant to multiple services for citizens that are the business of government (identified in the Federal Enterprise Architecture Business Reference Model).

B.1 Presidential Initiatives:

NASA has a critical role in implementing several recent major Presidential directives or initiatives, including:

- Climate Change Research;
- U.S. Integrated Earth Observation System;
- U.S. Ocean Action Plan; and
- Vision for Space Exploration.

NASA's programs addressing Earth science and applications from space are *essential* to the success of the first three presidential initiatives listed above, and will surely prove to be so to the fourth. NASA's contributions to the Earth sciences are unique, numerous, and critically important to future efforts to protect life and property, facilitate responsible environmental stewardship, and understand the Earth system.

B.1.1 Climate Change Research

Recognizing the importance of the climate change issue, President Bush has created an interagency, Cabinet-level committee, co-chaired by the Secretaries of Commerce and Energy, to coordinate and prioritize Federal research on global climate science and advance cleaner energy technologies.[1] This committee develops policy recommendations for the President and oversees the sub-cabinet interagency programs on climate science and energy technologies.

In July 2003, Energy Secretary Abraham, Commerce Secretary Evans, and White House Science Adviser Marburger released a 10-Year comprehensive Strategic Plan for the U.S. Climate Change. The plan describes a strategy for developing knowledge of variability and change in climate and related environmental and human systems, and for encouraging the application of this knowledge. After reviewing the Strategic Plan, the National Research Council commended its scope and content, stating that "[t]he plan articulates a guiding vision, is appropriately ambitious, and is broad in scope. It encompasses activities related to areas of longstanding importance as well as new or enhanced cross disciplinary efforts. Advancing science on all fronts identified by the program will be of vital importance to the nation."

[1] White House web page, "Addressing Global Climate Change," accessed May 9, 2005, URL http://www.whitehouse.gov/ceq/global-change.html

B.1.2 The U.S. Integrated Earth Observation System

On April 18, 2005, the White House announced the release of the Strategic Plan for the U.S. Integrated Earth Observation System (IEOS).[2] The plan will serve as the framework for the U.S. contribution to the Global Earth Observation System of Systems (GEOSS), a ten-year implementation plan involving nearly 60 countries to develop an integrated observation system to realize specific societal benefits. The U.S. hosted the world's first global Earth Observation Summit held in Washington, D.C. on July 31, 2003.

The U.S. government now has an over-arching strategy for integrating Earth Observations aimed at achieving identified societal benefits (observations required for leading edge research are identified and prioritized with the science community via the National Research Council). Previously there were pieces via science programs such as the Climate Change Science Program, but now the U.S. IEOS provides a coherent, overarching, broad strategy

The U.S. IEOS Strategic Plan is organized around nine specific societal benefits, providing a coherent and politically compelling rationale of crosscutting societal, scientific, and economic imperatives. These nine societal benefit areas are:

- Improve weather forecasting
- Reduce loss of life and property from disaster
- Protect and monitor our ocean resource
- Understand, assess, predict, mitigate, and adapt to climate variability and change
- Support sustainable agriculture and forestry, and combat land degradation
- Understand the effect of environmental factors on human health and well-being
- Develop the capacity to make ecological forecasts
- Protect and monitor water resources
- Monitor and manage energy resources

The U.S. IEOS Strategic Plan identifies (and recommends to OMB for investment) specific near-term opportunities.

An interagency working group made up of 15 federal agencies and 3 White House offices developed the U.S. strategic plan under the auspices of the National Science and Technology Council (NSTC) Committee on Environment and Natural Resources (CENR). The interagency working group was recently succeeded by a standing subcommittee under CENR called the United States Group on Earth Observation (US GEO), which will continue to develop implementation and integration plans for the United States system, and to provide input into the implementation of the global system of systems.

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[2] White House Office of Science and Technology Policy release, "U.S. Releases Earth Observation Strategic Plan to Take The Pulse of the Planet, April 18, 2005, URL http://www.ostp.gov/html/IEOSrelease4-18-05.pdf

B.1.3 U.S. Ocean Action Plan

On September 20, 2004, the U.S. Commission on Ocean Policy completed a thorough and expansive report, "An Ocean Blueprint for the 21st Century." On December 17, 2004, the President submitted to Congress his formal response, the *U.S. Ocean Action Plan*. The Bush Administration is focused on achieving meaningful results—making our oceans, coasts, and Great Lakes cleaner, healthier, and more productive. President Bush established by Executive Order a Cabinet-level "Committee on Ocean Policy" to coordinate the activities of executive branch departments and agencies regarding ocean-related matters in an integrated and effective manner to advance the environmental and economic interests of present and future generations of Americans.[3]

B.1.4 Vision for Space Exploration

<u>A Renewed Spirit of Discovery</u>: On January 14, 2004, President Bush announced a new vision for the Nation's space exploration program. The President committed the United States to a long-term human and robotic program to explore the solar system, starting with a return to the Moon that will ultimately enable future exploration of Mars and other destinations. The benefits of space technology are far-reaching and affect the lives of every American. Space exploration has yielded advances in communications, weather forecasting, electronics, and countless other fields.

B.2 <u>National Space Policy and NASA's Legislated Roles:</u>

B.2.1 U.S. Commercial Remote Sensing Space Policy.

In 2002 the United States Government began a broad review of U.S. space policies to adjust to the domestic and international developments in recent years that affect U.S. space capabilities.[4] The last update of the National Space Policy had been in 1996.[5] To date, the White House has released two major National Space Policy documents, the U.S. Commercial Remote Sensing Space Policy[6] in 2003 and A Renewed Spirit of Discovery[7] in 2004 (summarized in the previous section). The fundamental goal of U.S. commercial remote sensing space policy is to advance and protect U.S. national security and foreign policy interests by maintaining the nation's leadership in remote sensing space activities, and by sustaining and enhancing the U.S. remote sensing industry. Doing so will also foster economic growth, contribute to environmental stewardship, and enable scientific

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[3] Web page, "Committee on Ocean Policy," accessed May 9, 2005, URL http://ocean.ceq.gov/

[4] As recommended, for example, by "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, the Honorable D. Rumsfeld,, chair, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html

[5] The White House, National Science and Technology Council "Fact Sheet, National Space Policy," September 19, 1996, URL http://www.ostp.gov/NSTC/html/fs/fs-5.html. The actual policy statement is classified, and only this fact sheet is publicly available.

[6] White House Fact Sheet, "U.S. Commercial Remote Sensing Space Policy," May 13, 2003, URL http://www.whitehouse.gov/news/releases/2003/05/20030513-8.html

[7] White House Web Page, "President Bush Announces New Vision for Space Exploration Program," URL http://www.whitehouse.gov/infocus/space/index.html

and technological excellence. NASA serves as the lead agency for research and development in civil space activities. This policy requires that NASA:

- Rely to the maximum practical extent on U.S. commercial remote sensing space capabilities for filling imagery and geospatial needs.
- Focus U.S. Government remote sensing space systems on meeting needs that cannot be effectively, affordably, and reliably satisfied by commercial providers because of economic factors, civil mission needs, national security concerns, or foreign policy concerns.
- Develop a long-term, sustainable relationship between the U.S. Government and the U.S. commercial remote sensing space industry.
- Continue a program of long-term observation, research, and analysis of the Earth's land, oceans, atmosphere, and their interactions.
- Work with the DoC/NOAA, the DoD, the Intelligence Community, and the DoE to identify, develop, demonstrate, and transition advanced technologies to U.S. Earth observation satellite systems.

B.2.2. The Space Act:

The National Aeronautics and Space Act was initiated by the U.S. Congress in 1958, and helps define NASA's role within the U.S. government. It lists "the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space" as the first objective for NASA. It states that it is NASA's responsibility, regarding Earth science, to:

- Plan, direct, and conduct aeronautical and space activities
- Arrange for participation by the scientific community in planning scientific measurements and observations to be made through use of aeronautical and space vehicles, and conduct or arrange for the conduct of such measurements and observations
- Provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof
- Seek and encourage, to the maximum extent possible, the fullest commercial use of space
- Encourage and provide for Federal Government use of commercially provided space services and hardware, consistent with the requirements of the Federal Government
- Develop and carry out a comprehensive program of research, technology, and monitoring of the phenomena of the upper atmosphere as to provide for an understanding of and to maintain the chemical and physical integrity of the Earth's upper atmosphere
- Implement an appropriate research, technology, and monitoring program that will promote an understanding of the physics and chemistry of the Earth's upper atmosphere

NASA has been engaged in scientific remote sensing of the Earth from space from its beginnings as an agency, and this "as only NASA can" role has been affirmed and detailed in succeeding versions of the National Space Policy. [8]

B.2.3 Land Remote Sensing Policy:

In October of 1992, the Land Remote Sensing Policy Act was signed into law, and called for changes to the Landsat system. It calls for continued management of Landsat as an unclassified program by NASA and the DoD, maintained archiving of global Landsat data, and availability of Landsat data to non-profit users at lowest possible cost. In March 2005, a multi-agency group led by the Office of Science and Technology Policy reached a decision to secure continuity of Landsat type data via the National Polar-orbiting Operational Environmental Satellite System.

B.3 National Policies on Broad Access to Information:

Providing access to information and observations about the Earth is a fundamental responsibility for NASA under both the Space Act and the President's Management Agenda.

- One of NASA's functions as listed in the Space Act is to "provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." NASA's Earth Observing System Data and Information System provides over 29 million data products in response to 2.1 million queries each year.
- Within the President's Management Agenda, Expanded Electronic Government is one of the five government-wide goals to improve federal management and deliver results that matter to the American people. [9] Geospatial One Stop is an intergovernmental project in support of the President's Initiative for E-government. Geospatial One Stop builds upon its partnership with the Federal Geographic Data Committee (FGDC) to improve the ability of the public and government to use geospatial information to support the business of government and facilitate decision-making.[10] As a major source of Earth observations, NASA is one of the 19 member agencies in the FGDC established under OMB Circular A-16.[11] NASA's Distributed Active Archive Centers (DAACs) and Research, Education and Applications Solutions Network (REASoN) projects contribute to the U.S. capacity for data management of Earth observations. NASA is

[8] U.S. Public Law, "The National Aeronautics and Space Act of 1958," Public Law number 85-568, as Amended, URL http://www.hq.nasa.gov/ogc/spaceact.html,

[9] The Executive Office of the President, Office of Management and Budget, "The President's Management Agenda," Fiscal Year 2002, URL http://www.whitehouse.gov/omb/budget/fy2002/mgmt.pdf

[10] Web Page, "National Spatial Data Infrastructure, Geospatial One-Stop," URL http://www.geo-one-stop.gov/

[11] "OMB Circular A-16, Revised," August 19, 2002, URL http://www.whitehouse.gov/omb/circulars/a016/a016_rev.html

recognized for the Geospatial interoperability and participation in the OpenGIS Consortium and the FGDC.[12]

B.4 Relevance of NASA's science and innovation

Earth science and applications research is relevant to the business of the U.S. Government. The Federal Enterprise Architecture Business Reference Model is a function-driven framework for describing the business operations of the Federal Government independent of the agencies that perform them (see figure below).

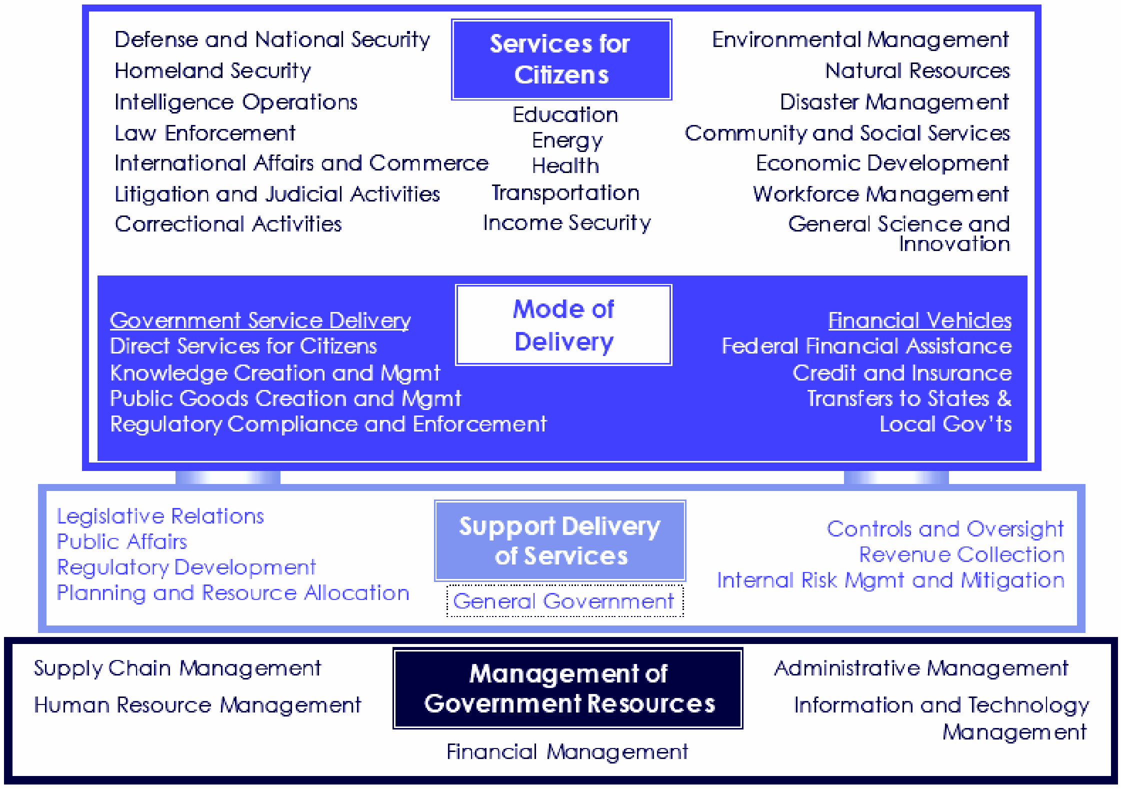


Figure B.2: Federal Enterprise Architecture Business Reference Model

The NASA's Applied Sciences program is pursing twelve applications of national priority in partnership with the U.S. government agencies that have management or regulatory mandates to provide these services to citizens.[13] The twelve NASA applications of national importance are:

[12] Web page, "NASA Contributions to GEO and IWGEO," accessed Oct. 6, 2004, URL http://earth.nasa.gov/visions/geoss.html

[13] NASA Office of Earth Science, "Earth Science Applications Plan," July 2004, URL http://www.earth.nasa.gov/visions/AppPlan.pdf. The most recent versions of the Applications Roadmaps are on pages 36 to 61.

Table A.2: Twelve Applications of National Priority

Agricultural Efficiency	Ecological Forecasting
Air Quality	Renewable Energy
Aviation	Homeland Security
Carbon Management	Invasive Species
Coastal Management	Public Health
Disaster Management	Water Management

NASA provides general science and innovation as its service to citizens, delivered through knowledge creation and management, yet the results are relevant to the broad business of Government.

C Unique Education and Outreach Opportunities Associated with NASA Earth Science and Applications from Space

Human beings are born with curiosity and imagination in abundance, with a natural desire for exploration and discovery. NASA recognizes its unique position to inspire the public through its fascinating science results from Earth and space, and propel the youth of our nation forward to be the scientists, engineers, and scientifically-literate leaders of tomorrow. Whether looking out into the unfathomable expanses of the universe, monitoring sea surface temperatures as they change through a year, witnessing the inundation of powerful tsunamis, registering atmospheric disturbances, or measuring gas levels, NASA delivers mesmerizing views that capture our eyes, turn our heads, and provide us with the opportunity to grasp events in a profound way. The spark of excitement and flash of awe kindles the flame of desire for exploration, discovery, and understanding. In preparing the "next generation of explorers," NASA must exercise its leadership in science, technology, engineering, and mathematics (STEM) education.

In order to adequately prepare the workforce of tomorrow, NASA needs not only to engage the public and inspire them towards careers in science and technology, but also to systemically support educators at all levels and venues to effectively communicate NASA science to all learners. NASA's Earth science research has particular relevance to key understandings youth are expected to achieve through their education [NSES, 1995]. NASA's may exercise powerful influence through its leadership in information infrastructure, systems thinking and modeling, research and development of new technologies, and applications of research to benefit society.

C.1 The Power of e-Education

NASA must continue to drive the development and application of innovations in information infrastructures and learning technologies, which make it possible to bring the results from our missions to learners in ways meaningful in their own lives. Digital information infrastructures provide learners of all ages inside and outside of the classroom with ready access to Earth system science resources. NASA is engaged in the ongoing production of very large geospatial data sets spanning the full spectrum of spatial and temporal scales. The challenge is to turn these vast quantities of data and information into knowledge products useful for education and communication to policy-makers.

We see a classroom of the future full of students who are explorers and educators who facilitate student discovery and learning. From a young age, learners are engaged in research and discovery through team-based projects that build and benefit their communities. NASA's comprehensive sensorweb for planet Earth is an essential element of this future, providing access to the real-time state of the planet through data from an integrated suite of sensors and data archives. Models to assimilate these data assist the student in building on past knowledge to understand the current state and forecast the future. The comprehensive data sets available from clusters of missions through the continuous awareness vision and NASA's recognition of the importance of the educational application of these data result in development of education-focused databases and visualization tools. These resources make it possible for students to participate in unique opportunities, such as climate, weather, or natural hazards forecasting activities and to "fly-through" data sets on student-generated paths based on their research questions. Life-long learners use these expanding data resources, models, and the shared expertise of the scientific community to improve their understanding of the planet, enhance their quality of life, promote their self-expression, satisfy their curiosity, and advance their research.

C.2 Role of Systems Thinking and Modeling

Systems thinking and modeling are essential components at the forefront of both NASA science and effective education. Earth is a system in which physical and chemical processes interact in complex cycles that involve the geosphere, atmosphere, hydrosphere, and biosphere. NASA's systems approach to studying Earth science provides the viewpoint from which we can ask a wide range of questions about the Earth and its evolution. Computer simulations of the Earth system are essential tools for the scientific community, both to answer research questions and to provide science-based knowledge to inform the public and policy makers. From the educational perspective, systems and models are unifying concepts across the sciences and are essential for students to understand as they develop their scientific literacy. NASA's scientific and personnel assets position it to make a unique contribution to development of an understanding of systems and models in education. Furthermore, the models developed by NASA scientists, in collaboration with their research partners, could be simplified and modified to address curriculum standards and support inquiry-based learning of a broad spectrum of learners.

C.3 Meaningful and Effective Implementation of Educational and Public Engagement

NASA research and development shapes our future in many ways. Technological breakthroughs improve our lives and lead to new commercial enterprises. New scientific insights enhance our ability to protect citizens from natural hazards and understand the world around us. In addition to working to develop an educated populace, well informed about NASA science, technologies, exploration, and discovery, NASA must intentionally pursue opportunities to build the workforce of tomorrow that will continue our discoveries into the future. In order to do this, NASA must proactively implement strategies to seek linkages to the educational community, specifically becoming involved on the state level in order to address state-level standards for education and learning. Building on programs that inspire, motivate, educate, and prepare students and their teachers through K-12 into undergraduate programs, NASA must also provide opportunities for students and researchers to become meaningfully engaged with NASA research, extending into collaborations with the private sector. These efforts must also intentionally include an emphasis on engaging populations historically underrepresented in science in the NASA adventure, such that these individuals see NASA as a desired, as well as a possible, career path. It is critical for the success of Earth science education at

NASA that opportunities are provided to open the science, technology, engineering, and math pipeline for all Americans, including underrepresented minorities.

C.4 Connecting Science and Education

Applications derived by NASA from its research programs make a unique contribution to enhancing the daily lives of the public through access to weather forecasts and predictions of tectonic hazards as well as through information that explains how choices in our daily lives impact our community, country, and the world. Often the missing link between NASA discoveries and public understanding is clear and effective communication. Future NASA Earth science research goals should be clearly benchmarked with relevant science, math, technology, and geography education standards, as well as posed in language that engages the person on the street. For example, "Distinguishing anthropogenic and natural aerosols and their effects on climate" is more likely to engage the public when communicated in the context of familiar topics, such as "volcanoes, cancer, and quality of life." Expression of research goals and their advance distribution to the public would also increase ability of the public to be engaged and involved in NASA Earth System Science missions as they happen, rather than only after the fact. Even more importantly, advance knowledge will allow educators of all types to prepare exhibits and lessons to share the awe of real-time discoveries about our home planet.

In accomplishing all these goals, it is critical that NASA focus on the unique role it has in education, and to work in partnership with other agencies, nonprofits, industry, educational institutions, and professional societies to most effectively and efficiently reach the population of learners that NASA needs to address.

D External Partnerships

D.1 Evolution of External Relationships:

NASA has a broad constituency and web of partnerships for its work in exploring the dynamic Earth system. While many other agencies are engaged in Earth science, NASA brings the global view from space, providing the global context in which to understand local, regional and global scale change. NASA also brings, from an expertise in systems engineering, complex problem-solving proficiency to the daunting challenge of understanding and protecting our home planet.

Over the last two decades NASA has used its "systems" expertise to lead a revolution in the way we study and understand the Earth. *Earth System Science*, the move to an integrated "systems" approach and away from narrow discipline or single-issue research "stovepipes" was the key innovation that revolutionized Earth science. Armed with the recommendations of the 1988 "Bretherton" report, NASA led this revolution with the development of the Earth Observing System.[14] NASA engaged in a deliberate strategy of supporting interdisciplinary Earth system science research and education as a way of growing this capacity in the nation's research and education communities. The most recent refinement has been to identify science focus areas as key integrating themes that build upon the capabilities of the diverse Earth science disciplines towards an integrated, predictive capacity. Setting long term goals built on the integrated results of broad research questions helps NASA and the community to establish and maintain scientific balance and relevance.

Today, NASA's Earth system science program integrates across the full breadth of science disciplines. Some researchers look at the key physical components of the Earth system (e.g., geologists, oceanographers, atmospheric scientists). Some researchers look at the key biological components of the Earth system (e.g., ecologists, biogeochemists, astrobiologists). Some researchers look at the key dynamic processes that cut across the components of the Earth system (e.g., meteorologists, climatologists, biologists, ecologists, hydrologists). Some researchers look at the key impacts of the Earth system on humans and society (e.g., natural hazards and disasters; food and fiber/agriculture, fisheries, and forestry; energy use and management; human health effects). Others look at the key impacts of humans and society on the Earth system (e.g., land cover and land use change; industrial emissions; resource management practices).

NASA is one of a few U.S. government agencies whose mandates are purely for research and technology development, without management or regulatory authority and responsibility. This research independence and NASA's credibility as an unbiased broker of scientific results are important intangible assets that NASA brings to Earth science issues with significant management, policy, and economic implications. In addition, this

[14] Bretherton, F., chair, "Earth System Science, A Closer View," Report of the Earth System Sciences Committee, NASA Advisory Council, January 1988.

independent role provides NASA the opportunity to advance the state-of-the-practice in exploration of the dynamic Earth system and transition new capabilities to our management and operational partners in the U.S. government.

D.2 External Constituencies and Corresponding NASA Roles:

As a result of this evolution in NASA's research relationships, NASA's Earth system science efforts are at the intersection of five major external constituencies. NASA's current roles reflect these external constituencies:

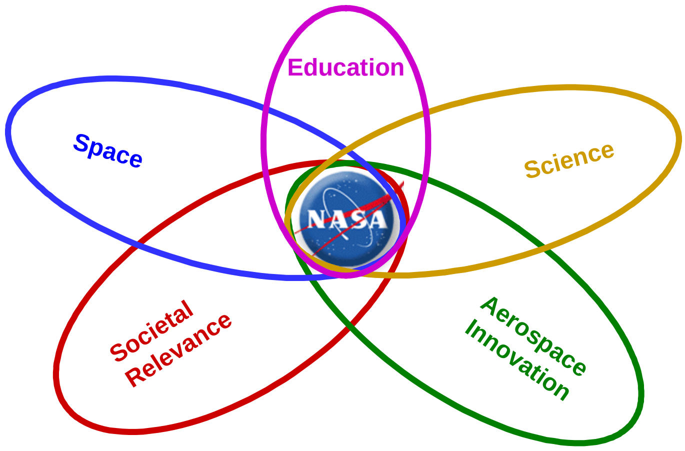


Figure A.3: NASA's Major External Constituencies

- **NASA is a Science Agency.** NASA conducts and sponsors research in key arenas where our air and space assets and our complex systems expertise can make defining contributions. NASA is a partner in the larger national and international science community, which is actively engaged in ground and space-based science of all types. NASA science priorities and implementation approaches are broadly reviewed through interagency committees, external advisory groups, and the National Academies.
- **NASA is a Space Agency.** NASA **defines** the leading edge of US civilian research and technology in and about space. NASA shares with the broader space community investments in launch capabilities and facilities, navigation and tracking facilities, etc. NASA coordinates with this broader community through a variety of mechanisms, including the Space Technology Alliance (with the National Security Space Community), the Committee on Earth Observation Satellites (CEOS, representing 41 international space-based Earth observation agencies and organizations), and the International Living With a Star initiative.
- **NASA is an Aerospace Innovation Agency.** NASA collaboratively addresses the technical challenges and develops capabilities to pursue its mission in partnership with the aerospace industry and technology sector. These include the aerospace companies that build our instruments, spacecraft, and supporting technologies as well as the academic researchers who develop new technological capabilities.

- **NASA enhances science, technology, engineering and mathematics education.** NASA addresses its mission to inspire the next generation of explorers through partnerships with the formal and informal education community. These partnerships enable an accessible, dynamic, and engaging learning environment for all citizens. This expands and deepens the Nation's appreciation and understanding of the Earth system and encourages pursuit of scientific and technical careers.
- **NASA's research is relevant to broad national priorities.** NASA conducts cutting-edge research that is relevant to society and human life. NASA's contributions are recognized and coordinated at the highest levels of the US government, such as the Committee on Climate Change Science and Technology Integration (CCCSTI) and the National Science and Technology Council (NSTC). NASA's Earth Science Applications Program is pursuing 12 applications of national priority in collaboration with over a dozen Federal agencies to enable NASA's Earth observations and research to improve the essential services these agencies provide to the Nation. NASA's Earth Science Applications program benchmarks practical uses of NASA-sponsored observations from remote sensing systems and predictions from scientific research and modeling. The approach is to enable the assimilation of science model and remote sensing mission outputs to serve as inputs to established partner agency decision support systems. The outcomes are manifest in enhanced decision support and the impacts are projected to result in significant socio-economic benefits.

NASA's strength is in addressing these overlapping interests. In many ways, the phrase "as only NASA can" in NASA's mission statement refers to these intersections. NASA is a science driven agency that serves the national interest. NASA addresses fundamental questions that inspire and motivate students. NASA is chartered under the space act to advance US leadership in aeronautical and space science and technology. If a NASA activity has compelling science or addresses critical national needs, while at the same time requiring the use of space or advanced aeronautical technologies, then that activity is a compelling match to NASA's overall charter, mission, and goals. If the activity can be pursued in a way that inspires and provides educational benefits, the match is even stronger.

D.3 Examples of Current Relationships:

The following are selected examples of NASA research activities that are directly relevant to major external constituencies.

- The Cabinet-level National Science and Technology Council (NSTC) is the principal means for the President to coordinate science, space, and technology in the diverse parts of the Federal research and development enterprise. An important objective of the NSTC is the establishment of clear national goals for Federal science and technology investments.[15] The Council has four committees, including the Committee on Environment and Natural Resources (CENR), the

[15] Web Page, "National Science and Technology Council," accessed Oct. 1, 2004, URL http://ostp.gov/nstc/html/nstc.html

Committee on Science, and the Committee on Technology. NASA is an active participant in the NSTC activities related to Earth system science, including the Subcommittees on Global Change Research, Ecological Systems, and Disaster Reduction,[16] as well as the United States Group on Earth Observations.[17]

- NASA is the largest contributor to the U.S. Climate Change Research Program, an interagency program established by the Executive Office of the President to integrate the Congressionally-mandated US Global Change Research Program and the Administration's Climate Change Research Initiative. NASA also participates in the U.S. Climate Change Technology Program. These programs are under the Cabinet-level Committee on Climate Change Science and Technology Integration (CCCSTI), established by the President to provide recommendations on matters concerning climate change science and technology; address related Federal R&D funding issues; and coordinate with Office of Management and Budget on implementing its recommendations.[18]
- NASA is a member of the US Weather Research Program. The USWRP is a partnership among science and operational governmental agencies, and the academic and commercial communities. The broad purpose of the Program is to increase the resiliency of the Nation to weather; that is, to ensure that the federal, state and local governments, the private sector and general public make well-informed and timely weather-sensitive decisions with respect to past, present, and future weather conditions. To achieve this end requires that the scientific and service communities work together to advance weather observing capabilities and fundamental understanding of weather and to use this understanding to improve weather prediction and enhance weather services provided to the Nation.[19]
- NASA develops and launches the Nation's weather satellites under a reimbursable agreement with NOAA, and is working with NOAA and DoD on the next generation, converged civilian and military polar-orbiting operational environmental satellite system.
- NASA has about 200 agreements with over 60 foreign nations for activities that Earth science and applications from space, and is active participant in a variety of international research programs and organizations, including the International Geosphere-Biosphere Programme, World Meteorological Organization, the G-8 sponsored Committee on Earth Observation Satellites, and a new international effort to create a Global Earth Observation System of Systems (GEOSS).

D.4 International Context:

Strengthening international co-operation on global Earth observation is on the world's agenda. Building upon the results of the 2002 World Summit on Sustainable

[16] Web Page, "Subcommittee on Natural Disaster Reduction," accessed Oct. 1, 2004, URL http://www.usgs.gov/sndr/
[17] Web Page, "Interagency Working Group on Earth Observations," accessed Oct. 1, 2004, URL http://iwgeo.ssc.nasa.gov/
[18] Web Page, "About the U.S. Climate Change Technology Program," accessed Oct. 1, 2004, URL http://www.climatetechnology.gov/about/index.htm
[19] Terms of Reference for the U.S. Weather Research Program (2001), URL http://box.mmm.ucar.edu/uswrp/program_organization/tor.html

Development,[20] the G-8 Leaders agreed at the Evian Summit in 2003 on an Action Plan on Science and Technology for Sustainable Development.[21] The Plan builds on U.S. initiatives to develop transformational technologies in three areas: energy, agriculture, and global observation.[22] Fifty-five nations now participate in the Group on Earth Observations (GEO) established as a permanent body at the third Earth Observation Summit in February 2005. At this summit these nations adopted the 10-year Implementation Plan for the Global Earth Observation System of Systems (GEOSS).

Nearly all of NASA's missions to Earth science and applications from space have substantial international participation, ranging from simple data sharing arrangements to ground validation to provision of instruments, satellite buses and launch services for space missions. We participate in the UNEP/WMO Triennial Ozone Assessment, the World Climate Research Program, the International Geosphere/Biosphere Programme, and the International Human Dimensions of Global Change Programme (IHDP). NASA scientists individually are key contributors to the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), which conducts a quadrennial assessment of the state of knowledge of climate change. The IPCC was initiated under the United Nations Framework Convention on Climate Change in 1992. NASA's wide range of international partnerships is documented in the publication "Global Reach", prepared by the Office of External Relations. NASA participates in the Millennium Ecosystem Assessment through the provision of satellite data and the involvement of individual scientists.

D.4 Linkage between national and international priorities

The following table (Table A.1) highlights key national priorities and their corresponding global context (with hyperlinks to relevant World Wide Web sources).

Table A.1: National Programs in a Global Context

Priority	National Programs	International Programs
Vision for Exploration	Understanding the Earth as the foundation for Planetary Exploration and Search for Life	*"Pursue opportunities for international participation to support U.S. space exploration goals"*
Global Earth Observation	NSTC CENR United States Group on Earth Observations (US GEO) Integrated Earth Observation System, 15 Agencies)	Group on Earth Observations (GEO) Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan
Climate Change	Climate Change Science Program (CCSP, 13 Agencies) Climate Change Technology Program (CCTP, 11 Agencies)	Intergovernmental Panel on Climate Change (IPCC)

[20] United Nations, "Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August-4 September 2002," A/CONF.199/20*, Pg. 63, URL http://ods-dds-ny.un.org/doc/UNDOC/GEN/N02/636/93/PDF/N0263693.pdf

[21] Summit Documents Web Page, "Science and Technology for Sustainable Development - A G8 Action Plan," Accessed Oct. 4, 2004, URL http://www.g8.fr/evian/english/navigation/2003_g8_summit/summit_documents/science_and_technology_for_sustainable_development_-_a_g8_action_plan.html

[22] White House Science and Technology Fact Sheet, "Fact Sheet: Action on Science and Technology," June 2, 2003, URL http://www.whitehouse.gov/news/releases/2003/06/20030602-15.html

Priority	National Programs	International Programs
Natural Hazards	NSTC CENR Subcommittee on Natural Disaster Reduction (SNDR, 14 Agencies)	International Strategy for Disaster Reduction
President's Management Agenda: E-Government	Geospatial One-Stop (GOS, 12 Agencies) and the Federal Geographic Data Committee (FGDC, 19 Agencies)	World Summit on the Information Society

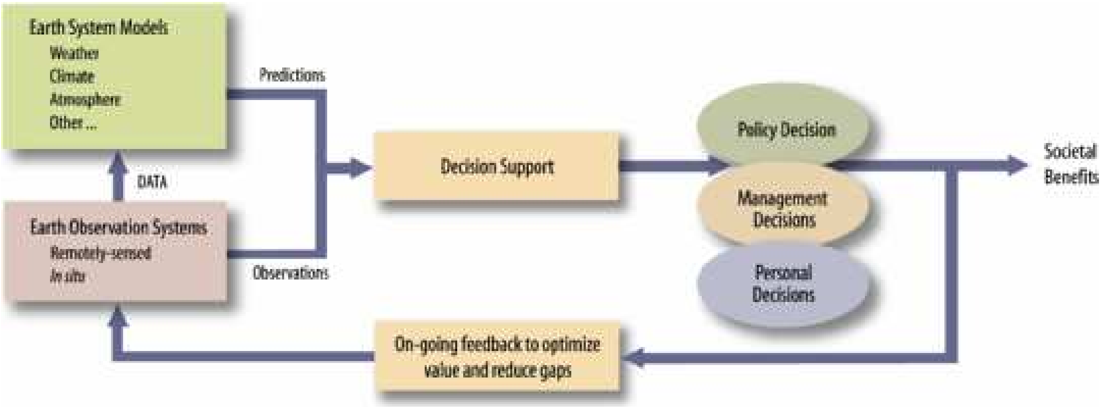
D.5 Evolution of External Constituencies

In order to achieve the societal benefits of a global system of earth observations, the predecessor to the United States Group on Earth Observations of the CENR developed a coordinated, multi-year plan for a U.S. Integrated Earth Observation System. Development and evolution of NASA science and technology will be fundamental to implementing the goals set forth in this plan, and coordination among external constituencies ranging from local to international will be required.

The paradigm of improvements in weather observations and prediction through cooperation at local to global scales enables NASA to anticipate the need for advances in observing, networking, and modeling technologies, advances in scientific understanding, and the need to develop cooperative relationships with a highly diverse intergovernmental community. Many of the technology challenges will be driven by questions that require data and analysis at multiple spatial and temporal scales. These, in turn, will require networked observations from multiple, disparate sources. Increases in expectations of locally-specific predictive capabilities will drive the space-based networks to more strongly include airborne and in situ networks as part of the integrated system. This will drive more emphasis on understanding and modeling the effects of global processes at local scales of information needs. NASA will need to draw upon the expertise of other federal, state, and local entities in much the same manner that NASA and NOAA have worked together to assimilate in in situ, ground-based, aircraft-based, and satellite vantage points in progressively higher resolution weather prediction models for societal benefit.

The Strategic Plan for the U.S. Integrated Earth Observation System establishes a framework for linking observations to societal benefits. By using a unifying system architecture this framework ensures that current and evolving systems are interoperable and the solutions can be easily expanded, extended, and/or replicated to address future challenges.

The following figure is from the Strategic Plan for the U.S. Integrated Earth Observation System. It depicts how remotely-sensed and in situ Earth observation systems provide data to Earth system models, and how these systems provide observations and predictions to decision support systems (tools, assessments, etc.) to inform policy, management, and personal decisions that provide benefits to society. The figure shows an on-going feedback loop to optimize the value of the overall system and reduce gaps in the ability to deliver timely and relevant information.



NASA science and technology research advances and enables new Earth observation systems and Earth system models. NASA works with partner agencies to benchmark use of research observations and predictions for decision support relevant to policy and management decisions

E Bibliography of Key Agency Documents and NRC Documents

The following is a list of relevant references organized around topic areas. Some documents were provided to the Committee members at the first meeting, and these documents are provided electronically. This list was drawn mainly from the Earth Science and Applications from Space Background Document (URL http://www.hq.nasa.gov/office/apio/pdf/earth/srm9plana.pdf). In some cases we have included web addresses (URLs) to on-line versions of the references. These were valid when the background document was prepared (Oct. 2004). Most but not all were updated or revalidated when this report was finalized (May 2005).

National Policy Framework:

- U.S. Public Law, "The National Aeronautics and Space Act of 1958," Public Law number 85-568, as Amended, URL http://www.hq.nasa.gov/ogc/spaceact.html
- The White House, National Science and Technology Council "Fact Sheet, National Space Policy," September 19, 1996, URL http://www.ostp.gov/NSTC/html/fs/fs-5.html. The actual policy statement is classified, and only this fact sheet is publicly available.
- White House Fact Sheet, "U.S. Commercial Remote Sensing Space Policy," May 13, 2003, URL http://www.whitehouse.gov/news/releases/2003/05/20030513-8.html
- White House Web Page, "President Bush Announces New Vision for Space Exploration Program," URL http://www.whitehouse.gov/infocus/space/index.html
- White House Web Page, "A Renewed Spirit of Discovery," January 23, 2004.
- Web Page, "National Science and Technology Council," accessed Oct. 1, 2004, URL http://ostp.gov/nstc/html/nstc.html
- "The Report of The Commission to Assess United States National Security Space Management and Organization," pursuant to Public Law 106-65, the Honorable D. Rumsfeld,, chair, January 11, 2001, URL http://www.defenselink.mil/pubs/space20010111.html

National and International Coordination of Global Earth Observation Systems:

- The Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan (As adopted 16 February 2005), available from the Group on Earth Observations web page at URL http://earthobservations.org/
- Final DRAFT Global Earth Observation System of Systems GEOSS 10-Year Implementation Plan Reference Document, available from the Group on Earth Observations web page at URL http://earthobservations.org/
- Strategic Plan for the U.S. Integrated Earth Observation System, available from the United States Group on Earth Observations web page at URL http://iwgeo.ssc.nasa.gov/
- Integrated Plan for the U.S. Integrated Earth Observation System Technical Reference Documents, available from the United States Group on Earth Observations web page at URL http://iwgeo.ssc.nasa.gov/:
  - Agriculture Technical Reference Document

  - Climate Technical Reference Document
  - Disasters Technical Reference Document
  - Ecological Forecasts Technical Reference Document
  - Energy Technical Reference Document
  - Human Health Technical Reference Document
  - Integration Technical Reference Document
  - Oceans Technical Reference Document
  - Water Technical Reference Document
  - Weather Technical Reference Document
- Additional Background Documents:
  - United Nations, "Report of the World Summit on Sustainable Development, Johannesburg, South Africa, 26 August-4 September 2002," A/CONF.199/20*, URL http://daccessdds.un.org/doc/UNDOC/GEN/N03/204/23/PDF/N0320423.pdf?OpenElement
  - Summit Documents Web Page, "Science and Technology for Sustainable Development - A G8 Action Plan," URL http://www.g8.fr/evian/english/navigation/2003_g8_summit/summit_documents/science_and_technology_for_sustainable_development_-_a_g8_action_plan.html
  - White House Science and Technology Fact Sheet, "Fact Sheet: Action on Science and Technology," June 2, 2003, URL http://www.whitehouse.gov/news/releases/2003/06/20030602-15.html
  - White House Web Page, "Science and Technology for Sustainable Development: "3r" Action Plan and Progress on Implementation," June 10, 2004, URL http://www.whitehouse.gov/news/releases/2004/06/20040610-53.html
  - Web page, "NASA Contributions to GEO and IWGEO," URL http://earth.nasa.gov/visions/geoss.html

NASA's Transformation -- Key Reports and Planning:

- NASA Strategic Plan
- NASA, "The Vision for Space Exploration," NP-2004-01-334-HQ, February 2004.
- A Journey to Inspire, Innovate, and Discover, June 2004 (the Aldridge Commission Report).
- The Need to Transform the Structure and Management of NASA, Report of the Roles, Responsibilities And Structures ("Clarity") Team, June 24, 2004.
- A Renewed Commitment to Excellence: An Assessment of the NASA Agency-wide Applicability of the Columbia Accident Investigation Board Report, January 30, 2004 (the Diaz Report).
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- Enhancing Mission Success -- A Framework for the Future, A Report by the NASA Chief Engineer and the NASA Integrated Action Team, January 2001.

NASA Earth Science Planning Activities:

- Earth Science Enterprise Strategy, October 1, 2003.
- NASA, "Earth Science Research Plan, 1/6/05 DRAFT." The previous version of this document is:
  - NASA, "Understanding Earth System Change: NASA's Earth Science Enterprise Research Strategy for 2000-2010," December 2000, available through URL http://www.earth.nasa.gov/visions/researchstrat/Research_Strategy.htm.
  - NASA Earth Science Focus Area Roadmaps. Updates to these roadmaps are included in the 1/6/05 DRAFT "Earth Science Research Plan. See URL http://www.earth.nasa.gov/roadmaps/index.html for the previous, versions of the roadmaps.
- NASA Report, "Earth Science Vision 2030 Working Group Report," March 2004, URL http://neptune.gsfc.nasa.gov/vision/Earth_Science_Vision_2030.pdf
- NASA, "Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions," March 3, 1999 (possibly less useful source representing earlier community involvement in planning NASA's future implementation).

NASA Earth Science and Applications Technology:

- "Earth-Sun System: Potential Roadmap and Mission Development Activities" explanatory cover sheet and December 23, 2004 presentation package. This contains the background information for George Komar's presentation at the January 2005 Committee meeting.
- See URL http://estips.gsfc.nasa.gov/ for access to the Earth Science Technology Integrated Planning System (ESTIPS). For examples of how NASA has engaged the community in developing and maintaining this database, see:
  - "Sensor & Platform Technology Requirements for Implementing NASA's Earth Science Research Strategy in the Next Decade: A Summary Report Based on the ESTO Technology Planning Workshop Held on March 5-6, 2003," available on the Web at URL http://estips.gsfc.nasa.gov/Home/docs/ESTOWorkhop20031.pdf
  - URL http://www.esto.nasa.gov/conferences/estc2004/ for information about the fourth annual Earth Science Technology Conference. To encourage greater participation, these annual conferences alternate between the East and West coasts.

NASA Earth Science Applications Planning Activities:

- NASA Office of Earth Science, "Earth Science Applications Plan," July 2004, URL http://www.earth.nasa.gov/visions/AppPlan.pdf. The most recent versions of the Applications Roadmaps are on pages 36 to 61.

NRC Decadal Survey:

- NASA, "Earth Science and Applications from Space: A Community Assessment and Strategy for the Future," Final version of charge to Committee, 11 August 2004.

- NRC, "Compilation of Comments on the Study and White Paper," Earth Science and Applications from Space, A Community Assessment and Strategy for the Future, August 17, 2004.

NRC and ESSAAC Advice to NASA and NASA's Responses:

- Steps to Facilitate Principal Investigator-Led Earth Science Missions (NRC, 2004)
- Assessment of NASA's Draft Earth Science Enterprise Strategy (NRC, 2003)
- Enhancing NASA's Contribution to Polar Science (NRC, 2001)
- Review of NASA's Earth Science Enterprise Research Strategy for 2000-2010 (NRC, 2001)
- Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data (NRC, 2002)
- Transforming Remote Sensing Data into Information and Applications (NRC, 2001)
- Toward New Partnerships in Remote Sensing (NRC, 2002)
- Using Remote Sensing in State and Local Government (NRC, 2003)
- Review of NASA's Earth Science Enterprise Applications Program Plan (NRC, 2002)
- The Role of Small Satellites in NASA and NOAA Earth Observation Programs (NRC, 2002)
- Report of the Task Group on Assessment of NASA Plans for Post-2002 Earth Observing Missions (NRC, 1999)
- Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond (NRC, 2004)
- Satellite Observations of the Earth's Environment (NRC, 2003)

NOTE: Some NRC reports relate to other topics (e.g., data policy, applications, weather, natural hazards, climate, or air quality) and are listed elsewhere.

- URL http://www.earth.nasa.gov/visions/ESSAAC_minutes.html for ESSAAC advice.
- Bretherton, F., chair, "Earth System Science, A Closer View," Report of the Earth System Sciences Committee, NASA Advisory Council, January 1988 (historical advice that led to EOS, the Earth Observing System).

National Information and Data Policy:

- The Executive Office of the President, Office of Management and Budget, "The President's Management Agenda," Fiscal Year 2002, URL http://www.whitehouse.gov/omb/budget/fy2002/mgmt.pdf
- Web Page, "National Spatial Data Infrastructure, Geospatial One-Stop," URL http://www.geo-one-stop.gov/
- "OMB Circular A-16, Revised," August 19, 2002, URL http://www.whitehouse.gov/omb/circulars/a016/a016_rev.html

- Down to Earth: Geographic Information for Sustainable Development in Africa (NRC, 2002)
- Review of NASA's Distributed Active Archive Centers (NRC, 1998)

National and International Weather Research and Applications:
- Terms of Reference for the U.S. Weather Research Program (2001), URL http://box.mmm.ucar.edu/uswrp/program_organization/tor.html
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National Natural Hazards Research and Applications:
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- Solid Earth Science Working Group, "Living on a Restless Planet," 2002, available through URL http://solidearth.jpl.nasa.gov/PAGES/report.html

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- OUR CHANGING PLANET, The U.S. Climate Change Science Program for Fiscal Years 2004 and 2005, A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, A Supplement to the President's Budgets for Fiscal Years 2004 and 2005, July 2004, available through URL http://www.climatescience.gov/
- Strategic Plan for the US Climate Change Science Program, 2003. For access to the plan and the NRC review, please see the "Strategic Plan for the Climate Change Science Program" web page at URL http://www.climatescience.gov/Library/stratplan2003/default.htm
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- Issues in the Integration of Research and Operational Satellite Systems for Climate Research II. Implementation (NRC, 2000)
- Committee on Global Change Research, "Global Environmental Change: Research Pathways for the Next Decade," National Academy Press, 1998, available through URL http://www.nap.edu/catalog/6264.html. The National Academy sometimes reviews NASA's Earth system science programs as part of larger national efforts. Such was the case with this 1998 "pathways" report, which addressed decadal recommendations for the U.S. Global Change Research Program. This was essentially a decadal assessment of NASA's research in the context of the larger, national program.
- Our Common Journey (NRC, 1999)

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- U.S. Commission on Ocean Policy, *An Ocean Blueprint for the 21st Century*, Final Report, Washington, DC, 2004, ISBN#0–9759462–0–X, available through URL http://www.oceancommission.gov

Air Quality Research and Applications:

- Global Air Quality: An Imperative for Long-Term Observational Strategies (NRC, 2001)

F Acronym List

AIRS: Atmospheric InfraRed Sounder
APIO: Advanced Planning and Integration Office
ARC: Ames Research Center
Cal/Val: Calibration/Validation
CCCSTI: Committee on Climate Change Science and Technology Integration
CCSP: Climate Change Science Program
CCTP: Climate Change Technology Program
CENR: Committee on Environment and Natural Resources
CEOS: Committee on Earth Observation Satellites
CFC: Chlorofluorocarbon
CRM: Capability Roadmap
DAAC: Distributed Active Archive Center
DoC: Department of Commerce
DoD: Department of Defense
DoE: Department of Energy
EDR: Environmental Data Record
EOS: Earth Observing System
EOSDIS: Earth Observation System Data Information System
ESMF: Earth System Modeling Framework
ESSP: Earth System Science Pathfinder
ESTO: Earth Science Technology Office
FGDC: Federal Geographic Data Committee
FY: Fiscal Year
GB: Gigabytes
GEO: Geosynchronous Earth Orbit
GEOSS: Global Earth Observing System of Systems
GSFC: Goddard Space Flight Center
IEOS: International Earth Observing System
IHDP: International Human Dimensions of Global Change Programme
InSAR: Interferometric Synthetic Aperture Radar
IPCC: Intergovernmental Panel on Climate Change
IR: Infrared
JPL: Jet Propulsion Laboratory
L1: 1st Libration Point
LaRC: Langley Research Center
LDCM: Landsat Data Continuity Mission
LEO: Low Earth Orbit
MARS: Monterey Accelerated Research System
MMI: Measurement Maturity Index
MODIS: Moderate Resolution Imaging Spectroradiometer
MOOS: Monterey Bay Aquarium Research Institute Ocean Observation System
MS&A: Modeling, Simulation, and Analysis
NASA: National Aeronautics and Space Administration
NIR: Near Infrared

NIST: National Institute of Standards and Technology
NOAA: National Oceanic and Atmospheric Administration
NPOESS: National Polar Orbiting Environmental Satellite System
NPP: NPOESS Preparatory Project
NRC: National Research Council
NSF: National Science Foundation
NSTC: National Science and Technology Council
OCO: Orbiting Carbon Observatory
OLI: Operational Land Imager
OMB: Office of Management and Budget
PB: Petabytes
R&D: Research and Development
RC: Research Center
REASoN: Research, Education and Applications Solutions Network
SCCOOS: Southern California Coastal Ocean Observing System
SRM: Strategic Roadmap
STEM: Science Technology Engineering and Mathematics
TB: Terabytes
UAV: Unmanned Aerial Vehicle
UCAR: University Corporation for Atmospheric Research
UNEP: United Nations Environment Programme
USGEO: United States Group on Earth Observation
USGS: United States Geological Survey
USWRP: US Weather Research Program
UV: Ultraviolet
VHF: Very High Frequency
VIIRS: Visible Infrared Imager/Radiometer Suite
Vis: Visible
WMO: World Meteorological Organization

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
EARTH SCIENCE AND APPLICATIONS FROM SPACE STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Earth Science and Applications from Space Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on research and technology development to advance Earth observation from space, improving scientific understanding, and demonstrating new technologies with the potential to improve future operational systems Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

Sun-Solar System Connection

May 22, 2005

TABLE OF CONTENTS

Sun – Solar System Connection Roadmap

NASA Objective #15:

Explore the Sun-Earth system to understand the

- Sun and its effects on:
    - Earth,
    - the solar system,
    - the space environmental conditions that will be experienced by human explorers,
- and demonstrate technologies that can improve future operational systems.

NASA Objective #15 maps to the following National Objectives (from the Vision for Space Exploration):

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations
- Develop innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests
- Study the Earth system from space and develop new space-based and related capabilities for this purpose

Executive Summary

NASA's goal for future research and exploration within its Sun-Solar System Connection program is to observe and understand the complex phenomena associated with space weather by studying the Sun, the heliosphere and planetary environments as a single, inter-connected system. Such an understanding will represent not just a grand intellectual accomplishment for our times - it will also provide knowledge and predictive capabilities essential to future human and robotic exploration of space and will serve key societal objectives in important ways. Herein, we describe current plans for NASA's research programs in this area and the guiding principles we will follow in pursuit of forthcoming exploration challenges.

The exotic environment of space beyond Earth's protective atmospheric cocoon is highly variable and far from benign. Strongly influenced by the variability of the sun, a host of interconnected physical processes occur that affect the habitability of other space locales and the health and safety of travelers to those destinations. Building on NASA's rich history of exploration of the Earth's neighborhood and distant planetary systems, we will develop the quantitative knowledge needed to help assure the safety of the new generation of human and robotic explorers.

With focused research programs addressing specific space environmental hazards we will help guide the design and operations of safe and productive Exploration missions. At the same time we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space.

This scientific exploration will target the highly coupled system that stretches from the sun's interior to planetary neighborhoods and the vast expanses of interplanetary space. We are now transforming human understanding of this fascinating global system of systems, so closely connected that the same explosive event on the sun can produce power outages on the Earth, degradation of solar panels on interplanetary spacecraft, fatal damage to instrumentation in Mars orbit, and auroral displays at Saturn, effects that span the entire solar system. By expanding and deepening that understanding, we will not only develop a predictive capability to address hazards to space travelers and to important technological assets closer to home, but we will learn how the fundamental space processes interact to affect the habitability of other distant environments, beyond our own solar system.

Our near-term goals will be achieved by pursuing three groups of strategic missions.

The Solar-Terrestrial Probe missions will address fundamental science questions about the physics of space plasmas and the flow of mass and energy through the solar system. For example, Solar–B, a partnership mission led by Japan, will be launched in 2006 to observe how magnetic fields on the Sun's surface interact with the Sun's outer atmosphere, which extends millions of miles into space. The STEREO mission, also to be launched in 2006, will provide an unprecedented view of the three-dimensional distribution of magnetic fields and particle flows throughout the heliosphere. And, the Magnetospheric Multiscale Mission, to be launched in 2011, will explore the fundamental physical processes responsible for the transfer of energy from solar wind to Earth's magnetosphere and the explosive release of energy during solar flares.

The Living With a Star missions will enhance scientists' knowledge of Earth–Sun system aspects that directly affect life and society. The Solar Dynamics Observatory, to be launched in 2008, will observe the solar interior and the Sun's atmosphere continuously to determine the causes of solar variability. The Radiation Belt Storm Probes, to be launched in 2011, will determine how space plasmas are accelerated to hazardous energies, thereby enabling scientists to predict changes to planetary radiation environments and protect space explorers. The Ionospheric / Thermospheric Storm Probes, to be launched in 2015, will help scientists understand, to the point of acquiring a predictive capability, the effects of geomagnetic storms on the ionosphere / thermosphere–a region in the atmosphere located approximately 50 to 800 miles above Earth's surface. Last, the Solar Sentinels, also to be launched in 2015, will provide understanding on the transition and evolution of eruptions and flares from the Sun to the planetary environments.

In the years ahead, portions of this spacecraft fleet will be configured into constellations - smart, strategically-located satellites that can work together to provide the timely, on-demand data and analysis to users who enable the practical benefits for scientific research, national policymaking, economic growth, hazard mitigation and the exploration of other planets in this solar system and beyond.

The interplay among observation, simulation, modeling and theory is viewed as essential for the vitality of our space science program. In some cases, a model or simulation will provide specific predictions to spur the course of future observation. In other cases, unexplained observations will lead to the development of new theories and the creation of entirely new models. As part of our exploration-based missions, we plan to continue supporting fundamental theory, modeling, data assimilation, and simulation programs, the development of space weather modeling frameworks, and the transition to applications-based codes necessary for space weather operational predictions. The burgeoning maturity of current, comprehensive theoretical modeling systems, spanning many regions and times scales, provides the essential underpinnings for NASA's effort to integrate and synthesize knowledge of the complete system of systems.

Lastly, as an essential element of its plan to meet these challenging requirements, NASA will invite active participation by international and national partners to support the exploration and research program. It will also build and deploy exciting educational tools that will inspire and educate new generations of students and the American public. These partnerships, technologies, and educational materials will support and advance the space programs of all nations.

Part I. A New Science for the Age of Exploration

Human space exploration has transformed our understanding of the solar system. It has revealed a fascinating nested system of systems, so closely connected that an explosive event on the Sun produces effects that span the entire solar system. Through judicious use of a number of operating missions, we have achieved system surveillance over parts of the heliosphere, and have been able to examine the causal linkages between its parts. We have observed spectacular coronal mass ejections, power outages on the Earth, degradation of spacecraft solar panels and circuits, destruction of atmospheric ozone, inflation and ablation of planetary upper atmospheres, fatal damage to instrumentation in Mars orbit, auroral displays on Saturn, and, months later, radio disturbances at the edge of the solar system where it meets the interstellar medium. In short, we have observed that space contains weather.

Classically, the structure and processes of our environment had been understood in terms of gravitation and pressure. Since space exploration began in 1957, we have learned that space is filled with matter and electromagnetic fields whose importance is belied by their invisibility. Unsheltered from the Sun's pervasive UV radiation field, matter in space enters the fourth state: a conducting *plasma* of electrically charged electrons and ions, flowing and reacting to highly variable electromagnetic forces. Human experience provides no experience with the behavior of such plasma atmospheres, and they behave in ways for which we have little or no physical intuition.

Owing to their conductivity, moving plasmas generate electrical currents and magnetic fields. Many exotic phenomena ensue, some of which resemble *turbulent* fluid flows, but impart so much energy to a subset of plasma particles that they ionize many more atoms when they come in contact with cooler states of matter such as gases, tissues, or semiconductor circuits. Magnetic field lines act to link their source plasmas into coherent cells, much as droplets of water are defined by surface tension. When such cells of plasma come into contact with each other, their magnetic fields *reconnect*, creating a linkage between the two cells and coupling them to each other so that motions of one drive motions of the other. Electrical currents flow to generate the coupling forces, and electromotive forces are generated that *accelerate* charged particles.

The robotic exploration of our universe has clearly shown that electromagnetically driven processes act at the center of every stellar system. Our own solar system is driven by the Sun, a magnetically variable star. The Vision for Space Exploration will eventually free mankind from the gravitational forces that have held us through history. Space explorers will learn to live within the magnetically controlled space environment and, through our NASA exploration missions, every citizen will be able to see and experience these things.

Our program will help assure the assure the safety of the new generation of human and robotic explorers At the same time we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space We will develop a predictive capability to address hazards to important technological assets closer to home and learn how fundamental space processes may affect the habitability of other distant environments beyond our own solar system

The Earth and the Sun are linked together to form the system that has given origin and sustenance to our lives. The story of how this came to be, over the history of the solar system, is nothing less than a Creation Narrative. It is the most compelling mystery faced by humankind. The physical processes and the evolutionary paths embedded in this combined system are studied in the Earth-Sun System division of the Science Mission Directorate. We examine the Earth and Sun system today for insights into questions concerning how the system evolved so as to produce and sustain life, what will happen to this unique environment through the course of time, and how it will affect us.

With human activity limited mainly to low Earth orbit since the mid-70's, we have been reconnoitering the solar system (and beyond) using robotic spacecraft and telescopes for much of that time. In 2005, Voyager passed through the solar wind termination shock and into the heliosheath, nearing the edge of the solar system. Though we have not visited the inner boundary of the solar atmosphere, the sun is bright enough reveal a great deal about itself through remote imaging, spectroscopy, and polarimetry.

The first broad survey of the solar system is essentially complete and we are now beginning to revisit the planets, including Earth, for studies of greater depth. The region around the Earth remains an important astrophysical laboratory for the study of the physical processes that are of broad relevance to astrophysics. Moreover, these processes are by now known to have influenced the habitability of the Earth and are therefore relevant to the possible existence of life elsewhere in the solar system or Universe. We have barely begun to scratch the surface of the history of our solar system over geologic time, having only recently determined that planets are commonplace around other stars. In at least one such case we can discern the signature of an atmosphere being ablated by a stellar wind. In another case, X-rays are emitted from a young stars that is not fully ignited, showing that electromagnetic and plasma processes become active very early in the life of a planetary system.

The United States is now embarking on an ambitious new journey of exploration to the Moon, Mars, and beyond. NASA has been challenged to establish a sustained presence on the moon by the end of the next decade with the purpose of enabling Martian exploration thereafter. The will to achieve this Vision for Space Exploration presents the agency with great opportunity and sobering demands.

Success in this venture requires advanced understanding of the complex physical systems that link the variable star at the center of our solar system with the Earth and other planets. The harsh and dynamic conditions in space must be characterized and understood in some detail if robots and humans are to safely and productively travel and explore the Moon and Mars.

The biological effects of the energetic particle radiation environment outside of low-Earth orbit remain largely unknown. Astronauts aboard the International Space Station (ISS) accumulate significant radiation exposure and energetic particle events significantly impact space station operations. Safe and productive travel outside Earth's protective magnetic cocoon, whether to the Moon or Mars, will require new predictive capability for solar particle events. Even well designed hardware is damaged or degraded by extreme conditions in space. And astronauts spending more than a few days in space will need to take shelter from episodic exposure to lethal doses of solar energetic particles.

Space weather and solar variability affect critical technologies used on Earth as well, for example satellite communications, navigation, remote sensing, and power distribution. Increasing reliance on vulnerable global systems demands active management in response to variations in the space environment. In many ways, our space weather approach is analogous to earlier steps taken by scientists to understand and predict weather in the Earth's atmosphere. We must also observe and understand the detailed phenomena, generate theoretical models that can be validated and verified against observed reality, build data assimilative predictive systems, and then develop operational decision support systems can are tailored closely to the needs of end-users and rigorously tested and improved over time. In this way and by these means, NASA's Sun-Solar Systems connections program will bring sound science to serve society.

Space weather is analogous in some ways to, yet fundamentally different from, the tropospheric weather that is so familiar to us, yet difficult to predict beyond a few days. It is analogous in its nonlinear complexity across an even larger range of scales. Systems this large cannot be reduced to a linear combination of interacting parts, through detailed study of those parts. Space weather is fundamentally different in that electricity and magnetism are at least as important as the more familiar forces of gravity and pressure. Measuring, characterizing, and understanding these processes cannot generally be done with images and common intuition. Localized measurements cannot be easily interpreted to generate a global picture. Conversely, the global picture does not provide insight into the small-scale physical processes of the system. For example, the magnetic reconnection that regulates much of the interaction between the solar wind and the Earth's magnetosphere cannot be observed remotely and it takes place in a rapidly moving location several Earth radii above the planet on a spatial scale of a few kilometers and temporal scale of several milliseconds.

Answering a specific science and or exploration question often requires a narrowly focused mission to a particular location with a unique instrument. For example, measuring flows in the solar interior requires a continuous series of velocity measurements at millions of locations on the solar disk. However, Sun – Solar System Connection science increasingly depends on combining multi-point *in situ* measurements with remote imaging. Again, by analogy with meteorology, combining a network of distributed local with global measurements (a meteorological Great Observatory) will enable the development and testing of predictive models that improve with time and experience.

Currently the SSSC Great Observatory includes satellites that hover near L1 – a million miles upstream in the solar wind, circle over the Sun's poles, orbit the Earth, and are approaching the first boundary between the interstellar medium and the Sun's domain, the heliopause. As each set of scientific questions is answered, the observatory evolves with the addition of new spacecraft. Soon the two STEREO spacecraft will drift away from Earth to provide the first stereoscopic views of the Sun, The Solar Dynamics Observatory (SDO) will image the Sun from geosynchronous orbit, the Radiation Belt Storm Probes will probe the processes that accelerate particles to hazardous radiation levels, and the four Magnetospheric Multi-Scale (MMS) spacecraft will fly in tight formation to explore the multiple scales of reconnection, turbulence, and particle acceleration in the magnetosphere of the Earth.

In this strategic roadmap for the Sun – Solar System Connection we explore the strategic planning consequences of a stated U.S. national objective for NASA: "Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational systems."

New knowledge of this system enables safe and productive exploration. Exploration enables new scientific understanding. The knowledge has utility for society. Our high priority science and exploration objectives address each of these needs. It is vital, compelling and urgent.

Part II. Achieving the Vision

Chapter 1. Sun-Solar System Connection: The Science

Introduction

Our world's new generation of space researchers inherited great legacies from the exploratory missions and discoveries of earlier decades. Their success in conducting a robust program of exploration at new scientific frontiers will bequeath to future generations a similar legacy of achievement and inspiration. Because the purpose of exploration is to understand the unknown, the precise benefits of their future space research and their path to success defy prediction. Progress will require continuous adaptation to exciting diversions and new directions.

Building on such a rich history of exploration, we now seek to transform human understanding of this fascinating system of systems that are so closely connected. The same explosive event on the Sun that produces power outages on Earth can also degrade solar panels on interplanetary spacecraft, produce mission-ending damage to instrumentation at Mars, produce radio waves and aurora at the outer planets, and even change the fundamental interaction of our heliosphere with interstellar media. We will not only develop a predictive capability to address hazards to space travelers and important technological assets closer to home, but we will also learn how the fundamental space processes interplay to affect the habitability of other distant environments. Our strategic plan for the future consists of three scientific objectives:

Opening the Frontier to Space Environment Prediction

The sun, our solar system and the universe consist primarily of plasma, resulting in a rich, complex and interacting set of physical processes, including intricate exchanges with the neutral environment we will encounter on our return to the moon and our journey to Mars, we must develop a complete understanding of the many processes that occur with such a wide range of parameters and boundary conditions within these systems.

As the foundation for our long-term research program, we plan to develop a complete understanding of the fundamental physical processes of our space environment–from the Sun to the Earth, to other planets, and beyond to the interstellar medium. We will systematically examine similar processes in widely different regimes with a range of diagnostics techniques to both test our developing knowledge and to enhance overall understanding. The universal themes of energy conversion and transfer, cross-scale coupling, turbulence and nonlinear physics have been chosen as near-term priority targets. The five fundamental processes that have been identified as the critical immediate steps are: magnetic reconnection, particle acceleration and transport, the generation and variability of magnetic fields, cross-scale coupling across boundaries and large structures, and nonlinear energy and momentum transport and coupling in atmospheres. Both in situ and remote sensing observations will be required, providing a three dimensional large-scale perspective as well as a detailed small-scale microphysics point of view. With our increasingly sophisticated understanding of such basic processes, we will open the frontier of predictive modeling across the solar system.

Understanding the Nature of Our Home in Space

Mankind does not live in isolation; we are intimately coupled with the space environment through our technological needs, the habitability of the planets and the solar system bodies we plan to explore, and ultimately the fate of our Earth itself. We regularly experience how variability in the near-Earth space environment affects the activities that underpin our society.

We plan to better understand our place in the Solar System by investigating the interaction of the space environment with the Earth and the effect of this interaction on humankind. Building on our new knowledge of fundamental processes, we plan to characterize and develop a predictive knowledge of the impact of the space environment on society, technology, and our planet. This will be accomplished both by direct investigation of the local environment and by what can be learned about life on Earth through studying other environments. Human life and society provide the context in which these investigations are conducted.

As we extend our presence throughout the solar system, we will be increasingly interested in the planetary environments that await us and how the lessons learned can be applied to our home on Earth. A casual scan of the solar system is sufficient to note that habitability of life in general, and humankind in particular, is a rare congruence of many events. At least some of these factors, especially the role of magnetic fields in shielding planetary atmospheres, are a subject of immense interest. We believe we know some of the features that make planets habitable, but there is much more to be understood.

Safeguard Our Outward Journey

The great variety of space environment conditions will have a significant impact on our future space explorers, both robotic and human. We plan to pursue, with all due vigilance, the research necessary to assure the safety and the maximum productivity of our explorers. We plan to develop the capability to predict space environment conditions from low Earth orbit to the Moon and Mars. Addressing space weather issues is necessary for optimizing the design of habitats, spacecraft and instrumentation, and for planning mission and operations scenarios, ultimately contributing to mission success.

Building on our knowledge of fundamental processes, we plan to understand those aspects of the space environment essential for enabling and securing space travel. Good engineering data is already flowing into exploration-based planning and implementation because the Sun-solar system community knows how to explore useful scientific directions. Our space plasma research community is poised to provide the next generation of measurements, simulations and models that will be useful to the implementation of manned and robotic missions to the Moon, Mars, and other planetary bodies. Such parameterizations of the space environment will be essential inputs for solutions to the challenging engineering problems that must be solved for successful and economical exploration activities.

Objective F: Open the Frontier to Space Weather Prediction

Understand the fundamental physical processes of the space environment – from the Sun to Earth, to other planets, and beyond to the interstellar medium.

The sun, our solar system and the universe consist primarily of plasma, resulting in a rich, complex and interacting set of key fundamental physical processes, including intricate exchanges with the neutral gas in planetary atmospheres. To predict the behavior of the complex systems that control the environments we will encounter on our return to the moon and journeys to Mars necessitates the development of a complete understanding of these processes. These key processes occur in many locations often with very different ranges of parameters and boundary conditions. As a result, both in situ and remote sensing observations are utilized, often providing a three dimensional large-scale perspective, as well as a detailed small-scale microphysics view. Our ability to quantitatively examine the same process in different regimes with a variety of measurements both tests our developing knowledge and enhances our understanding. The research focus areas of Objective F identify critical steps to provide the detailed knowledge required to enable the safe and productive exploration via development of accurate forecasting of the space environment. These areas are magnetic reconnection, particle acceleration, the physics of plasma and neutral interactions, and the generation and variability of magnetic fields with their coupling to structures throughout the heliosphere. These research focus areas all share the universal themes of energy conversion and transport, cross-scale coupling, turbulence and nonlinear physics – themes which are fundamental to the understanding of space and planetary systems. In addition they all include processes that can be influenced by large-scale boundaries or by coupling between regions with very different parameters (for example, cold, dense neutral atmospheres with energetic particles). With our increasingly sophisticated understanding of these fundamental physics process, we will reach the frontier developing predictive models. Objective F is, therefore, designed to provide the fundamental physics underpinnings that will enable predictive capability for Objectives J and H.

The fundamental importance of magnetic reconnection, the rapid conversion of magnetic energy to particle energy, in solar flares, CMEs and geospace storms is well recognized is the focus of RFA F1. This explosive release of enormous amounts of energy can be potentially devastating to space assets and voyaging humans, and have serious effects on worldwide communications. Although we have developed an initial picture of where reconnection occurs and the observable results, the detailed physical mechanisms, in particular, the microphysics and the role of large-scale topology, is not understood. This focus area will deliver the fundamental understanding of this universal process in the very different regimes where it occurs.

Within the solar system many other mechanisms, including small-scale waves, shocks and quasi-static electric fields, energize particles. Because these energetic particles have the most direct impact on human and robotic space explorers, a detailed understanding of these acceleration processes, the regions in which they operate and the boundary conditions that control them is crucial to the exploration of space. Providing this understanding is one goal of RFA F2. In addition, the origin and acceleration of the solar wind is a mystery. The bulk of solar wind particles are not energetic enough to damage spacecraft systems, but much of the interaction between the sun and planets is mediated by the solar wind, making the understanding of its acceleration a fundamental component of the Sun-Earth system science.

RFA F3 is designed to explore the fundamental physics of plasma and neutral coupling. This coupling encompasses a variety of mechanisms and regions from turbulence and change exchange in the solar wind to gravity waves and chemical/collisional interactions in in planetary atmospheres and This RFA has a goal comprehensive understanding of the nonlinear processes and inter-related roles of these processes to enable the quantitative predictions of plasma neutral neutral interactions from atmospheric scales to heliospheric scales. This RFA has specific applicability to the operation of satellites in the Martian atmosphere and mitigation of the effects of global change, as well as habitability of planets.

The existence of the magnetic fields of the Sun and planets is a key element of the Sun-Solar System connection and is the focus of RFA F4. The creation these fields – the dynamo problem – remains one of the outstanding problems in physics. How dynamos operate in such widely different systems from stellar interiors to planetary cores is poorly understood. Because the solar magnetic field controls the structure of the heliosphere and, thus, the entry of galactic cosmic rays into the solar system, it is imperative that we understand the origin and variability of the solar magnetic field. The Earth's interior dynamo sustains the geomagnetic field, providing the shield that enables life to flourish in the harsh radiation environment of space. Solving the dynamo problem will provide the key understanding to allow us to better predict and anticipate changes in the magnetic fields from the Sun to the Earth and beyond.

Research Focus Area F1: Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms.

Reconnection is the rapid conversion of magnetic energy into particle energy. It is an important, cross-scale coupling process in a variety of space plasmas ranging from the magnetotail of the Earth to solar flares on the Sun. Solar flares, coronal mass ejections, and geospace storms are all initiated and energized by reconnection -- often with potentially devastating effects to space systems. The explosive conversion of magnetic energy originates in a volume of space known as the diffusion region. This region is very small when compared to the large scales in space. For example, reconnection at the Earth's magnetopause surface (the boundary separating the solar wind and terrestrial magnetic fields) occurs in a region with an area of the order of hundreds of square kilometers compared to a total surface area of approximately 60 billion square kilometers. Properly instrumented spacecraft have not sampled the diffusion regions in situ in the near-Earth environment and imaging of the Sun does not currently have the ability to resolve the diffusion region associated with solar flares. Thus, the physical processes that initiate and control reconnection have eluded our understanding.

The two investigations for this RFA are:

Investigation F1.1. What are the fundamental physical processes of reconnection on the small-scales where particles decouple from the magnetic field?

Relevant Mission: MMS

Investigation F1.2. What is the magnetic field topology for reconnection and at what size scales does magnetic reconnection occur on the Sun?

Relevant Missions: RAM, SIRA, MC, MMS, DBC, SDO, Solar-B, SEPM, CLUSTER, THEMIS, SHIELDS, STEREO, DOPPLER, IMAGE, POLAR, TIMED

Research Focus Area F2: Understand the plasma processes that accelerate and transport particles

One of the most dramatic hallmarks of magnetized plasmas is their tendency to convert energy from one form to another, leading to fast bulk flows and to the selective energization of small subsets of particles to surprisingly high energies. A variety of such acceleration and energization processes operate within our solar system, with consequences that are both fascinating and threatening. Very high-energy particles accelerated at the sun and within interplanetary space present a serious hazard to human and robotic exploration of the solar system, while energetic particles produced within planetary magnetospheres can have deleterious effects on important technological assets. Predicting these effects requires a fundamental understanding of where and how particles are accelerated and how they are transported from the acceleration sites to other regions. More than one mechanism can operate to produce a given energetic particle population and the nature of the seed population from which the accelerated particles are drawn is a crucial part of the puzzle.

The four associated investigations for this RFA are:

Investigation F2.1. How are charged particles accelerated to high energies?

Relevant Missions: SEPM, Sentinels, SIRA, SPI, Telemachus, Wind, ACE, SWB, Heliostorm, L1 Observations, STEREO, AAMP, GEC

Investigation F2.2. How are energized particles transported?

Relevant Missions: Sentinels, SPI, Telemachus, SIRA, WIND, SWB, SEPM, GEC, RBSP, AAMP,

STEREO, SOHO

Investigation F2.3. How is the solar wind accelerated and how does it evolve?

Relevant Missions: Solar Probe, Doppler, Solar Orbiter, SPI, STEREO, L1 Observations, SOHO, IHSentinels, Heliostorm, Great Observatory

Investigation F2.4. How are planetary thermal plasmas accelerated and transported?

Relevant Missions: MC, DBC, CLUSTER, THEMIS, IMAGE, POLAR, TIMED, AAMP, ADAM, MARS, ITMWaves, ITMC

Research Focus Area F3: Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system

This RFA focuses on those energy and momentum transfer processes that are characterized by nonlinear interactions and by coupling between plasmas and neutral particles. Turbulence is example of a very important multi-scale, nonlinear process that transports particles and fields effectively, but is not well understood. Numerical simulations and laboratory experiments demonstrate that, in the presence of rotation or magnetic fields, turbulent motions create small-scale and large-scale dissipative structures. Another example are the many pathways by which energy is transformed and redistributed throughout the upper atmospheres of planets. The Earth's atmosphere is periodically pumped and heated over a range of spatial and temporal scales, giving rise to the excitation of a spectrum of small-scale gravity waves, tides, and longer-period oscillations. Connected with these processes is the inherent variability of the atmosphere over daily to millennial time scales. In addition, electrodynamic and mass coupling along magnetic fields are fundamental physical processes that cut across many disciplines of space science. The interface between the heliosphere and the interstellar medium is a coupling region about which we are just beginning to learn. Finally, mass loading through ionization and charge exchange is a phenomenon of broad interest from planetary and cometary atmospheric erosion to energetic particle creation and loss.

There are five investigations for this RFA:

Investigation F3.1 What governs the coupling of neutral and ionized species at various spatial and temporal scales?

Relevant Missions: ITSP, GEC, ITMWaves, ITMC, ADAM, VAP, MARS

Investigation F3.2 How do energetic particles chemically modify planetary environments?

Relevant missions: SECEP, ADAM, ITMWaves, TIMED, MARS

Investigation F3.3 How do the magnetosphere and the ionosphere-thermosphere (IT) systems interact with each other?

Relevant Missions: GEC, AAMP, ITSP, RBSP

Investigation F3.4. How do the heliosphere and the interstellar medium interact?

Relevant Missions: ISP, HIGO, IBEX, Voyagers 1&2, Pluto-Kuiper

Investigation F3.5. How do the neutral environment in planetary and cometary systems affect the global morphology through charge exchange and mass loading processes?

Relevant Missions: VAP, STEREO, SCOPE

Research Focus Area F4: Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.

The Sun's variable magnetic field is the ultimate energy source for solar particle acceleration and its structure controls the entry of galactic cosmic rays into the solar system. Closer to home, the reversals of Earth's magnetic field can lead to periods of reduced protection from the harsh radiation environment of space. The process responsible for the existence and behavior of these magnetic fields – the dynamo – involves the twisting and folding of weak fields so as to change and amplify them. Solving the problem of just how dynamos operate in such widely different environments from planets to stars will allow better predictions of the magnetic field changes at both the Earth and the Sun. This understanding is essential to describing the coupled Sun-Solar System Connection and has important implications for the exploration of our solar system. There are four investigations which address these issues.

There are four investigations associated with this RFA:

Investigation F4.1. How do subsurface flows drive the solar dynamo and produce the solar cycle? How do solar and stellar dynamos evolve on both short and long-term time scales?

Relevant Missions: SDO, SPI, Telemachus, Stellar Imager, Solar-B, SOHO

Investigation F4.2. How are open flux regions produced on the Sun, and how do variations in open flux topology and magnitude affect heliospheric structure?

Relevant Missions: Ulysses, Solar Polar Imager, Telemachus, SWB, SOHO, ACE, Sentinels, Farside, SHIELDS

Investigation F4.3. How do planetary dynamos function and why do they vary so widely across the solar system?

Relevant Missions: Cassini, JPO, Messenger, WIND, ACE, ADAM, SECEP

Investigation F4.4: Understand the ionosphere-thermosphere dynamo interaction, and its variability.

Relevant Missions: GEC, ITSP, ITMC

Objective H - Understand the Nature of Our Home in Space

Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields

We do not live in isolation; we are intimately coupled with the Sun and the space environment through our technological needs, the habitability of planets and solar system bodies we plan to explore, and ultimately the fate of Earth itself. Variability in this environment affects the daily activities that constitute the underpinning of our society, including communication, navigation, and weather monitoring and prediction.

This Objective attempts to understand our place in the Solar System by investigating the interaction of the space environment with Earth and its impact on us and on our home, either directly or by what can be learned about life on Earth by studying other environments in our solar system and beyond. Our scientific goal is to understand the physical processes connecting Earth with the space environment. Our applied goal is to protect society and its technological infrastructure from space hazards and long-term climate change. We will improve technological efficiency by exploiting our understanding of Earth and its place in space. Human life and society provide the context for our investigations.

This context is not limiting. As we extend our presence throughout the solar system, we are interested in the planetary environments awaiting us and how the study of these environments can be applied to our home on Earth. Habitability of life and humankind in particular, is a rare congruence of many factors. These factors, especially the role of the Sun as a source of energy to planets and the role of magnetic fields in shielding planetary atmospheres, are a subject of immense importance. We understand some of the features that make planets habitable, but key questions remain.

The intimate coupling of solar system processes, the interplanetary medium, and the near-Earth environment, requires comprehensive study of this coupled system through a series of investigations covering these regions. Investigations of impacts on humankind must start from the Sun, understand the cause of eruptive disturbances and solar variability over multiple time scales, follow propagation and evolution of solar wind disturbances through the interplanetary medium to Earth, and finally investigate the interaction of solar radiative emission and the solar wind with Earth's coupled magnetosphere-ionosphere-atmosphere system. Our Research Focus Areas (RFAs) have been formulated to understand the creation and evolution of solar disturbances from the Sun to the Earth (RFA H1), the response of the coupled near-Earth environment to these disturbances (RFA H2), the role of the Sun as the principal energy source in our atmosphere (including the impact of long-term solar variability on Earth's climate) (RFA H3), and how stellar activity and magnetic fields affect planetary evolution habitability (RFA H4). We seek to understand the Sun so we can predict solar variability and the evolution of solar disturbances as they propagate to the Earth. We then seek to understand the response of the near-Earth plasma regions and their impact on society as well as the atmospheric responses over short and long time scales. We put the Earth and planets elsewhere in context, through study of the solar photon and particle impact on other solar system bodies, and of the evolution of solar and stellar activity over the age of planetary systems. The RFA's of this objective focus on both internal linkages and external forcing mechanisms.

Research Focus Area H1: Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment.

The climate and space environment of Earth is primarily determined by the impact of plasma, particle and electromagnetic radiation output from the Sun. The output in turn is determined by the solar variability over various time scales, starting from the convective time-scales to the 22-year solar magnetic cycle. The variability is linked to the emergence of magnetic field from below the photosphere and its eruption as flares and coronal mass ejections into the heliosphere. X-ray flares can severely degrade radio communications through its ionospheric effects, coronal mass ejections can create large magnetic storms at Earth, and solar energetic particle events can pose serious threats to technological assets and astronauts in near-Earth orbit. Longer-term events include changes in solar irradiance that can affect Earth's climate.

There are four investigations associated with this RFA:

Investigation H1.1 - How do solar wind disturbances propagate and evolve from the Sun to Earth?

Current missions that support this investigation are SOHO, Wind, TRACE, RHESSI, ACE and Ulysses. Future enabling missions are STEREO, SOLAR-B SDO, Inner Heliospheric Sentinels, SIRA, SEPP, Doppler, SHIELDS, Solar Orbiter, Heliostorm, and Solar Weather Buoys.

Investigation H1.2 - What are the precursors to solar disturbances?

Current missions that support this investigation are SOHO, Wind, TRACE, and RHESSI. Future enabling missions are SDO, STEREO, SIRA, Solar B, SHIELDS, and SEPP.

Investigation H1.3 - Predict solar disturbances that impact Earth.

Current missions that support this investigation are SOHO, Wind, TRACE, and RHESSI. Future enabling missions are SDO, Solar-B, STEREO, Heliostorm, SHIELDS, SIRA, SEPP, and IHS.

Research Focus Area H2: Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.

The near-Earth space environment, geospace, is unique in the solar system and central to the protection of Earth and its inhabitants. This region includes the magnetosphere, ionosphere, and thermosphere (MIT) bound together as a tightly coupled system. The variability within geospace and the nearby interplanetary environment is generically termed space weather. Much of space weather is driven by the external processes discussed in the pervious section. In addition, internal drivers of the MIT region such as the upward propagation of gravity waves, wave-particle interactions, and auroral current systems are equally important and must be investigated. The consequence of internal drivers is that even in quiet solar wind conditions, there can be significant variability within the MIT region.

Geospace is the location of most of our space activities. Communication, navigation, Earth weather and remote sensing, emergency location, defense reconnaissance, and NASA missions are all affected by space weather. Space weather also causes disturbances of electric power grids and sensitive electronic systems on the ground. These include navigation systems used by commercial airliners. The technological systems sensitive to disturbances in geospace are increasing in importance and urgency to human society.

There are three investigations associated with this RFA:

Investigation H2.1 - What role does the electrodynamic coupling between the ionosphere and the magnetosphere play in determining the response of geospace to solar disturbances?

Current missions that support this investigation are Cluster, Polar, TIMED, and IMAGE. Future enabling missions include RB and IT storm probes, MMS, GEC, GEMINI, and MC.

Investigation H2.2 - How do energetic particle spectra, magnetic and electric fields, and currents evolve in response to solar disturbances?

Current missions that support this investigation are Cluster, Polar, TIMED, and IMAGE. Future enabling missions include RB and IT storm probes, MMS, GEC, GEMINI, and MC.

Investigation H2.3 - How do the coupled middle and upper atmosphere respond to external drivers and with each other?

Current missions that support this investigation are, Polar, TIMED, IMAGE, and AIM. Future enabling missions include IT Storm Probes, ITM Waves, SECEP, Tropical ITM Coupler.

Research Focus Area H3: Understand the role of the Sun as an energy source to Earth's atmosphere, and in particular the role of solar variability in driving change.

Solar energy in the form of photons and particles drives the chemical and physical structure of Earth's atmosphere. For example, ultraviolet and more energetic radiation deposited globally throughout the stratosphere, mesosphere, and thermosphere is responsible for formation of the ionosphere. Also, while particles primarily deposit their energy at high latitudes, the resulting ionization, dissociation, and excitation of atoms and molecules can have a global effect due to dynamical processes that transport energy around the globe. Ultimately these processes combine to drive the temperature and chemical composition of the entire Earth's atmosphere. A key example of how atmospheric modification by the Sun affects life is stratospheric ozone which acts as a human UV shield. The very existence of the ozone layer is a direct result of solar energy deposition. Nitric oxide created at higher altitudes by processes involving solar energy may be transported to lower altitudes where it can destroy ozone.

Because life depends on the atmosphere and its climate, study of solar energy driven atmospheric variations is critically important. Solar energy and its changes have effects throughout the atmosphere including the troposphere where humans live. Despite this, the strength and variability of atmospheric solar energy deposition remain poorly understood. In addition, coupling processes that spread effects of energy deposition in altitude and latitude are not well understood. To address these issues, spectral observations of solar energy deposition resolved in space and time as well as theory and modeling of dynamical processes that distribute effects of solar energy are required.

There are three investigations associated with this RFA:

Inves*tigation H3.1 - How do solar energetic particles influence the chemistry of the atmosphere, including ozone densities?*

Current missions supporting this RFA are IMAGE and TIMED. Future enabling missions are AIM, ITSP, GEC, L1-Monitor, SECEP, ITM Waves, and CNOFS.

Inves*tigation H3.2 - What are the dynamical, chemical, and radiative processes that convert and redistribute solar energy and couple atmospheric regions?*

Current missions supporting this RFA are IMAGE and TIMED. Future enabling missions are AIM, ITSP, GEC, L1-Monitor, SECEP, ITM Waves, and CNOFS.

Inves*tigation H3.3 - How do long term variations in solar energy output affect Earth's climate?*

Current missions supporting this RFA are IMAGE and TIMED. Future enabling missions are AIM, ITSP, GEC, L1-Monitor, SECEP, ITM Waves, and CNOFS.

Research Focus Area H4: Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.

Plasmas and their embedded magnetic fields affect the formation, evolution and destiny of planets and planetary systems. Our habitable planet is shielded by its magnetic field, protecting it from solar and cosmic particle radiation and from erosion of the atmosphere by the solar wind. Planets without a shielding magnetic field, such as Mars, are exposed to those processes and evolve differently. Planetary systems form in disks of gas and dust around young stars. Stellar ultraviolet emission, winds, and energetic particles alter this process, both in the internal structure of the disk and its interaction with its parent star. The study of similar regions in our solar system, such as dusty plasmas surrounding Saturn and Jupiter, help explain the role of plasma processes in determining the types of planets that can form, and how they later evolve.

There are four investigations that study how and when planets become habitable.

Inves*tigation H4.1 - What role do stellar plasmas and magnetic fields play in the formation of planetary systems?*

Current missions that support this investigation are TIMED. Future enabling missions are SDO, Solar Probe, RBSP, MAD, Jupiter Polar Orbiter, SI. Future contributing missions are Widefield Infrared Survey Explorer, Space Interferometry Mission, Terrestrial Planet Finder, James Webb Space Telescope.

Inves*tigation H4.2 - What is the role of planetary magnetic fields for the development and sustenance of life?*

Current missions that support this investigation are TIMED and ACE. Future enabling missions are ITSP, GEC, SDO, L1 Monitor, and MAD.

Inves*tigation H4.3 - What can the study of planetary interaction with the solar wind tell us about the evolution of planets and the implications of past and future magnetic field reversals at Earth?*

Current missions that support this investigation are ACE, TIMED. Future enabling missions are ITSP, GEC, SDO, L1 Monitor, MAD, L1 Mars.

Objective J: Safeguarding our Outward Journey

Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space

There are many space environment conditions (i.e. energetic particle and electromagnetic radiation plus plasma and neutral particle environments) that will have a significant impact on implementing the vision for exploration. By characterizing the extremes and variability of the space environment and developing the capability to nowcast and forecast the dynamic conditions in space, we provide a key support to the vision. This objective focuses on the science necessary to ensure safety and maximize productivity of both human and robotic space explorers. It includes the near-Earth and planetary environments and the robotic and technological systems that support human space flight.

Addressing these issues is necessary for optimizing spacecraft and instrument design, planning mission and operations scenarios, ensuring the safety and maximizing the success and productivity of both robotic and human exploration. Much of the variability in the space environment is driven by solar activity such as flares and coronal mass ejections (CMEs). The underlying thread that links all three of the roadmap objectives is achieving a detailed understanding of the basic physical processes required to enable prediction (Objective F), with the emphasis here on the practical needs of supporting Exploration. The distinction between Objective J and Objective H (which focuses on the science needed to understand how life and society are affected by the space environment) is the emphasis on understanding the variability of the space environment and its potential for violent change with the purpose of enabling and securing space travel.

Objective J is divided into four Priority Research Focus Areas (RFAs). RFA J1 is focused on *characterization* of the space environment to be encountered by human and robotic explorers, including the extremes as well as the variations to be expected. The second and third RFA build on the first and focus on developing the capability to *predict* space environmental conditions throughout the heliosphere. RFA J2 is focused on the capability to predict the **onset** of solar activity and solar disturbances as the source of potentially hazardous space weather events, while RFA J3 is focused on the capability to predict the nature and severity of environmental hazards associated with the **propagation** of solar disturbances through the heliosphere. RFA J4 is focused on the characterizing and understanding the impact of space weather on planetary environments for the purpose of mitigating risk in exploration activities, such as spacecraft staging in LEO, or EDL activities at Earth and Mars.

Research Focus Area J1: Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

There are fundamentally two ways in which understanding the dynamics of the space environment, the boundary conditions and sources which drive it, can assist future human and robotic exploration: 1) *characterizing* the variability and extremes, and 2) *developing the predictive capability* to nowcast and forecast transients (solar energetic particle events, CMEs, magnetic storms, substorms, etc.). Characterizing the extremes of the space environment requires understanding the variables that modulate the conditions as well as their dependence on location within the solar system and the relevant boundary conditions that may influence the conditions. In other words, it requires a knowledge both of internal mechanisms and external drivers, including drivers and sources of the variability at the Sun. As a result, developing and applying an understanding of the dynamic space environment (its boundary conditions and the interplanetary medium which modulates its extremes) is an important element of this objective.

There are three investigations associated with this RFA:

Investigation J1.1 - What is the variability and extremes (worst case) of the radiation and space environment that will be encountered by future human and robotic explorers, both in space and on the surface of target bodies?

Relevant Missions: THEMIS, RBSP, ITSP, IHSentinels, SWB, L1/HelioStorm, MSL, LRO and The Great Observatory[TGO] (esp. ACE, Wind, Polar, Cluster, TIMED)

Investigation J1.2 - How does the radiation environment vary as a function of time and position, and how should it be sampled to provide situational awareness for future human explorers?

Relevant Missions: MMS, RBSP, SWB, IHSentinels, L1/Heliostorm, Solar Probe, MARS and TGO (esp. ACE, Wind, Ulysses)

Investigation J1.3 - What is the relative contribution to the space radiation environment from Solar Energetic Particles and Galactic Cosmic Rays and how does this balance vary in time?

Relevant Missions: IHSentinels,L1/HelioStorm, SWB, Mars GOES, and TGO (esp. ACE, Wind, SOHO,ULYSSES)

Research Focus Area J2: Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

Successful space weather forecasting entails reliable characterization of impulsive solar disturbances as well as accurate knowledge of the global corona and solar wind through which they propagate. One also needs to forecast space weather events in magnetospheres and ionosphere-thermospheres of planets, which are caused by solar activity and/or are a response to changing interplanetary conditions. One aspect is the prediction of “all clear” periods, when EVAs can be safely accomplished. This requires spacecraft observations of the entire solar surface both to follow the evolution of active regions over the full solar disk and to observe complex active regions that may be magnetically connected to human or robotic explorers in transit to or on the Moon or Mars. On longer time scales, we need to develop the ability to predict when and where active regions will arise and what the heliospheric, magnetospheric and ionospheric-thermospheric consequences will be.

Three are three investigations associated with this RFA:

Investigation J2.1 - What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances, and what determines their magnitude and energetic particle output?

Relevant Missions: IHSentinels, SEPM, DOPPLER, SHIELDS, RAM and TGO (esp. SOHO)

Investigation J2.2 - What heliospheric observations, and empirical models are needed to enhance the predictive capability required by future human and robotic explorers?

Relevant Missions: DO, IHSentinels, SEPM, Solar Probe, SWB, L1/HelioStorm, MAD, LRO, RBSP, ITSP, GEMINI, MC, MMS, THEMIS, STEREO and TGO (esp. ACE, Wind, SOHO, Polar, TIMED, Cluster)

Investigation J2.3 - What geospace and planetary atmospheric observations, and empirical models are needed to provide the predictive capability required by future human and robotic explorers?

Relevant Missions: TIMED, C/NOFS, ITSP+ITIMager, THEMIS, RBSP, MMS, MC, AAMP, GEMINI, IMC, GEC, ITMWaves, L1/HelioStorms, MAD, ITMC, SECEP and TGO (esp. Polar, TIMED, Cluster)

Research Focus Area J3: Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

Energetic particles from flares, CME shocks and galactic cosmic rays are a known radiation hazard to human and robotic explorers. To maximize the safety and productivity of these explorers, we need to develop the observational and modeling tools for more accurately predicting the arrival times, durations, and severity of their impacts. To a lesser degree, shocks and plasma disturbances are important since they can damage space hardware. From an operational point of view, an improved predictive capability will reduce the *false-alarm rate* and enable longer periods of extravehicular/surface activity for human explorers. This RFA involves developing an understanding of the acceleration mechanisms and propagation of solar disturbances, and does not include understanding the triggering of solar events, which are included in RFA J.2. Both are needed for a complete understanding of these events. Objective F provides the foundation for understanding the fundamental processes related to shocks and particle acceleration.

There are three investigations associated with this RFA:

Investigation J3.1 - How are Solar Energetic Particles (SEPs) created and how do they evolve from their coronal source regions into interplanetary space?

Relevant Missions: IHSentinels, SEPM, DOPPLER, Solar Probe, STEREO and GO

Investigation J3.2 - How do solar magnetic fields and solar wind plasma connect to the inner heliosphere and what is the nature of the near-Sun solar wind through which solar disturbances propagate?

Relevant Missions: Solar Probe, IHSentinels, SEPM, DOPPLER, SO and TGO (esp. SOHO)

Investigation J3.3 - How are energetic particles modulated by large-scale structures in the heliosphere (magnetic fields throughout the solar system) and what determines the variations in the observed particle fluxes?

Relevant Missions: STEREO, IHSentinels, MMS, MagCon, SWB, L1/HelioStorm and TGO (esp. Ulysses, Wind, ACE)

Research Focus Area J4: Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

Understanding and characterizing the near planet environments is essential to maximize the safety, productivity and mitigation of hazardous conditions for human and robotic exploration activities. There are many issues related to space weather effects within planetary environments. One is reliable communications and navigation for spacecraft and surface crews. This requires improved understanding of Earth's and Martian ionospheres. A second is neutral density variability affecting aerobraking, aerocapture and EDL. Another is the trapped energetic particles and plasmas which create hazardous conditions that impact the safety and productivity of exploration activities. While the Sun and its variability are external drivers of these environments, there are also many internal processes that must be understood. Planetary space weather develops through the interaction of the solar wind with the planetary magnetic fields and plasmas, the interaction of solar photons with plasma and neutral populations, the interaction with the atmosphere below, and via internal processes such as dynamos, wave interactions, magnetic reconnection, electric fields, transport and chemistry. To understand the planetary conditions essential for exploration, scientific investigations are targeted for the "near-planet" environments. Because initial staging activities and transport of human and robotic explorers occurs in geospace, understanding this environment is particularly important. The near-Earth characterization and understanding provides a baseline for modeling the impact of space weather in other planetary environments and will guide the development of follow-on planetary investigations and missions.

There are five investigations associated with this RFA:

*Investigation J4.1 - To what extent does the hazardous near-Earth radiation environment impact human and robotic explorer's safety and productivity?*Relevant Missions: THEMIS, MMS, RBSP, MC, IMC, GEC, AAMP, ITSP, L1/HelioStorm and TGO (esp. Polar, ACE, Wind, Ulysses, Geotail)

Investigation J4.2 - What Level of Characterization and Understanding of the Dynamics of the Atmosphere is Necessary to Ensure Safe Aerobraking, Aerocapture and EDL Operations at Mars?

Relevant Missions: GEC,MAD/MARS, ITMWaves and TGO (esp. TIMED, CNOFS)

Investigation J4.3 - To what extent does ionospheric instability, seasonal and solar induced variability affect communication system requirements and operation at Earth and Mars?

Relevant Missions: CNOFS, ITSP+ITImager, L1/HelioStorms, MAD/MARS and TGO (esp. TIMED)

Investigation J4.4 - What is the effect of energetic particle radiation on the chemistry and the energy balance of the Martian atmosphere? Relevant Missions: AIM, MSL, MAD/MARS, Mars GOES, GEC, SECEP, ITMC and TGO (esp. TIMED)

Investigation J4.5 - What are the dominant mechanisms of dust charging and transport on the Moon and Mars that impact human and robotic safety and productivity?

Relevant Missions: MAD/MARS, Mars Goes, LRO, plus Moon and Mars Landers and Rovers, Laboratory SR&T program

Chapter 2. Sun-Solar System Connection: The Program

Principles and Policies

The strategy presented in this document has been derived from the NASA Objective for SSSC to address the vital, urgent, and compelling needs of the nation. The community based SSSC Roadmap committees have solicited input from the constituents of the program, both internal and external, in formulating the plan. The proposed SSSC Program implements the best science and exploration effort that can be accomplished within the budget constraints of the program. The recommended program has two options, one that fits within the expected resource cap with some specifically identified augmentations and another that is optimized to address the science goals in a more reasonable time frame with increased mission synergy. The program is highly responsive to the requirements for the Vision for Space Exploration and consistent with the recommendations of the relevant decadal surveys of the National Academies and previous Roadmaps.

Implementation Strategy

The science and exploration program described in the previous chapter occupies a valuable niche in the NASA Science Mission Directorate. SSSC research will develop knowledge that transforms our understanding of the universe and our place in it. SSSC investigations provide practical understanding and measurements of areas that affect our technological society and enable safe and productive exploration of the Moon, Mars, and beyond. And missions and technology to explore the solar system enable the science of the division.

The interplay of exploration, discovery, and understanding provide the guidance for prioritizing the program elements. Exploration of Mars and other destinations in the solar system provides the opportunity to measure conditions in different environments that help us understand our own world. New physical understanding of the Sun and its interactions with planetary magnetospheres provide information about the habitability of worlds near other stars. These all contribute to developing future operational systems that support the needs of our increasingly technological society.

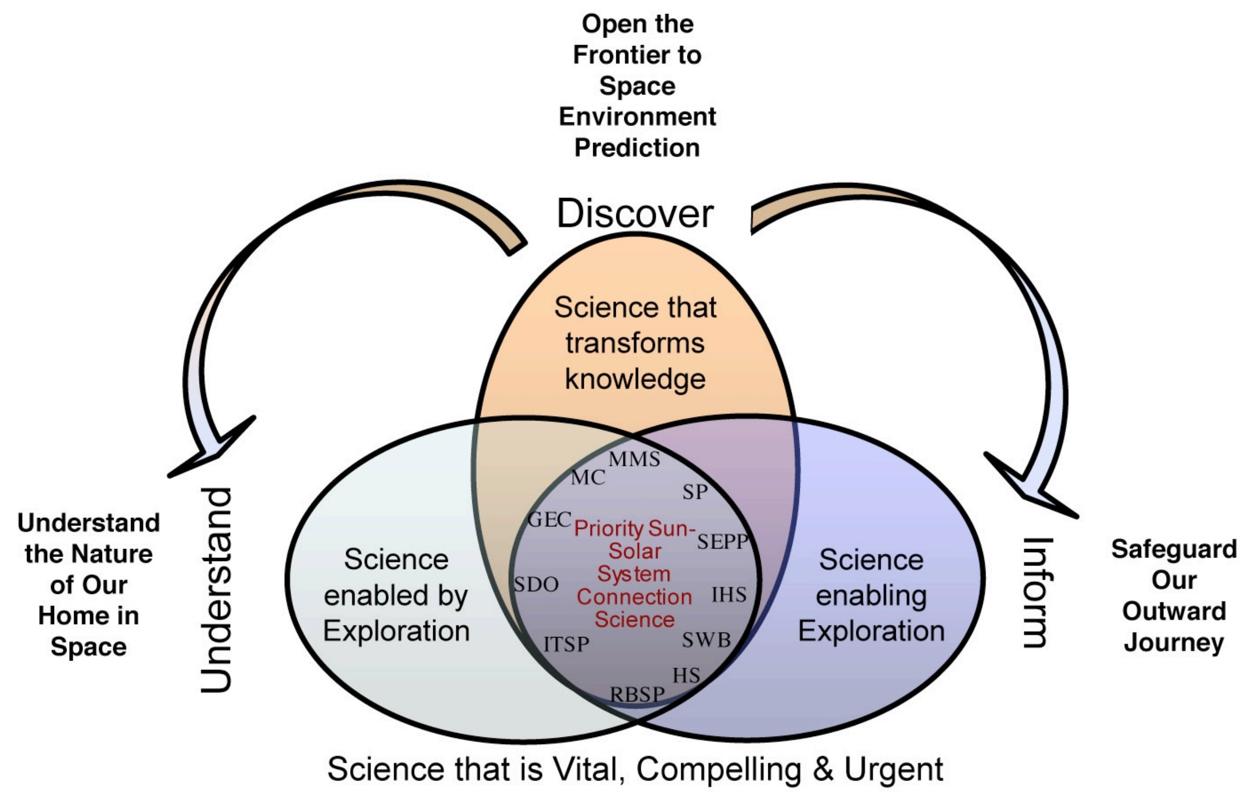


Figure Caption: The intersecting ovals illustrate the intersection of three categories of science: discovery science that is enabled by exploration, science that transforms our understanding, and science that informs to enable exploration. At the intersection is the ‘sweet spot’ where the highest priority SSSC missions lie.

The objectives, research focus areas, and investigations defined in the previous chapter describe realms of scientific inquiry that will take decades to complete. The road map to progress have been charted by identifying a series of targeted outcomes necessary to accomplish the desired objectives. The targeted outcomes in the accompanying table have been established after careful consideration of the research focus areas, consolidation of investigation requirements, anticipation of the capabilities likely to be available and required at different times, and estimation of available resources. The outcomes have been ordered in phases to develop the scientific understanding necessary to support the needs of society and the exploration program.

	Phase 1: 2005-2015	Phase 2: 2015-2025	Phase 3: 2025-beyond
Open the Frontier to Space Environment Prediction	Measure magnetic reconnection at the Sun and Earth Determine the dominant processes and sites of particle acceleration Identify key processes that couple solar and planetary atmospheres to the heliosphere and beyond	Model the magnetic processes that drive space weather Quantify particle acceleration for the key regions of exploration Understand non-linear processes and couplings to predict atmospheric and space environments	Predict solar magnetic activity and energy release Predict high energy particle flux throughout the solar system. Understand the interactions of disparate astrophysical systems
Understand the Nature of our Home in Space	Understand how solar disturbances propagate to Earth Identify how space weather effects are produced in Geospace Discover how space plasmas and planetary atmospheres interact Identify the impacts of solar variability on Earth's atmosphere	Identify precursors of important solar disturbances Quantify mechanisms and processes required for Geospace forecasting Determine how magnetic fields, solar wind and irradiance affect the habitability of solar system bodies Integrate solar variability effects into Earth climate models	Enable continuous scientific forecasting of conditions throughout the solar system Determine how stellar variability governs the formation and evolution of habitable planets Forecast climate change (joint w/ Earth Science)
Safeguard our Outward Journey	Determine extremes of the variable radiation and space environments at Earth, Moon, & Mars Nowcast solar and space weather and forecast "All-Clear" periods for space explorers near Earth	Characterize the near-Sun source region of the space environment Reliably forecast space weather for the Earth-Moon system; make first space weather nowcasts at Mars Determine Mars atmospheric variability relevant to Exploration activities	Analyze the first direct samples of the interstellar medium Provide situational awareness of the space environment throughout the inner Solar System Reliably predict atmospheric and radiation environment at Mars to ensure safe surface operations
	• ***Develop technologies, observations, and knowledge systems that support operational systems***		

Each anticipated achievement in the table has been thoroughly considered. Each targeted outcome requires advances in understanding of physical processes. Measurement capabilities must be available to develop that knowledge. Deployment of missions, development of theoretical understanding, and availability of infrastructure systems are required to provide that measurement capability. For each outcome in the table the necessary understanding, capabilities, and implementation have been traced. The scientific flow-down charts are available at the SSSC 2005 Roadmap web site (sun.stanford.edu/roadmap) and an example chart will be found in an Appendix. The requirements in the flow-down charts often overlap; so the results have been consolidated. Finally a balanced set of missions was chosen to address the most critical science and exploration topics in each phase. The missions have been assigned to program elements and resources identified to implement them. Information gained in earlier missions must be used to decide the selection and ordering of later flight opportunities.

Strategic Considerations

The SSSC objectives identify robust goals that are vital, urgent and compelling. Obviously no unique strategy exists now that addresses the scientific and programmatic needs, fits within the anticipated budget profile, and anticipates all developments over the next 30 years. The developing requirements of the Vision for Space Exploration, the increasing need for understanding external influences on our home planet, and the transformational science required to develop predictive capabilities for the space environment require a broad approach to address interlocking needs and demand considerable flexibility in the implementation.

The program combines relies on several elements: strategically planned missions in the Solar Terrestrial Probes (STP) and Living With a Star (LWS) lines to address widely recognized critical problems; competitively selected Explorers to optimize responsiveness to strategic needs; continued operation of existing space assets as part of the SSSC Great Observatory; low cost access to space for unique science, community health, and instrument development needs; technological development; supportive, targeted research and analysis programs; and a strong effort in education and public outreach. Partnerships with other areas of NASA and other agencies, both U.S. and international, are essential. Each of these program elements is described in more detail below.

Flagships missions address very difficult problems in scientific areas that confront major road blocks to future progress. Flagship missions have great promise for scientific advance, but may cost four or more times as much as an Explorer. Missions of this scope cannot be accomplished within the current resource limits of the program without fatally compromising the rest of the program. Flagship missions are identified separately as top priorities for additional funding.

Science by Phase

The Roadmap committees considered three decade-long phases in formulating a plan. The achievements of each phase inform decisions made about implementation in subsequent phases. The phases roughly correspond to development cycles in the Exploration Initiative. Phase 1 ends in 2015 and includes missions launched by that date; Phase 2 ends in 2025 and Phase 3 in 2035. Achievements identified in Table 2.1 correspond fairly well to these phases.

Our Phase 1 program presumes the continued operation of missions in the Great Observatory. The baseline Phase 1 program includes only new missions that are already in development or whose announcement is expected in the very near future. STEREO, Solar-B, and MMS in the STP program, SDO and RBSP in the LWS program, and the selected Explorers: AIM, THEMIS, and IBEX. Additional Explorers will close gaps in the program. The solar sail demonstration mission and the ADAM Mars Scout mission also occur in Phase 1. Solar Probe should be launched in this phase, though data from the first plunge through the corona will not be available until Phase 2. This set of investigations provides a very powerful tool for accomplishing the achievements listed in Table 2.1. An optimized program would accelerate these and some of the missions identified for early in Phase 2. The multiple synergies and comprehensive views afforded by the Great Observatory as it evolves and develops during this interval are a testimonial to the investments and achievements of the past decade in Sun Earth Connection science at NASA. The first crucial set of questions required to open the frontier to space weather predictions, understand the nature of our home planet, and safeguard our outward journey have been largely anticipated in the existing program plan. SSSC is clearly poised to make significant progress in the next 10 years on these important questions.

Phase 2 includes missions scheduled for launch between 2015 and 2025. GEC and MagCon address the next set of fundamental problems in the STP program. They too depend on continued context observations from the evolving SSSC Great Observatory. The LWS Program plans to launch two missions relatively early - IH Sentinels and ITSP. These rely on measurements from SDO and RBSP to realize their full potential. Later two smaller missions, SEPM and Heliostorm/L1 will address questions about hazardous space weather directed toward the Earth-Moon system. Toward the end of Phase 2 a choice between terrestrial and heliospheric mission priority will need to be made (as described in the previous section). The pace of launches is somewhat slower and the comprehensive coverage of the connected system available early in phase 2 will likely diminish toward the end of the decade if missions do not continue to function past their expected life times.

Missions beyond 2025 in Phase 3 have been identified in the previous section because we already know many of the scientific questions that will probably remain unanswered. The priorities will be adjusted depending on what is learned and on progress in the Exploration Initiative, but it is clear that constellations of spacecraft will be required in new regions to resolve spatial and temporal changes in the magnetosphere and in interplanetary space where remote global sensing is not possible. Technological development and selection of Explorers may allow some objectives to be achieved earlier.

Several missions of great interest cannot be implemented even during this time period. A few are limited by technology, but more are limited by resources, particularly those having to do with comparative magnetospheres and planetology.

The SSSC Roadmap promises significant accomplishment. The science requirements derived from the national objectives for NASA can be accomplished with the resources available. With additional resources an optimized plan has been crafted that will be significantly more productive. The near term course is clear and decision points for the future have been identified.

Program Elements

The implementation of the SSSC program is currently funded though several sources. Missions come from the Solar-Terrestrial Probe Program, the Living With a Star Program, and the Explorer Program. Rockets and balloons provide low-cost rapid access to space. The fleet of existing missions makes up a Great Observatory that evolves as new missions are launched and new combinations of observations are made. Focused research and analysis programs lead to new understanding and contribute to new investigation requirements. The support of data, computing, and community infrastructure ensures that progress will continue to be made. Each of these program elements is described below. We first describe briefly the mission strategy for each line. We then discuss each phase of the program and how the proposed mission set meets the requirements in the tables described above.

Solar Terrestrial Probes

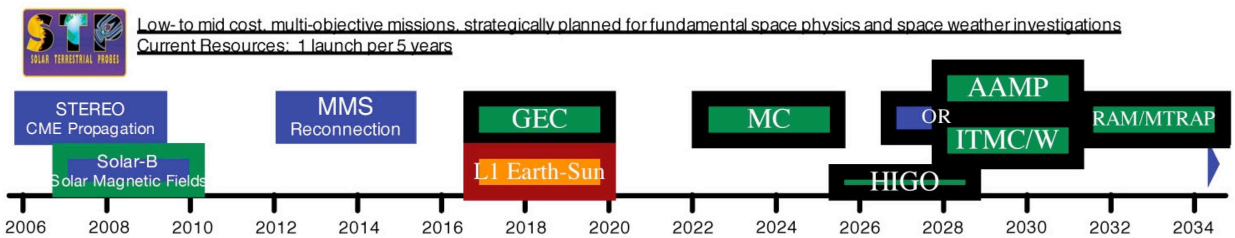
The Solar Terrestrial Probe investigations focus on specific scientific areas required to advance our fundamental understanding of the Sun – Solar System Connection. Subsequent missions target the ‘weakest links’ in the chain of understanding. STP missions are strategically defined and investigations are competitively selected.

STP is one of two strategic lines for the Sun-Solar System Connection. Strategic mission lines afford the space physics community the opportunity to plan specific large missions to address one or more of the research focus areas and thus make significant progress in elucidating the fundamental processes of the coupled Sun-Earth system. In addition, such capable spacecraft missions often result in unexpected new discoveries.

The future and existing mission priority has been re-evaluated in light of the new priorities at NASA that are reflected in the objectives derived in this Roadmap. STP missions currently in development are STEREO, Solar-B, and MMS. The first STP mission, TIMED, was launched in 2001 to study the influences of the Sun and humans on the mesophere and lower thermosphere/ionosphere. These missions strongly support the current objectives explained in this Roadmap and musts be completed as scheduled. Solar-B is a joint mission with the Japanese space agency, JAXA, and it will provide the high-resolution solar observations needed to understand magnetic energy storage and release in the solar atmosphere. STEREO will observe coronal mass ejections and other structures moving in the interplanetary medium from two spacecraft in solar orbit to understand how CME’s reach Earth. The set of four MMS spacecraft will probe the most critical regions of geospace to measure magnetic reconnection.

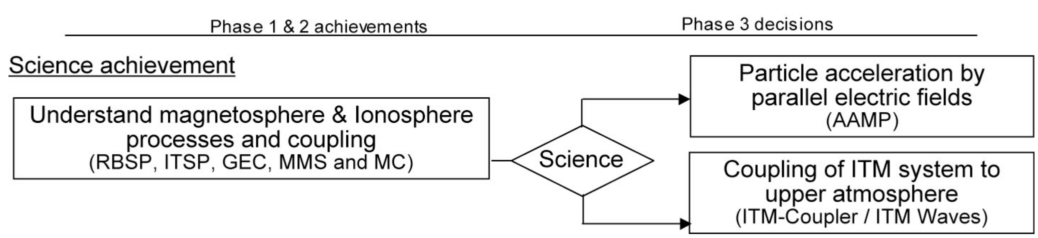
In order to support the fundamental science necessary to open the frontier for prediction of space weather effects, this Roadmap identifies GEC and MagCon as the next two STP missions. GEC will measure the poorly observed region just below stable satellite orbits where the interactions of the charged and neutral components of the atmosphere become more important – the linkage between the ionosphere and magnetosphere. MagCon, now slated for launch in 2022, provides comprehensive measurements of processes in the magnetosphere with a fleet of spacecraft. These and the other missions we identify are described in more detail in the next Section.

Coupled with the rest of the program, these missions promise the best assault on the important problems facing SSSC. The five-year spacing between launches in the current budget is not ideal, not only because progress is slow, but because synergy between missions is curtailed. We have identified participation in the L1 Earth-Sun mission that is being proposed in the Earth Science roadmap as one exciting candidate for augmentation of the STP line. Measurements of the external radiation and particle inputs to the Earth environment are essential for understanding the radiation budget. The scope of the SSSC portion of this mission will depend on the timing and capabilities of the Earth science mission.

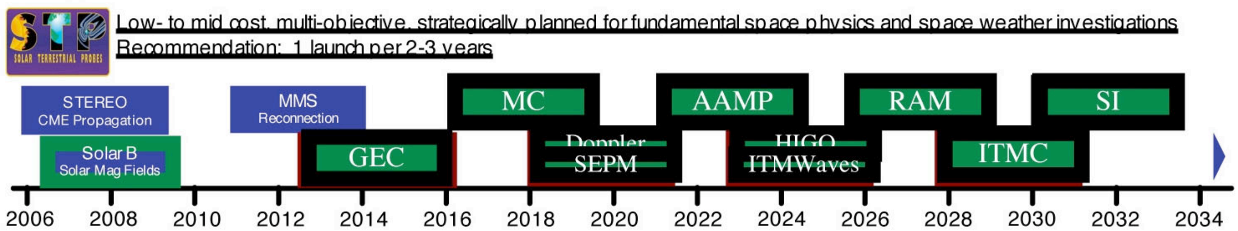


The figure shows the missions identified for flight through 2035 in our current budget projection.

If additional funds are be made available to restore the planned 2.5 year cadence of STP missions the MMS, GEC, and MagCon missions should be flown more quickly. They should be followed by Doppler & SEPM, two smaller missions that could be combined to provide spectroscopic observations of the solar corona (DOPPLER) and remote sensing of the sources of solar energetic particles (SEPM). These two missions particularly benefit from overlap with the inner heliospheric and solar missions planned in the LWS line. Next, AAMP focuses on particle acceleration too, but in the auroral region around Earth. Two more small missions, HIGO and ITM Waves, complete phase 2 of our plan in this optimized scenario. A revamped HIGO complements the IBEX Explorer recently selected to explore the outer boundary of the heliosphere; HIGO will measure the components of the interstellar medium that survive into the sub-Jovian solar system. ITM Waves concentrates the wave processes fundamental to the coupling between distinct altitude regions and on the overall dynamics of the Earth’s atmosphere.



Phase 3 STP missions will measure reconnection near the Sun and observe lower latitude disturbances in the ionosphere-thermosphere-mesosphere; a stellar imager will resolve activity on other stars to enable us to complete our objectives. Even later, more ambitious missions to explore the interactions of external drivers with other worlds in the solar system, specifically Titan, Venus, and Io, could be accomplished in partnership with others to address questions of habitability and atmospheric evolution. Larger telescopes to remotely probe the solar transition region would complete our understanding of how energy propagates from the Sun outward and remote sensing of other planetary environments would close the path at the receiving end.



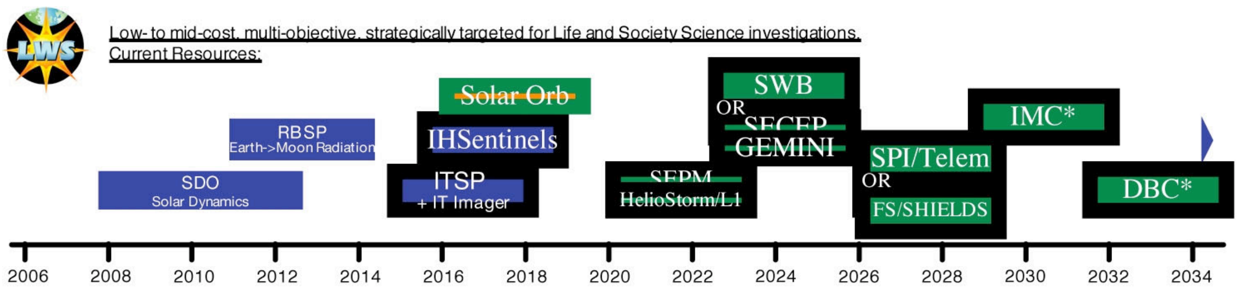
The figure shows the mission identified for flight through 2035 in our optimized scenario. The synergy of mission is apparent.

Living with a Star

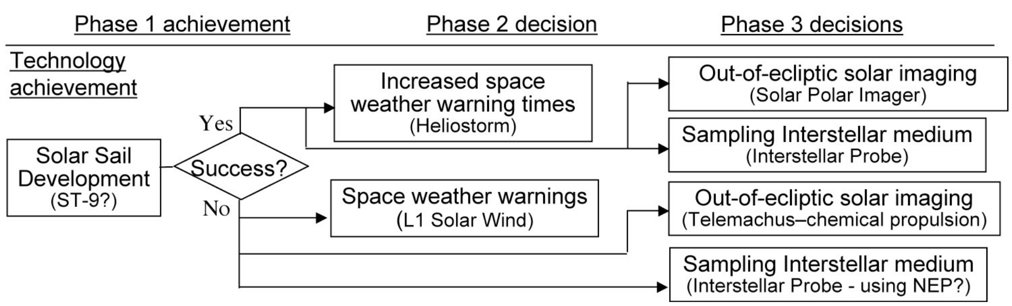
The Living With a Star program emphasizes the science necessary to understand those aspects of the space environment that affect life and society. The ultimate goal is to provide a predictive capability for the space weather that affects us. LWS missions have been formulated to answer specific science questions needed to understand the linkages among the interconnected systems that affect us. LWS investigations build on the fundamental knowledge gained by the STP missions and very directly address the needs of the Vision for Exploration and Objective H and J of this Roadmap. Significant planning has already informed the crafting of a coordinated LWS program that includes strategic missions, targeted research and technology development, a series of space environment test bed flight opportunities, and partnerships with other agencies. Partnerships are crucial to LWS because the vast number of complex physical connections between and within the Sun-Earth system cannot be addressed by a few missions.

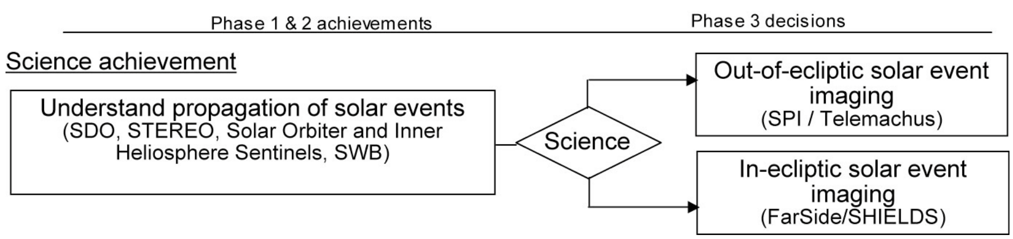
Two missions are currently in development or about to be announced: the Solar Dynamics Observatory (SDO) and the Radiation Belt Storm Probes (RBSP). The first LWS mission, SDO, is expected to launch in 2008 to understand the mechanisms of solar variability by measuring the solar interior, atmosphere, and EUV spectral irradiance. Two pairs of geospace storm probes complement SDO to measure the terrestrial environment at the same time. The first, RBSP, is planned for a 2011 launch; it will quantify the source, loss, and transport processes that generate Earth's radiation belts and cause them to decay. The second, the Ionosphere-Thermosphere Storm Probes (ITSP) also includes a separate imaging instrument.

Our Roadmap concurs with earlier recommendations that the next two LWS missions should complete the geospace storm probes by launching ITSP and explore radial evolution of structures with the Inner Heliosphere Sentinels (IHS) mission. The priority of the ITSP mission is driven by the very practical need to aid communications and navigation; ITSP will survey the global distribution of ionospheric and thermospheric densities, ionospheric irregularities, and geomagnetic disturbances as a function of varying solar and geospace conditions. The Exploration Initiative raises the priority of the IHS mission because hazardous space weather near Earth cannot be understood without it. In our realistic scenario for LWS these two missions are launched within a year of each other in 2015 and 2016. Our optimized scenario moves these missions up to increase the synergy with RBSP and SDO and to provide earlier information for the design of systems for the return to the Moon later in the decade. We also identify an important partnership opportunity with ESA's Solar Orbiter mission that complements the IHS in situ measurements and will provide solar observations from a different vantage point.



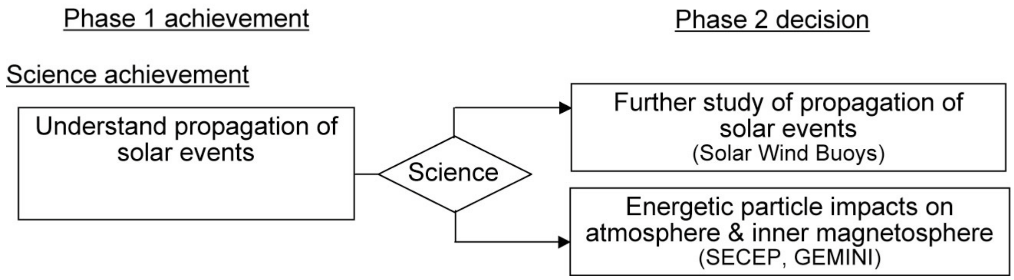
The next LWS missions in Phase 2 address understanding solar energetic particle (SEP) production near the Sun (with the SEPMission) and better measurement of the inputs to geospace with Heliostorm or an L1 Mission. These two missions can be smaller in cost than typical strategic missions. The choice between Heliostorm and an L1 mission is complex. Heliostorm would use solar sails to hover another hour or two upstream of the L1 point in the solar wind; this mission depends on a timely demonstration flight of solar sail technology. Measurement of incoming solar wind parameters is crucial to many other investigations, so depending on Heliostorm, the status of the Earth Science L1-Earth-Sun mission, lifetime of existing assets, and partnerships with other agencies, we have reserved some small amount of resources for L1 observations.





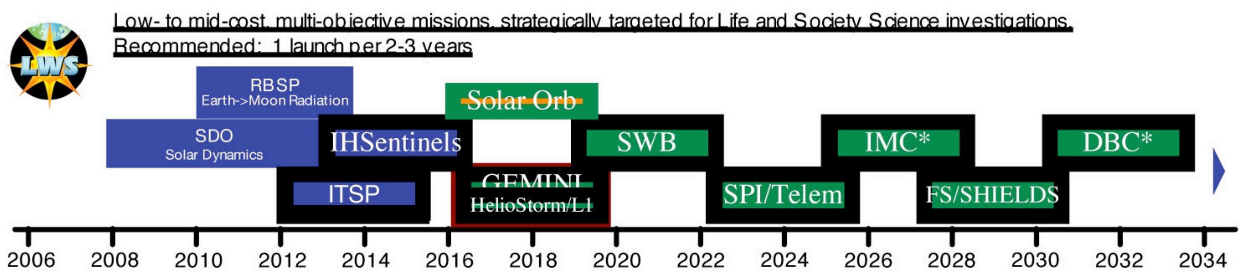
Subsequent Phase 2 mission selection in the LWS program depends on future developments in the program. Priorities will shift based on progress of the Exploration Initiative and what we learn from spacecraft launched in the next ten years. Our baseline program shows a choice preceding the 2022 launch of either Solar Weather Buoys (SWB) or a pair of smaller missions, SECEP and GEMINI. The SWB mission provides for about a dozen in situ observing platforms circling the Sun at 1 AU to fully understand how the solar wind and hazardous disturbances propagate outward from the Sun. SWB could become part of the early warning system needed to support safe and productive journeys to Mars and beyond. SECEP (Sun Earth Coupling by Energetic Particles) will explore the destruction of ozone by solar energetic particles; SECEP will measure the precipitating energetic particle influx as well as the descending odd nitrogen and odd hydrogen compounds and ozone densities. The Geospace

Magnetosphere-Ionosphere Neutral Imagers (GEMINI) will provide the first 3-D observations of the global geospace dynamics in response to external solar drivers and internal coupling. The decision will be based on what is learned from STEREO, SDO, and the IHS missions on the one hand and MMS, RBSP, ITSP, and GEC on the other.



Later Phase 3 choices in the LWS program would select among high-latitude solar observations necessary to understand the solar cycle and interior, two or three solar imagers stationed far from Earth to provide global coverage, a constellation of spacecraft to understand the inner magnetosphere, and exploration of the day-side boundary layer where energy from the solar wind crosses the magnetopause. The prioritization of these missions depends on results from earlier investigations.

In our optimized scenario the ordering changes slightly as shown in the accompanying chart.



The Explorer Program

The Explorer program is an indispensable element of the strategic Roadmap plan. Explorer missions fill important gaps in the proscribed program. The investigations target very focused science topics that augment, replace, or change strategic line missions. Highly competitive selection assures that the best strategic science of the day will be accomplished.

Missions currently in development, AIM, THEMIS, and IBEX, address important targeted outcomes. AIM (Aeronomy of Ice in the Mesosphere) will explain polar mesospheric clouds formation and variability as well their relationship to global change in the upper atmosphere and the response of the mesosphere to solar energy deposition. THEMIS (Time History of Events and Macroscale Interactions during Substorms) addresses the spatial and temporal development of magnetospheric substorms – one of the fundamental modes of the magnetosphere. IBEX, the Interstellar Boundary Explorer, will image the entire 3D configuration of the boundary region of our heliosphere, the vast (~100AU thick) region where the solar wind decelerates because of the pressure of the local interstellar plasma.

Because future selections are determined competitively in response to evolving strategic conditions, identification of specific future accomplishments at this time is impossible; however, numerous candidate missions have been identified (see the SSSC Roadmap web site for examples). The Explorer program has long been critical to maintaining the strength of the Sun-Earth Connection (now Sun-Solar System

Connection) science program. It affords a regularly recurring opportunity to fly exciting new missions, selected by peer-review for the best science with a relatively short response time, utilizing state-of-the-art instrument development. In addition, the program provides the opportunity for instrument teams to participate in missions-of-opportunity provided by other agencies (DOD, etc) or international programs. These missions-of-opportunity allow the space physics community to obtain the data necessary for specific strategic goals at a fraction of the cost of a dedicated mission. SEC Explorers are responsible for major scientific achievements that have profoundly transformed our understanding of the Sun-Earth system. Some highlights include: visualization of the global dynamics of the geospace system by IMAGE, the first gamma ray imaging by RHESSI, discovery of coronal magnetic complexity by TRACE, discovery of trapped anomalous cosmic rays in Earth's magnetosphere by SAMPEX, and discovery of small-scale size parallel electric fields in the auroral acceleration region by FAST.

Explorers demonstrate the ability of the science community to respond rapidly to decision points, an important element in the strategy put forth in the Vision for Space Exploration initiative. Decision points can allow us to take advantage of a new scientific discovery that suggests the need for a new mission, new instrumentation development that provides the opportunity to address questions previously not accessible, or new technologies or analysis techniques that enable a less costly mission. Enabling rapid response of the SSSC community to such promising scientific opportunities ensures that science goals are met in the most cost and time effective manner. Results from such missions in turn may lead to development of new strategic missions or modifications of existing ones.

The Explorer program also plays a key role in developing and maintaining the scientific and engineering community needed to meet the objectives the Roadmap, NASA, and the nation. Explorers provide hands-on training of instrumentalists, both scientists and engineers, thus enabling SSSC strategic missions, and directly contributing to the NASA Mission element: "to inspire the next generation of explorers". Managing cost-constrained missions such as Explorers requires specialized expertise.

Flagship and Partnership Missions.

Urgent need for progress across a range of topic areas means that all of the SSSC resources cannot be applied to a single problem for an extended interval. Yet some major roadblocks to progress simply cannot be overcome with missions supportable in the strategic lines available to SSSC. Solar Probe in the immediate term, and Interstellar Probe and Stellar Imager in the more distant future are flagship missions that address such problems.

Solar Probe will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity. Solar Probe is the first flight into the Sun's corona, only 3 solar radii above the solar surface. Accurate predictions of events that disturb the Earth's human systems and affect deep space explorers require this understanding. Solar Probe can only be achieved with specific budget augmentation towing to the cost of ensuring its survival in an extreme environment. That said, the science and technology definition team currently investigating Solar Probe concludes that the mission is ready for a new start now. The decadal surveys and this roadmap identify Solar Probe as the highest priority flagship mission requiring an augmentation in funding.

Interstellar Probe will be the first mission to leave our heliosphere and directly sample and analyze the interstellar medium. It requires an advanced in-space propulsion system, such as a solar sail or nuclear electric propulsion, to reach the upstream interstellar medium at a distance of 200 AU within 15-20 years. The mission will be the first specifically designed to directly measure the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields. On its way, it will provide only the second opportunity after Voyager to directly observe the region of interaction between the solar wind and the interstellar medium, from the termination shock to the heliopause and beyond.

Stellar Imager (SI) is a challenging mission that will obtain the first direct resolved (1000 pixel) images of surface magnetic structures in stars like the Sun. The SI will develop and test a predictive dynamo model for the Sun and Sun-like stars using asteroseismology and by observing the patterns in surface magnetic fields throughout activity cycles on a large sample of Sun-like stars.

Partnerships provide another method to increase scientific return. Several missions have been identified in our plan that rely on partnerships with other pasts of NASA, as well as other U.S. government and international agencies. Within NASA the solar sails demonstration project will lay the ground work for Heliostorm, Solar Polar Imager, and Insterstellar Probe. The Jupiter Polar Orbiter planned by the solar system exploration division has direct relevance to understanding planetary magnetospheres. Pluto-Kuiper should provide another opportunity to explore the outer heliosphere. Multiple opportunities for partnership have been identified as part of the International Living With a Star (ILWS) program. Partnership with ESA on Solar Orbiter should be explored in the very near term as a way to optimize and enhance the IHS, SHIELDS, and SEPM investigations.

Enabling information about the aeronomy and dynamics of the Mars atmosphere is required for aerocapture, entry, descent, and landing. The Mars Scout program provides an opportunity for a collaborative mission such as ADAM. Future missions to refine our knowledge of the interaction of the Martian environment with the Sun will also be collaborative. The SECEP mission, designed to understand ozone production, is a prime candidate for collaboration with our Earth Science colleagues. The L1-Earth-Sun mission to understand the Earth's radiation budget is another potential partnership with Earth Science.

The Sun-Solar System Connection Great Observatory – Evolving to Meet the Needs of the Vision for Exploration

The strategic objective addressed in this roadmap is intrinsically one of *connections*, of influences extending over vast distances to produce dramatic effects throughout the solar system. Because these connections are mediated locally by largely invisible agents -- plasmas and magnetic fields -- the science of Sun-Solar System Connections must be based on multi-point *in situ* measurements from platforms distributed throughout the solar system, supplemented with remote-sensing measurements wherever possible.

In recent years the power of simultaneous observations at multiple vantage points has been clearly demonstrated by what has come to be known as the Sun-Solar System Connection "Great Observatory." Our Great Observatory is a fleet of solar, heliospheric, geospace, and planetary spacecraft working together to help understand solar activity and its interaction with geospace and other planetary systems throughout the solar system. Like NOAA's system for observing and predicting terrestrial weather, this observatory utilizes remote sensing, in situ measurements, data analysis and models to provide physical understanding and predictive capability for space weather. The diverse measurements across distributed spatial scales are linked by a variety of models that serve to fill in the gaps in the observations and help predict tomorrow's space weather. The measurement capabilities include imaging the Sun; sensing *in situ* and remotely the disturbances in interplanetary space; and measuring particles, fields, and radiation in geospace, remotely and *in situ*. Continuing and evolving this distributed observatory to meet the needs of the Vision for Space Exploration is one of the community's highest priorities.

The very large "Halloween Solar Superstorms" described in in the next section are show an example of the unique and powerful capability of the Great Observatory to view a system of systems. The effects of the solar storms from the Sun to the Earth and beyond were observed simultaneously in key regions and from specific vantages. It would not have been possible to link the consequences of these superstorms at Earth and Mars to the solar drivers without this collection of satellites and the human and computational resources to interpret the data. The power of the Great Observatory comes from the combination of multiple operational assets, focused and large-scale models, and associated data analysis. Many of the spacecraft are SSSC missions, but additional "observation posts" are provided by spacecraft such as Mars Global Surveyor (MGS), Cassini and the Hubble Space Telescope. For example, from MGS, we learned that the fluxes of solar energetic particle radiation caused by the superstorms were quite different at Mars than at Earth. Our Great Observatory will need to evolve and expand to fully understand why these responses were different in order to meet the needs of the Vision for Space Exploration.

The Great Observatory is vital to explain fundamental physical processes at work throughout the complex, coupled system that is the Sun-Solar System. For example, magnetic reconnection between the interplanetary and Earth magnetic fields is the critical physical process determining the size of a geomagnetic storm. We have greatly increased our understanding of the role of this process by relating upstream solar wind measurements to both data near the small dayside reconnection site and to satellite-based images of the corresponding ionospheric airglow emissions. Similarly, using assets spread throughout the solar system, we have significantly improved our understanding of how solar activity modulates galactic cosmic ray radiation. These discoveries about the foundational physics of our solar system were made possible by the combined resources of our Great Observatory: the coupled observations, the detailed data analysis, the extensive modeling efforts, and the knowledge of the underpinning theory. The resultant increase in knowledge improves our capability to predict the space environment that human and robotic explorers will experience and provides the foundation for future operational systems.

The Great Observatory will continue to evolve as new spacecraft join and old ones retire or change their operating modes. Both missions in their prime phase and missions in extended phases (supported by MO&DA) provide the variety of observation posts needed to study the Sun-Solar System Connections, as demonstrated by the Halloween Storms. A great strength of the Great Observatory fleet is that it is regularly evaluated and reviewed by the community to maximize the return on the agency investments. The Senior Review process determines which spacecraft are most necessary to meet the needs of the Sun-Solar System Connection program as defined by the community-developed Roadmap document. The criteria for retention include relevance to the goals of the SSSC; impact of scientific results as evidenced by citations, press releases, etc.; spacecraft and instrument health; productivity and vitality of the science team (e.g., publishable research, training younger scientists, education and public outreach); promise of future impact and productivity (due to uniqueness of orbit and location, solar cycle phase, etc.); and accessibility and usability of the data.

New missions are selected for inclusion in the Great Observatory on the basis of their demonstrated ability to satisfy the same criteria discussed above for successful operating missions. The most important of these, from the perspective of strategic planning, is relevance. To meet the new needs of the Vision for Space Exploration, new missions will be needed in order to characterize, understand and predict the dynamic environmental conditions in space to maximize the safety and productivity of both human and robotic space explorers. At the same time, some existing missions are demonstrably vital and irreplaceable and will need to be maintained in order to meet the agency objectives.

Example of the Great Observatory: The Halloween Solar Storms

The violent solar eruptions of late October and early November 2003 are the best observed outbreak of intense solar activity to date. These events, referred to as Halloween Storms, are extreme events in terms of both their source properties at the Sun and their heliospheric consequences. The plasma, particle and electromagnetic consequences of these events were felt throughout the heliosphere thanks to the distributed Great Observatory.

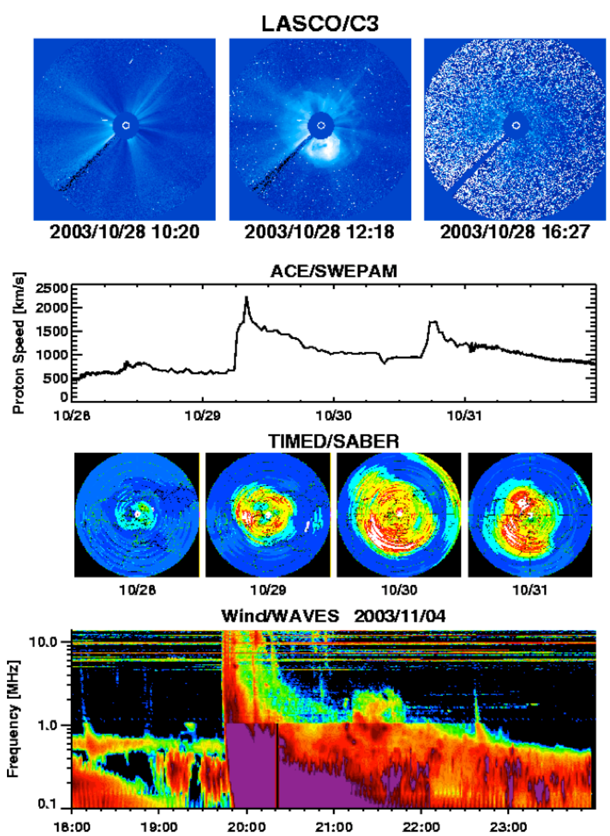
Disturbances associated with two of the eruptions arrived at Earth in less than a day, providing benchmark data for space weather purposes. Historically, there were only 13 such events including the

Carrington event of 1859 September 1. Several aspects of the Halloween Storms including active region size and potential energy, flare occurrence rate and peak intensity, CME speed and energy, shock occurrence rate, SEP occurrence rate and peak intensity, and the geomagnetic storm intensity displayed extreme behavior.

About 59% of the reporting spacecraft and about 18% of the onboard instrument groups were affected by these storms: electronic upsets, housekeeping and science noise, proton degradation to solar arrays, changes to orbit dynamics, high levels of accumulated radiation, and proton heating were observed. Most earth-orbiting spacecraft were put into safe mode to protect from the particle radiation. Major impact also occurred on the society: about 50,000 people in southern Sweden (Malmoe) experienced a blackout, where the oil in a transformer heated up by 10 degrees; surge currents were observed in Swedish pipelines; several occurrences of degradation and outage of GPS systems; several teams on Mount Everest felt interference in high-frequency radio communications.

The solar energetic particle event on October 28, 2003 and resulted in a significant ozone depletion between 50 and 80 km from the ground. A ten-fold enhancement in the ionospheric total electron content over the US mainland occurred during October 30-31. Extraordinary density enhancements in both the magnetosphere and ionosphere coinciding with intervals of southward IMF and high-speed solar wind were observed.

The storms arrived at Mars and the MARIE instrument on board the Mars Odyssey succumbed to the onslaught of radiation. The storms continued to the orbits of Jupiter and Saturn as detected by Ulysses and Cassini, respectively. Wind, Ulysses and Cassini radio instruments also observed a radio burst resulting from colliding CMEs on November 4, 2003 from widely different vantage points. Finally, the disturbances reached Voyager 2 after about 180 days, piled up together as a single merged interaction region (MIR), which led a large depression in cosmic ray intensity, lasting more than 70 days. Although it is not unusual that such solar eruptions occur during the declining phase of a solar cycle, these events bench mark the level of understanding we have on the behavior of the sun over different time scales. The fleet of spacecraft in the Great Observatory helped us not to be taken by surprise by the Halloween Storms.



Caption: *The solar corona from SOHO before, during and after the fast halo coronal mass ejection (CME) on October 28, 2003 (top row). The image taken after the CME is seriously degraded by the energetic particles from the CME. This CME and the next one on October 29 resulted in record solar wind speeds as measured by the Advanced Composition Explorer (second row). Outgoing energy flux radiated by the atmospheric nitric oxide at 5.3 micron as measured by TIMED increased drastically during the October 2003 storms (third row). The fastest CME of this period occurred on November 4 collided with a preceding CME to produce an intense radio signature detected by Wind spacecraft (bottom). This signature was also detected by Ulysses and Cassini spacecraft from distant locations in the heliosphere.*

Low Cost Access to Space

The Low Cost Access to Space (LCAS) program, with key elements of the sounding rocket and balloon (suborbital) programs, is an essential component of NASA's space physics research program, providing cutting-edge new science discoveries utilizing state-of-the art instruments in a rapid turn-around responsive environment. These investigations are science driven, but also play two other important roles that are not available in any other flight programs-training of experimental space physicists and engineers and the development of new instruments and instrumental approaches which are verified by actual spaceflight.

A recent example of this three-pronged role from the suborbital program is the new understanding of auroral physics obtained in a series of rocket flights that both developed the state-of-the-art instrumentation and the pathfinding science discoveries leading up to one of the first NASA small explorers, FAST. Figure 1 (to be provided in final roadmap) shows how new, higher altitude rockets demonstrated the importance of microphysics and the need to make extremely high time resolution measurements to elucidate the acceleration processes. The 'top hat' plasma detectors, developed by C. W, Carlson for these rockets, are now common on space plasma missions, providing 3D, high time resolution electron and ion measurements. The rocket program provided Dr. Carlson (who became the FAST PI after a long association with the sounding rocket program) with the opportunity to develop project management skills and also provided the hand-on training of graduate students who became the instrument leads on the FAST satellite.

The other key component of LCAS are solar physics balloon missions which have an outstanding record of scientific discoveries. For example, the LASCO coronagraph on board the SOHO spacecraft enabled systematic studies and arrival time predictions of coronal mass ejections aimed at Earth. The solar telescopes on the RHESSI Explorer mission used hard X-ray imaging spectroscopy, high-resolution nuclear gamma-ray line spectroscopy, and gamma-ray line flare imaging to reveal the energy release process in solar flares in greater detail than ever before. These achievements can trace their heritage to balloon-borne instruments flown in the continental U.S. and in Antarctica.

An essential ingredient of the Vision for Exploration is a source of well-trained engineers and scientists who understand the demands of building and delivering spaceflight systems and hardware. The LCAS program provides an important, hands-on training ground for these human resources -- graduate students participate in the entire life cycle of a scientific space mission, from design and construction to flight, and data analysis. No other flight programs have time scales that fit that of a Ph. D. thesis. The rocket program alone has resulted in more than 350 Ph.D.s! In addition, a rocket or balloon project offers the chance for younger scientists to gain the project management skills necessary for larger missions such as Explorers or larger missions.

The combination of science, advanced instrument development, and training makes LCAS a critical path item for achieving NASA's national space science goals.

Scientific Research and Analysis

Achieving NASA's objectives requires a strong scientific and technical community to envision, develop and deploy space missions, and to apply results from these missions for the benefit of society. Such a community currently exists within the United States. It is a world leader in space physics research and exhibits a diverse spectrum of sizes and specialties, based at universities, government facilities, and industrial labs.

The continued health of our research community, and thereby the support for NASA objectives, is dependent on many factors. These factors include a robust infrastructure of funding opportunities and resources to enable and maintain research initiatives; low-cost access to space for science, prototype development, and training; and a strong education and public outreach program to inspire and recruit new scientists and engineers.

The term infrastructure often refers to tangible assets, such as launch facilities or communications enabled by the Deep Space Network (DSN). These assets are a critical element of mission conception and execution. For example, long before major strategic missions are selected an extensive development program begins with first generation 'brass board' instrument concepts; this is followed by near-Earth testing exploiting Low Cost Access to Space (LCAS) opportunities. More mature concepts can be tested in Explorer-class missions. The IMAGE and STEREO mission concepts provide two excellent, current examples of this process.

However, in addition to investing in hard assets and flight missions, NASA must invest heavily in intellectual infrastructures through its programs of research grants: SSSC Supporting Research and Technology (SR&T), LWS Targeted Research and Technology (TR&T), SSSC Theory Program, Applied Information Systems Research (AISR), Guest Investigator (GI), etc.

NASA must also invest in analysis infrastructures that support computing and data analysis efforts. This is a critical element in the symbiotic advance of scientific understanding through mission design: scientists use data from existing missions to improve theories and models, which then suggest measurements for the next mission. Large-scale numerical calculations, such as the temporal evolution of fundamental equations in three dimensions, require massive supercomputers. Without a cutting edge computing infrastructure such computations are not possible. A strong computing structure is also needed to support data analysis, especially for increasingly large and complex data structures.

Fortunately, much of this supporting infrastructure is in place, as evidenced by examples ranging from computing architectures such as the Columbia supercomputing project, the Community Coordinated Modeling Center (CCMC), and NASA's Applied Information Systems Research Program, to strong EPO efforts and innovative programs such as NASA's Summer Faculty Fellowship program.

Nonetheless, our research community faces significant challenges in the immediate future, challenges that directly affect our ability to meet NASA's goals and support national objectives. The most significant challenges are those of training new researchers while maintaining the corporate memory of an experienced work force. By way of illustration, NASA and its supporting contractors will soon have large portions of its work force eligible for retirement. By some estimates the services of as much as two-thirds of the most experienced scientists, technicians, and managers could be lost in the near future.

The maintenance of existing research teams and investigators is of paramount importance to a healthy and robust scientific community. There is a real danger that the loss of 'critical mass' of research teams will begin to impinge on NASA's science and exploration goals. This is especially important for hardware development teams who have a high startup investment and have difficulty in keeping technical expertise in uncertain funding cycles. NASA support for low-level hardware development is generally deemed insufficient to support truly innovative instrument development. Only the largest teams are perceived as capable of competition for hardware development. Paradoxically, the opposite can be said about modeling support, in that large-scale modeling are not sufficiently funded for the tasks they face. In all cases, there must be a balance between large and small research efforts, as well as between pure and applied science.

Training opportunities at the graduate and undergraduate levels provide an introduction to all aspects of space missions, including instrument development, mission operations, data analysis, and theory and modeling. These are often the first opportunities for students to experience the excitement of working in space physics and provide the primary means of recruiting these students into the space physics community. NASA programs that provide low-cost access to space such as rocket, balloon, and airplane missions, are especially useful for training in that students can contribute to mission design and operations while obtaining data in a timely fashion for analysis. This is particularly important in light of the long development times for complex missions that can exceed the normal tenure of graduate education.

Universities have traditionally provided the bulk of the training function, though innovative co-operative programs provide additional training opportunities in non-University settings. The needs for a robust training program are thus necessarily tightly linked to education and public outreach goals and deserve high priority.

The challenges discussed above are not new. The community has previously considered these problems and voiced concerns and suggested mitigation efforts through community efforts such as the recent NRC Decadal Survey, which offered specific recommendations to improve education and public outreach efforts as well as strengthening the solar and space physics enterprise. These recommendations are still relevant and endorsed by this Roadmap.

NASA's SR&T, TR&T, and GI programs are the traditional underpinning of most research teams and individual investigators and have been repeatedly recognized as such in community strategy documents. They have provided a significant contribution to the vast body of knowledge needed for direction and implementation of NASA's initiatives. Unfortunately, recent budget pressures have forced delays in some of these programs and the potential impact of these delays must be acknowledged.

NASA SSSC also benefits from research funded by other agencies, such as NSF's CEDAR, GEM, and SHINE research programs and the Center for Integrated Space-Weather Modeling (CISM), an NSF Science and Technology Center. In light of the importance of non-NASA research to NASA's research infrastructure, inter-agency cooperative programs must be supported.

In summary, this Roadmap recommends that NASA pursue programs across a broad spectrum of size and duration and that a portion of the budget be reserved for small levels that might otherwise be overlooked. NASA should also seek to expand current partnerships with Industry, Universities, and other agencies. For example, current successful EPO efforts tend to focus on K-12 levels without adequate resources for the critical later years when college students are making career decisions and may need additional inspiration to continue toward a career in space physics.

Chapter 3. Technology Investments

Develop Technologies, Data, and Knowledge Systems to Improve Future Operational Systems

Innovation is the engine that drives scientific progress, through development of new theories, invention of new technologies that lead to improved measurements, or entirely new capabilities. SSSC must embrace the development, infusion, and study of new technology, both for its stimulating effect on science (enabling and enhancing new missions), and because of the key role that understanding and predicting the space environment presents for the safety of other NASA missions and of our global infrastructure that is increasingly space-based.

Continuing progress in the characterization, modeling, and prediction of the Sun-Solar System Connection (SSSC) will require technological development in a number of key areas. Highly desirable capabilities include:

• Simultaneously sample space plasmas at multiple points with cost-effective means (e.g., MMS, LWS Storm Probes, and Sentinels); measure phenomena at a higher resolution and coverage in order to answer specific scientific questions (e.g, GEC);

• Achieve unique vantage points such as upstream of the Earth-Sun L1, polar orbit around the Sun, or even beyond the heliosphere;

• Develop the next generation of capable, affordable instrumentation;

• Enable the return of vast new data sets from anywhere in the solar system;

• Synthesize understanding from system-wide measurements using new data analysis and visualization techniques.

The highest priority SSSC technology needs follow these key focus areas:

1. Developing compact, low-cost spacecraft and launch systems;

2. Achieving high ΔV propulsion (solar sails);

3. Designing, building, testing, and validating the next generation of SSSC instrumentation;

4. Returning and assimilating large data sets from throughout the solar system;

5. Analyzing, data synthesis, modeling, and visualization of plasma and neutral space environments throughout the solar system.

"Enabling and Enhancing Technologies for Sun-Solar System Connection Missions" (Table to be provided in final roadmap) outlines the dependence of these key technologies from high-priority missions, and also outlines the importance of other areas such as avionics, formation flying, structures & materials, power, and low cost access to space. The number of spacecraft required is displayed versus time in a Figure to be provided in the final roadmap entitled "Sun-Solar System Connection Cluster and Constellation Missions." Missions with "clusters" of spacecraft (in the range of 2-6 spacecraft) seek lower unit costs, while constellations missions such as Magnetospheric Constellation (30-36) and Solar Wind Buoys (12-15) could be enabled by ST-5 nanosats.

1. Developing compact, low-cost spacecraft and launch systems

Because of the complexity and large scale of solar system plasmas, progress requires clusters or constellations of spacecraft making simultaneous multi-point measurements (e.g., Inner Heliospheric

Sentinals, MMS, Magcon, and GEC). For multi-spacecraft missions enabling and enhancing technologies include the development of low mass, power, and volume instrumentation as well as low mass, economical spacecraft. These two developments are linked in the sense that smaller, better integrated, spaceflight instrumentation packages could be accommodated on smaller, less expensive launch platforms.

Reducing the unit cost of multiple space systems will require efforts on multiple fronts, many system issues wholly unrelated to typical performance-driven technology development. One area of technology important to this issue is the development of low-power electronics for space systems and instruments. Flight validation of one LPE component and technique (CULPRIT Reed-Solomon Encoder on ST5) is scheduled for 2006, and support for further development was provided by NASA' Exploration Systems Directorate in 2004 (ECT NRA). Power dissipation at the component level can be reduced by factors of 50-100 over conventional technology. If LPE technology can was available system-wide, power consumption on satellite systems could be reduced by up to 70%, enabling system-wide benefits and providing spacecraft designers with greater flexibility reducing weight, size and cost.

2. Enabling high ΔV propulsion (solar sails)

Progress in key areas of Sun-Solar System science requires access to unique vantage points both in and outside the heliosphere. One such key vantage point is high-inclination, heliocentric orbit which would enable unprecedented imaging of solar polar regions. Mission concepts relying on existing technology use either 5 years of solar electric propulsion, yielding just a 38° inclination in the inner heliosphere (Solar Orbiter), or rely on a Jovian gravity assist and conventional propulsion to provide an eccentric 0.25 x 2.5 AU polar orbit (Telemachus).

The solar sail is envisioned as a cost-effective means of propelling spacecraft in the inner solar system to very high velocity ($\Delta v > 50$ km/s). Because they rely on the Sun's continuous supply of photons to provide low-thrust propulsion, solar sails also enable missions in non-Keplerian orbits that are currently not feasible by other means. Solar sails would enable three important SSSC missions:

• Heliostorm, providing greater warning of energetic particles accelerated by CME's via measurements upstream of the Earth-Sun L1 point;

• Solar Polar Imager, providing remote sensing of solar poles from a near-optimal vantage point--circular, 0.5-AU, 75° inclination heliocentric orbit;

• Interstellar Probe, a cost-effective means of sampling interstellar space.

A solar sail consists of a reflective membrane and supporting structure that is deployed or constructed in space. As a result of development by the Ins-Space Propulsion Technologies Project, sail technology has advanced considerably in recent years. In 2004, two 10-m systems were tested in vacuum on the ground, followed by two 20-m systems in 2005. This recent development has moved the solar sail from the realm of science fiction to science fact.

Because of the nature of a solar sail—a gossamer and reflective membrane meant for deployment and to fly in space—there are fundamental limits to further validation and maturation on the ground. In fact, building, deploying and flying a hundred-meter-class solar sail for a strategic Science mission will first require a Solar Sail Flight Validation or "Sail Demo" mission. The sail demo will develop and operate in space a deployable solar sail, one that provides measurable acceleration, and that can be steered. The flight experiment will test and validate the models and processes for solar sail design, fabrication, deployment, and flight. Such models and processes can then be used *with confidence* to design, fabricate, and operate the larger solar sails needed for strategic missions.

A sail demo is a candidate concept for the New Millennium Program's ST9 mission scheduled for

2010. Scale-up of the technology to 100-m lengths needed by Heliostorm could occur 5-6 years after a successful sail demo. After flight of a 100-m-class solar sail and a few years additional development, scale-up to still larger sails such as for Solar Polar Imager (~160-m edge length) are imaginable from there. Three decades hence, the deployment of a truly monumental, high-temperature sail required by a mission like Interstellar Probe (200-m radius) could be tended by human crews operating near libration points.

3. Enabling the development of the next generation of SSSC instrumentation

SSSC missions carry a wide range of instrumentation designed to make in-situ measurements within space plasmas and remote sensing measurements of plasma processes from within the sun to the planets and out to the edge of the heliosphere. The development of new instruments and instrument concepts is crucial to the future of SSSC science, driven by the need to refine and improve instruments, reduce their mass and power consumption and enable new measurement techniques. Progress in instrument technology development is needed at all TRL levels, from basic concepts for new detectors (MEMS based plasma detectors that could be used on MagCon, for example) to system level demonstration of improved instruments (e.g. Compact Doppler/Magnetographs for missions such as Doppler). The development of these instruments will proceed from formulation of new ideas and designs (perhaps based on technologies developed in other fields), basic proof of concept, fabrication of test models, laboratory testing, and finally flight validation. It is important to maintain a balanced program that supports all levels of this development, particularly the final stages that enable instruments to be used in-flight. The most costly and time consuming development stages are those directly preceding flight on science missions, largely because of the specialized equipment required. In order to continue to lead the world in space science research, NASA must support the development and maintenance of space-quality test facilities, including those capable of simulating the particle and radiation environments encountered during spaceflight missions. For some of these applications, NASA's low-cost access to space (LCAS) program provides an ideal avenue for testing and validation. A prime example of this paradigm is the development of top-hat style plasma detectors. These were first conceived for studies of the Earth's auroral regions, and were first flown on sounding rockets. Their successes in this area led directly to instruments being flown on highly successful magnetospheric missions. Another important avenue for assessing the effects of the variable space environment on potential flight instruments (and other technologies) is the Space Environment Testbed Program.

Specific component technologies that would benefit SSSC missions include: large area, deep well CCDs, active pixel sensors, low noise micro-channel plates, foil technology for ENA imagers, high performance EUV mirrors, UV blind ENA imagers, low-mass high voltage power supplies advanced X-ray optics and detectors, thin solid-state energetic particle detectors, compact, accurate magnetic sensors and small dead-layer solid state detectors. At the system level, many payloads on future SSSC missions will be severely mass and power constrained (MagCon and Solar Weather Buoys, for example): Technologies that reduce sensor and electronics mass and power would be particularly useful. In addition to these focused technology needs, missions may benefit from serendipitous use of technologies developed in other fields. For example, the incredible shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and more power efficient ionization sources.

4. Enabling the return of large data sets from throughout the solar system

As our exploration of the sun-solar system connection proceeds, SSSC missions will place an increasing demand on NASA’s communication resources. Many missions would be significantly enhanced by increased communications bandwidth. High bandwidth communication would benefit missions that image the sun, such as Solar Polar Imager or Doppler, by allowing high cadence, high resolution imaging in multiple spectral channels. As solar remote sensing missions are deployed beyond earth orbit, these benefits become more critical: missions such as SHIELDS or Farside Sentinel will study the sun from multiple vantage points, requiring spacecraft to be operated up to 2 AU from the earth. Closer to Earth, missions will require multiple spacecraft to explore the geospace environment, separating the effects of variations in time and space and examining the structure of complex boundaries. Large numbers of individual spacecraft (in MagCon, for example) distributed throughout geospace will stretch the capabilities of the current communications infrastructure. As we venture further out in the solar system, with missions such as Jupiter Polar Orbiter, HIGO and Interstellar Probe returning the required data places an increasing burden on spacecraft, driving cost and complexity. Considered individually, the above missions may be achievable with current technology, however pursuing system-wide SSSC science goals will be enabled by enhancements to our communications technology.

Several technologies will contribute to the solution to this problem. Planned enhancements to the Deep Space Network (DSN), replacing outdated 70m and 34m antenna with arrays of smaller antenna working at Ka-band, will increase the available bandwidth substantially, while also providing the flexibility to communicate with multiple spacecraft simultaneously. Using 200 such antennas, for example, would enable Kbps communication from an Interstellar Probe at 100 AU, providing the type of data provided by the ACE or Ulysses missions throughout the solar system to the edge of the helisosphere. Optical communication would also provide a substantial increase in communication bandwidth and additionally provide the capability for high-bandwidth point-to-point communication for missions monitoring the interplanetary radiation environment. The next generation DSN is expected to provide both enhanced RF and optical communications. Arrays of small antennas plus other RF improvements (transmitters, inflatable antennas, transponders, for example) together with optical communication would provide orders of magnitude increase in science data rates. RF arrays would also enable a significant increase in the number of spacecraft that can be supported, particularly in closely spaced clusters.

5. Enabling the analysis, modeling, and visualization of solar system plasmas

As we continue to explore the Sun-Solar System connection, the requirement to effectively model the systems we study becomes more critical. In many missions (e.g. the Inner Heliosphere Sentinels or MagCon) modeling will be a critical element of the mission itself, while other modeling efforts will be required to assimilate the data collected by multiple missions into coherent models. The necessary groundwork for these activities has already begun - examples include NASA's Information Power Grid, a joint effort between government, academia, and industry to provide large scale, distributed computing resources to the scientific and engineering communities. The Columbia supercomputer, uses 10,240 Intel Itanium 2 processors and provides an order of magnitude increase in NASA's computing capability. The goal of producing integrated models, and software frameworks that link these models, is also being address, with organizations such as NASA’s Coordinated Community Modeling Center (CCMC),the NSF funded Center for Integrated Space Weather Modeling (CISM) and the Center for Space Environment Modeling at the University of Michigan. These efforts are by definition cross-disciplinary, requiring expertise in numerical analysis, high-performance computational science, and solar, interplanetary, magnetospheric, ionospheric and atmospheric physics. Modeling and theory programs such as these will need to be expanded deal with the demands of increasingly complex data sets and simulations that encompass the entire solar, heliospheric and geospace environments. As new computer capabilities emerge, SSSC scientists will construct broader ranging and more complex models that will allow us to predict the behavior of solar system plasmas based on the assimilation of data from our Great observatory.

One of the great challenges faced by current and future SSSC missions is visualization of complex data sets measured by multiple spacecraft in a simultaneous, coherent fashion. Current efforts include the

VisBARD project, funded by NASA's Applied Information Systems Research Program. In this project, space science data are displayed three-dimensionally along spacecraft orbits that may be presented as either connected lines or as individual points. The data display allows the rapid determination of vector configurations, correlations between many measurements at multiple point, and global relationships. Events such as vector field rotation and dozens of simultaneous variables that are difficult to see in traditional time-series line-plots are more easily visualized with such a tool. Future data sets will be even more extensive requiring ever more sophisticated visualization tools. In analyzing future spacecraft data and comparing them with data available from the rest of the SSSC Great observatory, pattern and feature recognition will become increasingly valuable, allowing large datasets to be mined for events, particularly those detected by multiple platforms. Data structures like the Virtual Solar Observatory and Virtual Heliospheric Observatory will allow such mining, enhancing the value of our data repository and making data more accessible to the science community. Visual representation of imaging data is also critical to its analysis and interpretation, as well as providing a ready means to engage the public. A wide range of SSSC image data will be produced: γ-ray, X-ray, UV, visible, IR radio and neutral atom instruments will all produce data requiring image visualization. Tools aimed at producing images of these data are an important part of our current technology, however future missions (STEREO, SDO, IBEX and GEMINI, for example) will continue to place demands on technological capabilities, as image formats increase in size and more complex multi-dimensional data sets need to be visualized.

Part III. Linkages between Sun-Solar System Connections and other NASA Activities

Chapter 1: Exploration and Fundamental Science

Something hidden. Go and find it. Go and look
behind the Ranges---
Rudyard Kipling (1865-1936), "The Explorers" (1903)

The primary goal of the Vision for Space Exploration is the implementation of "a sustained and affordable human and robotic program to explore the solar system and beyond." This simple statement has profound consequences on how to prioritize the science programs that are needed to accomplish the new vision. How is the SSSC community to respond, when its traditional culture has been the scientific investigation of processes fundamental to space physics? Advice came recently from the Space Studies Board of the National Academy of Sciences who offered five guiding principles, the first of which was:

Exploration is a key step in the search for fundamental and systematic understanding of the universe around us. ***Exploration done properly is a form of science***.[2]

The answer for the SSSC community becomes clear when we realize that the converse of the guiding principle also holds: ***Exploration cannot be done properly without science***.

Exploration must be well-planned; history is rife with narratives of expeditions that ended fruitlessly or, even worse, tragically. In reality, ***properly*** implies ***safely, efficiently, and economically***. There are many examples of pragmatic problems facing the successful implementation of the Exploration Vision, ranging from the prediction of the space radiation environment to the design of the critical entry of a Crew Exploration Vehicle into the Martian atmosphere. In both cases, the science that enables exploration activities is drawn from the same science that is used to investigate the fundamental processes on the Sun, the planets, and in the heliosphere from its inner boundary to the outer boundary with the interstellar medium.

The pursuit of fundamental science not only enables Exploration but it also transforms our understanding of how the universe works. Current SSSC missions are producing a steady stream of transformational science that is rewriting the textbooks of past decades. Some recent examples:

Direct evidence from IMAGE and Cluster that magnetic reconnection in the earth's protective magnetosphere can open "holes" that allow solar wind to leak through continuously for hours – much longer than theorists predicted.

Surprising information from SOHO about the hidden workings of the subsurface solar dynamo that generates the Sun's magnetic field.

A new understanding of the acceleration sites of solar energetic particles based on RHESSI gamma ray observations.

The puzzling complexities of the outer boundary of the solar wind discovered by the Voyager-1 spacecraft, our most distant explorer.

The new pragmatic challenges of the Exploration Vision will dictate re-focused and intensified scientific exploration. This exploration will bring forth exciting discoveries, but only if it has the same broad scientific base that has nurtured the SSSC community to its current maturity. Why? Because space science is replete with pivotal discoveries that came from unexpected quarters, from areas of sound but seemingly tangential research. We would not now be understanding the details of the acceleration of solar energetic particles revealed by RHESSI if space scientists in the 1970's (Reuven Ramaty among them) had not worked out the details of gamma-ray line emission in the solar atmosphere (a subject that struck many as esoteric in those days).

This SSSC Foundation Roadmap differs from its predecessors in that it clearly responds to the new priorities in space science. Nonetheless, it preserves the momentum of our community's achievements and maintains continuity with past strategic planning. Appropriate missions recommended by previous studies are carried forward, while new missions are put forward that will produce the science required for the success of the Vision for the moon (2020) and Mars (2035). Each of these new missions is soundly conceived in fundamental science objectives while being efficiently designed to do the science that will support the Vision of Space Exploration. Well-planned science cannot help but generate exciting discoveries while still delivering the promised results.

Chapter 2: Linkages Between SSSC Strategic Roadmap and other NASA Strategic Roadmaps

Sun-solar system connection (SSSC) science is focused on space plasma physics, which encompasses the sun and processes and phenomena that determine the space environment near the sun, the Earth-moon system, throughout interplanetary space to the very boundary of the solar system, and in the vicinity of every solar system body. To the degree that the space environment matters to humans or their technological systems, either on Earth or in space, SSSC science has application to human activities. Penetrating energetic particles and photons, produced by acceleration and radiation processes in space plasmas, profoundly and adversely impact any exposed living organism through cellular damage and mutation. They also adversely impact exposed technological systems through episodic and cumulative damage to microcircuits and cumulative degradation of certain materials. Therefore, processes that produce and transport energetic radiation are of direct interest to modern humans. Space weather in the vicinity of planetary bodies affects upper atmospheric state (density and wind distributions critical to vehicle aerocapture, ascent, and descent scenarios) and ionospheric state (spatial and temporal electron density distributions that influence navigation systems and all high band-width communications). The situation for long-duration space flight is somewhat analogous to deep-ocean operations of naval ships. Vessels are designed to survive in various climatic conditions; yet the weather, which can be extreme, limits operations and determines how vessels should be configured in any situation. Similarly, operations in space, i.e., EVAs, maneuvers, operations on lunar and planetary surfaces, and safe harbor (atmospheric) entrance and exit, will depend on the space weather. As in the modern terrestrial case, space weather awareness, understanding, and prediction will be essential enabling activities with respect to space exploration operations. Therefore, we recognize strategic linkages between the SSSC Roadmap and all three Exploration roadmaps (Lunar exploration, Mars exploration, and the development of the Crew Exploration Vehicle).

The effects of space weather on Earth's atmosphere are of special interest. Enhanced ozone depletion is a documented consequence of energetic particle precipitation. We are aware of space plasma processes that erode the Earth's atmosphere, removing ~10^3 kg of Hydrogen and Oxygen daily, and much larger quantities during space storms. We have performed computer simulations that lead us to infer even greater loss of atmospheric constituents at Mars, which lacks the shielding provided by an intrinsic magnetic field. The potential role of local space weather and/or solar variability in terrestrial climate change is as yet unknown. The state of the Earth's ionosphere is thought to be subtly modified by terrestrial seismic activity. Quantitative determination of the intrinsic terrestrial magnetic field requires an accounting of field sources external to the solid Earth. These external sources are dominated by electrical currents carried in the space plasmas surrounding the Earth. For these reasons, we also recognize strategic linkages between the SSSC Roadmap and the Earth Science Roadmap.

The same processes and phenomena that drive space weather in our solar system also shape the environment throughout the universe. We have a typical, variable, main sequence star (the Sun) in our back yard. We live on a fully habitable planet that is largely protected from elements of our local space environment by a magnetic shield (what we call a magnetosphere), a feature not shared by all astronomical, or even planetary bodies. As we try to understand the remote universe and its potential to evolve life, it is imperative that we take as full account as possible of the 'specimens' we hold in our hands, so to speak. Therefore, we recognize important linkages between the SSSC Roadmap and other scientific roadmaps that seek to understand nearby planetary systems (SRM03) and the larger universe (SRM08) and also between the SSSC Roadmap and the roadmap to search for other habitable planets (SRM04).

Chapter 3: Linkages Between SSSC Strategic Roadmap and NASA Capability Roadmaps

Continued progress in Sun-Solar System Connection (SSSC) science requires new capabilities based on the development of new technology. Future technology needs are driven by diverse requirements. Cluster and constellation missions are required to simultaneously sample large-scale space plasmas at multiple points (Magnetospheric Constellation, Inner Heliospheric Sentinals, Solar Weather Buoys, Dayside Boundary Layer Constellation, Inner Magnetospheric Constellataion). Highly focused missions require improved measurement resolution and sensitivity (MMS, GEC, RAM, MTRAP, GEMINI, DOPPLER). Missions with special orbital requirements will need in-space propulsion. Examples include requirements to dwell at a point upstream in the solar wind from the L1 libration point (Heliostorm), to achieve a polar heliocentric orbit (Solar Polar Imager), or to escape from the solar system (Interstellar Probe). As the missions in our roadmap are developed, they will require new technologies in instrumentation, data visualization, communication, and analysis systems. Future SSSC technology needs fall into several focus areas:

Propulsion and Power: A number of SSSC missions will study solar system plasmas from unique vantage points. Propulsion systems that can supply a larger delta-V than conventional rocket engines, or that can provide large delta-V without a large mass or power penalty, can enable such challenging missions. For high-performance, cost-effective propulsion in the inner solar system, or for exiting the solar system in timely fashion, solar sails are the ideal choice. Significant ground demonstrations of solar sail technologies have been performed already. We encourage continued development of this technology and support the idea of a flight demonstration during Phase 1 of this roadmap (CY 2005 – 2015). We also encourage renewed capacity to produce RTGs that have low-EMI, high-efficiency power conversion.

Micro-spacecraft: Owing to the large scale and complexity of solar system plasmas, future discoveries will depend on deployment of spacecraft in clusters and constellations, making simultaneous multi-point measurements within plasmas under study. Enabling technologies will include low mass/power/volume instruments, and low mass, low cost spacecraft.

DSN: NASA's Deep Space Network (DSN) is evolving to meet the communication and navigation needs of the agency's increasingly complex, data-intensive missions. Analysis of Sun-Solar System Connection roadmap missions suggests that, over the next 25 years, downlink rates will need to increase by a factor of at least 1,000, even from the more distant regions of our solar system. The trend toward multi-spacecraft missions will likely cause a large increase in the number of such supportable links back to Earth. Near-Earth missions should use and cultivate the continued evolution of commercial space networks.

Advanced Modeling: Advanced supercomputing is a vital capability for enabling space weather model development and innovative data analysis and visualization. Examples of successful innovation in this area include NASA's Information Power Grid, Project Columbia, and the VisBARD project.

Instrumentation: Many future SSSC missions will require development of new scientific instrumentation, including large focal plane arrays, large-scale adaptive optics, and solar-blind energetic particle and photon detectors. The development of hyperspectral and 3-dimensional detectors are needed for solar and geospace remote sensing. Miniaturization of high voltage power supplies will relieve mass and volume resource constraints. Increased quantum efficiency of UV and EUV detectors will enable significant savings in mass as small but sensitive instruments can be developed. The shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and power efficient ionization sources. Conductive polymers and other exotic materials and coatings may lead to development of solar blind detectors, new and better dust analyzers, and miniature mass spectrometers. It is important to develop and maintain ground test facilities for simulating particle and radiation environment in space. Radiation test facilities will be particularly important as technological innovations and the push to develop more power efficient instruments results in smaller electronic instrumentation. Ground testing is extremely valuable, but NASA's low-cost access to space (LCAS) program is required for complete testing and full validation of advanced instrumentation. An area of instrumentation where we should place significant development effort is in imaging, which provides more information than any practical number of single-point measurements. Imaging is crucial to understand the complex interacting set of systems that make up the sun-solar system if we are to have properly constrained and accurate predictive models that are critical to support exploration, including a sustained human presence in space. The three primary imaging tools include Energetic Neutral Atom (ENA), Radio Tomography, and Photon Imaging, that includes x-ray, extreme ultraviolet (EUV), far ultraviolet (FUV), visible (VIS) and infrared (IR).

Space Environment Testbeds (SET): SET is a technology development project that performs spaceflight experiments of new approaches for mitigating the effects of the dynamic space environment that are driven by solar variability. Its investigations validate new hardware, methods, models, and tools, all geared toward mitigating the effect of the space environment on systems.

Appendices

A. National Policy Framework and External Constituencies

National Policy— In addition to the National Space Policy, the U.S. House of Representatives Science Committee approved House Con. Resolution 189:

The International Heliophysical Year (ihy.gsfc.nasa.gov): H.Con.Res. 189, Celebrating the 50th anniversary of the International Geophysical Year (IGY) and supporting an International Geophysical Year-2 (IGY-2) in 2007-08. The resolution calls for a worldwide program of activities to commemorate the 50th anniversary of the most successful global scientific endeavor in human history - the International Geophysical Year (IGY) of 1957-58. The resolution also calls for an “IGY-2” that would be even more extensive in its global reach and more comprehensive in its research and applications.

NAS-NRC Space Studies Board, Committee on Solar and Space Physics Report: Assessment of the Role of Solar and Space Physics in NASA’s Space Exploration Initiative, draft report due September, 2004. The report is intended to review the roles that the solar and space physics program should play in support of the new NASA exploration goals. Specifically, the panel will analyze the missions and programs that were recommended by the 2003 NRC decadal study for solar and space physics, "The Sun to the Earth--and Beyond," and assess their relevance to the space exploration initiative; and will recommend the most effective strategy for accomplishing the recommendations within realistic resource projections and time scales.

B. U.S. External Partnerships and Relationships

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities have become more obvious. The nation’s efforts to mitigate space weather effects have placed more urgency on the need to understand the Sun, heliosphere, and planetary environments as a single connected system. External constituencies requesting and making use of new knowledge and data from NASA’s efforts in this area include the Federal Aviation Administration (FAA), the Department of Defense (DoD), National Oceanic and Atmospheric Administration (NOAA), the power industry, and the industry of satellite manufacturers and operators.

Constituencies within NASA include the Exploration Systems, Directorate, the Space Operations Directorate, the Deep Space Network, and the various satellite operations centers.

NASA Constituencies

	real-time space weather data	space environment specification	satellite anomaly diagnosis	navigation, radar, communication, transmission media error corrections	spacecraft subsystem technology transfer	models of space processes for use in nowcasting and forecasting
Satellite Operation Centers	●		●			
Space Operations Directorate	●	●				●
Exploration Systems Directorate		●				●
DSN/TDRSS/other communications	●			●		●
External Constituencies						
NOAA/NWS	●	●				●
FAA	●			●		
DoD	●	●	●	●		●
Commericial Satellite Operators	●	●	●		●	
Power Industry	●					●
Communication Industry	●			●		●

Table 1: NASA and external constituencies requesting and making use of new knowledge and data from NASA's Sun-Solar System Connections group.

C. International Cooperation

International Living with a Star: In the January of 2002, the Interagency Consultative Group (IACG) established the Internal Living with a Star (ILWS) program. The IACG consists of the heads of the space science programs of the European Space Agency (ESA), Japan's Institute of Space and Astronautical Science (ISAS), the National Aeronautics and Space Administration (NASA, USA), and the Russian Aviation and Space Agency (RASA). The charter for ILWS is to "stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity". Contributing organizations are listed at http://ilws.gsfc.nasa.gov.

Currently Operating Missions with significant International participation:
Solar Heliospheric Observatory (SoHO): partnership with ESA
Geotail: partnership with Japan/JAXA
Cluster: partnership with ESA
Ulysses: partnership with ESA

Missions in Development with significant International participation:
Solar-B: partnership with Japan/JAXA, ISAS, PPARC
Stereo: contributions from CNES, Switzerland, DLR, PPARC, ESA, Hungary
THEMIS: contributions from Canada, CNES, DLR, and Austria
MMS: contributions from recently-selected international partners
AIM: agreement with British Antarctic Survey, Australia

TWINS: contributions from DLR

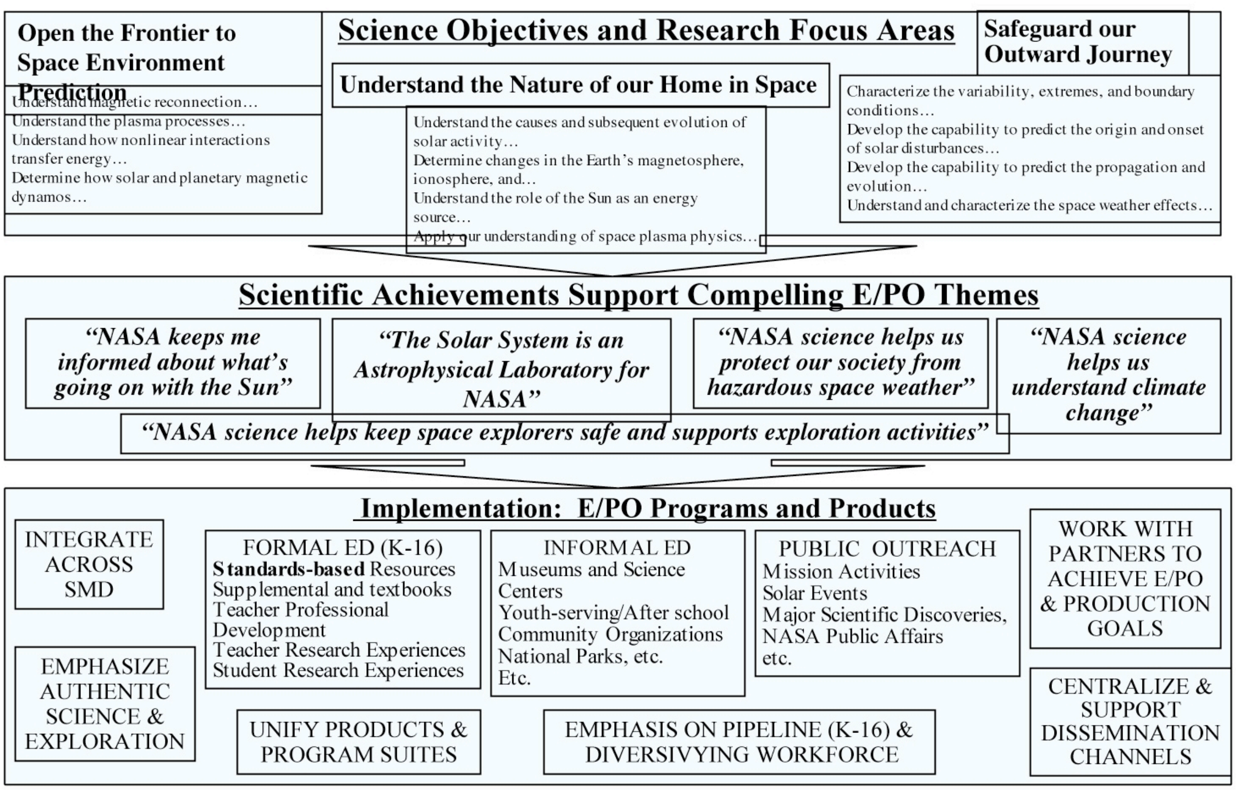
Near- term Mission Concepts:
Solar Orbiter: possible partnership with ESA
LWS/Geospace: possible contributions from to-be-selected international partners
LWS/Sentinels: possible contributions from to-be-selected international partners

D. Education and Public Outreach

Unique Education and Public Outreach (E/PO) opportunities associated with Sun-Solar System Connection Science

The top-level objectives, research focus areas and science achievements that constitute the Sun-Solar System Connection Strategic Roadmap for the next 30 years provide powerful opportunities for Education and Public Outreach from the SSSC scientific community (Chart A).

Chart A: Flow-down chart demonstrating that the Scientific Objectives and associated Research Focus Areas lead to E/PO themes that inform implementation



We recommend that E/PO activities stemming from the science achievements or milestones be developed to support the following five messages:

"NASA keeps me informed about what's going on with the Sun"

"The Solar System is an Astrophysical Laboratory for NASA"

"NASA science helps us protect our society from hazardous space weather"

"NASA science helps us understand climate change"

"NASA science helps keep space explorers safe and supports exploration activities"

These themes have been identified by the community because they are of high interest and relevance to the public and they span the range of scientific activity engaged in by the SSSC community, as indicated by the selected achievements articulated in this Roadmap and called out Table B. In addition, as Table C indicates, these themes map to the majority of the missions in the Roadmap.

Table B. Science Achievements from the Roadmap support SSSC E/PO Themes

Science Achievements* support SSSC E/PO Themes

SSSC Science Objectives	SSSC E/PO Themes	Phase I 2005-2015	Phase II 2015-2025	Phase III 2025-beyond
Open the Frontier to Space Environment Prediction	***"NASA keeps me informed about what's going on with the Sun"*** ***"The Solar System is an Astrophysical Laboratory for NASA"***	Characterize magnetic reconnection at the Sun and Earth Identify key processes that couple regions within and throughout the heliosphere	Understand the magnetic processes that drive space weather	**Predict solar system magnetic activity and energy release** Predict high energy particle flux throughout the solar system
Understand the Nature of our Home in Space	***"NASA science helps us protect our society from hazardous space weather"*** ***"NASA science helps us understand climate change"***	Identify how space weather effects are produced in geospace Identify the impacts of solar variability on Earth's atmosphere	Determine how magnetic fields, solar wind and irradiance affect the habitability of solar system bodies Identify precursors of important solar disturbances Integrate solar variability effects into Earth climate models	**Provide scientific basis for continuous forecasting of conditions throughout the solar system** Predict climate change
Safeguard our Outward Journey	***"NASA science helps keep space explorers safe and supports exploration activities"***	Nowcast solar and space weather and forecast "All-Clear" periods for space explorers near Earth	Reliably forecast space weather for the Earth-Moon system; make the first SW nowcasts at Mars	Analyze the first direct samples of the interstellar medium Reliably predict atmospheric and radiation conditions at Mars to ensure safe surface operations
Overarching E/PO Theme: *Scientific progress requires new knowledge systems and innovative use of technology: Measure and Characterize…Development of Models…Predictive Capability; from Sounding Rockets to Solar Sails*				

Table C. SSSC recommended missions identified with SSSC E/PO Themes

Missions Key to Science Achievements* identified with SSSC E/PO Themes

SSSC Science Objectives	SSSC E/PO Themes	Phase I 2005-2015	Phase II 2015-2025	Phase III 2025-beyond
Open the Frontier to Space Environment Prediction	***"NASA keeps me informed about what's going on with the Sun"*** ***"The Solar System is an Astrophysical Laboratory for NASA"***	Cluster, TRACE, Polar MMS, Solar Reconnection, RBSP, SDO, Solar-B, STEREO, THEMIS Auroral Imaging, L1monitor Cluster, L1-Monitor ITSP, IBEX, MMS, SDO, STEREO, L1monitor	IBEX, ITImager, MMS, RBSP, SDO, Solar-B, Stereo, THEMIS MagCon, Sentinels, Solar Probe, GEC, ITSP, L1, Solar Orbiter, Orbitals, RAVENS	SHIELDS, SPI, Farside, SWB, SPI , RAM, MTRAP, MagCon, IMC,DBC,Stellar Imager Assumes: ITSP, L1 monitor, SEPP, Auroral Imagers, Solar Sentinels, MTRAP, IMC, MagCon, DBC, AAMP
Understand the Nature of our Home in Space	***"NASA science helps us protect our society from hazardous space weather"*** ***"NASA science helps us understand climate change"***	ACE, Cluster, IMAGE, FAST, Polar, TIMED, GEC, MMS STEREO,ITSP+ITImager, RBSP, SDO, Rocket Campaigns IMAGE, TIMED, AIM, CNOFS ITSP + ITImaging, GEC, SDO, Rocket Campaigns	MSL, **Spitzer** **New:** MAD, TE TE, Lunar Solar Wind History Experiment **Europa Mission** SDO, ITSP, RBSP SP, DOPPLER, SEPP/NE,RAM, SIRA, SHIELDS, Solar Orbiter SECEP, ITMWaves , L1/L2 cont. global obs. RocketCampaigns	Existing: MagCon, AMS, ITM-Waves, GEMINI, Dayside Boundary Con. New:Rocket Campaigns/LCAS, IMC, ITC New?: Solar Polar Imager, TITMC, L1 Monitor (irradiance, particles),SECEP, SHIELD
Safeguard our Outward Journey	***"NASA science helps keep space explorers safe and supports exploration activities"***	TIMED, Soho, ACE, Cassini, Cluster, etc.: SDO, RBSP, ITSP, Inner Sentinels, L1 SW & SEP Monitor, MMS, MSL, Rocket Campaigns	Sentinels, SWB, Heliostorm/L1 Monitor, MagCon, IMC, GEC, GEMINI , DOPPLER, SHIELDS, SEPP, MTO, MAD, SPI	Interstellar Probe, HIGO, Telemachus, Outer heliosphere radio Assumes, results from robotic surveys of Mars and MAD + results from solar-interplanetary and Geospace missions (SDO, DP, HIS, RBSP, ITSP, LRO, Lunar experience etc) +... SCOPE, Telemachus
Overarching E/PO Theme: *Scientific progress requires new knowledge systems and innovative use of technology: Measure and Characterize…Development of Models…Predictive Capability; from Sounding Rockets to Solar Sails*				

Expanded and Invigorated Education and Public Outreach will be Essential to the Achievement of the Exploration Vision

NASA's Strategic Objective for Education and Public Outreach is to: *"Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation"*. The SSSC community emphasizes the connection between achievement of this strategic objective and the Exploration Vision. The development of the workforce needed to achieve NASA's Exploration Vision, including the scientific objectives described in this roadmap, will require that NASA's E/PO activities engage young people and capture their interest and passion. Furthermore, NASA's E/PO activities need to increase the capacity of our nation's education systems, both in (Formal: K-16) and out of school (Informal), to prepare students for scientific and engineering careers.

The E/PO themes articulated by the SSSC community indicate that their science and mission activities will be valuable hooks for E/PO. For example, the development of the capability to predict the variable radiation hazards and space weather conditions that our astronauts and robots will fly through and encounter on excursions to the Moon and Mars will be very exciting scientific work that the public will want to know about. New advances in the research of our Sun as an astrophysical laboratory will fuel the generation of authentic, science-rich education resources that will increase the capacity of the nation's education systems. Such new capabilities and discoveries can be connected to K-12 science education via appropriate national science education standards.

Developing the workforce to implement the Exploration Vision will require substantial focus

on underrepresented communities. Recent estimates of the demographic makeup of the science and engineering workforce in the USA indicate that this population is overwhelmingly white. Population projections to 2025, however, indicate that the percentage of traditionally underrepresented communities will increase relative to the current majority group. Thus, successful E/PO efforts designed to increase the workforce to achieve the Exploration Vision will benefit substantially by targeting under-represented groups.

An exciting example of E/PO targeted at underrepresented communities is NASA's Sun-Earth Connection Education Forum's (SECEF) Sun-Earth Day programming for 2005: Ancient Observatories: Timeless Knowledge. This broad program allowed NASA and Native American astrophysicists to share their research into the efforts of ancient cultures to understand the Sun, highlighting the importance of the Sun across the ages. Through programs such as these, SSSC scientists are conveying NASA's solar mission and research program activities to diverse audiences (both English and Spanish language materials have been disseminated).

Integrate messages and utilize best-practice strategies. Unification of NASA's scientific enterprise into the Science Mission Directorate presents opportunities for science education efforts in both the formal and informal arenas, as well as public outreach from across NASA, including the SSSC community. While each Division, mission, and individual scientist and engineer within NASA will have unique content and experiences to contribute to E/PO; integration into a single science directorate has the potential to be more effective in terms of message and approach. Moving forward, it won't matter if it's Space Science, Earth Science, Solar Physics or Biological Research, etc. – the 'brand' will be exciting, relevant NASA science. Furthermore, approaches to bring this content to the broadest possible audiences can take advantage of the best strategies of each of the former enterprises to create the strongest possible suites of products and programs.

SSSC Scientific Community is Vigorously Engaged in E/PO; and E/PO Efforts Align Well with SMD's Education Goals and Priorities

SSSC E/PO programs currently encourage the scientific community to share the excitement of their discoveries with the public. The programs enhance the quality of science, mathematics, and technology education, and help create our 21st century scientific and technical workforce. Efforts align with NASA's Science Mission Directorate's education goals and priorities to inspire and motivate students to pursue careers in science, technology, engineering and mathematics (STEM), and to engage the public in shaping and sharing the experience of exploration and discovery. In addition, E/PO programs include the development of tools for evaluating quality and impact, in order to identify and disseminate best practices in E/PO.

E/PO activities are currently integrated throughout the SSSC flight missions and research programs that support the SSSC scientific community. As the result a significant fraction of the Sun-Solar system scientific community contributes to a broad public understanding of the science and is directly involved in education at the pre-college and college level. Graduate student participation in SSSC research programs are enhanced by the Graduate Student Research Program, a cooperative program between NASA Education and the Science Mission Directorate.

Centralized efforts such as the Sun-Earth Connection Education Forum (SECEF; a partnership between NASA Goddard Space Flight Center and the University of Berkeley) strive to establish strong and lasting partnerships between the SSSC science and formal and informal education communities. These centralized efforts seek to

facilitate the involvement of SSSC scientists in E/PO activities; to develop a national network to identify high-leverage education and outreach opportunities and to support long-term partnerships, to provide ready access to the products of SSSC science education and outreach programs, and to

promote the participation of underserved and under-utilized groups in the SSSC science program by providing new opportunities for minorities and minority universities to compete for and participate in SSSC science missions, research, and education programs.

Vigorous E/PO programs also stem directly from various science programs within the SSSC community that effectively connect with and serve the E/PO needs of local communities.

Sun-Earth Day

Sun-Earth Day is an annual national program supported by SECEF. Since 2001 the SSSC community has shared the science of the Sun with educators, students, and the general public via informal learning centers, the Web, TV, and other media outlets through high-profile, well supported annual events. NASA science is connected to classrooms and museums in real time, and educational resources are disseminated via the Web and through NASA centers. In the context of an overarching emphasis on the Sun-Earth connection, a specific theme is created each year to continue to engage the public.

2001 - Having a Solar Blast
2002 - Celebrating the Spring Equinox
2003 - Live from the Aurora
2004 - Venus Transit
2005 - Ancient Observatories: Timeless Knowledge
2006 – Eclipse In a Different Light

Sun-Earth Day activities have broad reach. For example, the 2004 Sun-Earth Day website received 40 million hits in 40 hours. There were 1000 news reports on various TV channels, including 40 interviews with NASA scientists. More than 12,000 packets of educational materials were distributed to teachers, museums, and amateur astronomers in support of the 2004 Sun-Earth day programming.

As part of the 2005 Sun-Earth Day programming, in fall 2004, the Ancient Observatories: Timeless Knowledge website (sunearthday.nasa.gov) and the Traditions of the Sun website (www.traditionsofthesun.org) were launched to allow users to explore Chaco Canyon and other areas. Visited 500,000 times, these websites also highlight NASA research on the Sun and Native American solar practices within a larger historical and cultural context. Formal education programs engaged 75,000 teachers and 225,000 students, with all 10 NASA Centers hosting events. 100 NASA Explorer Schools also participated. Informal education efforts included programs hosted by 24 museums across the country; and training for Girl Scout Master Leaders who ultimately engaged some 10,000 girl scouts in Sun-Earth Day activities. The culminating event for Sun-Earth Day 2005 was a bilingual webcast live from Chichen Itza, which reached thousands of Hispanics and Native American participants.

The Solar and Heliospheric Observatory (SoHO)

The SoHO mission has a vigorous dissemination program of images for informal audiences and media outreach, regularly distributing near-real time images of the Sun (LASCO and EIT images) on the Web, Weekly to the American Museum of Natural History's AstroBulletin, and to a variety of media publishers, including National Geographic. Lanticulars (3-D Sun and space weather motion cards) are a very popular tool for engaging students and the general public. Over 180,000 Lanticulars have been distributed.

The SoHO mission also has two model collaborations that target educators and students: FiMS (Fellowships in Mathematics and Science), a partnership grant with the Pennsylvania Department of Education (in 3 school systems), is a strong example of the power of working directly with the local formal education system. SoHO educators and scientists work with their local teachers to increase content knowledge and support their ability to develop and implement inquiry-based lessons that are tied to state standards and the current curriculum. The Endeavour program, a collaboration between SoHO/NASA and 18 school systems, gives teams of students real-life NASA problems to research. Students are supported by teacher team leaders that have been exposed to the content and training through professional development.

Efforts to broaden the reach of SoHO's E/PO efforts, English and Spanish presentations on the Dynamic Sun CD, and building your own spectroscope poster have been very effective. In addition, SoHO is bringing the science and exploration of our Sun to the visually impaired through their ground-breaking "Touch the Sun" book.

E/PO Challenges and Recommendations

Strong opportunities exist to further extend the power of SSSC science and related mission activities to engage and inspire students in formal education settings, audiences at informal learning centers (Museums, Science Centers, etc.), and general public audiences across the nation via the press and other communication outlets. Table D presents a summary of challenges to effective E/PO, and articulates a series of recommendations to expand and enhance NASA's E/PO activities.

Table D. Challenges and recommendations to effective E/PO

Challenge	Recommendation
E/PO efforts vary widely across NASA. This is a disadvantage for both PIs and for audiences. PIs are often in the position of inventing their own E/PO programs, products and activities; and audiences need to constantly learn anew how to take advantage of these efforts.	Generate uniform, standards-based product lines with themed content for schools, museums, and science centers, and the press and media outlets. Invest production resources in development of core products that can be used appropriately by range of E/PO partners.
The formal, K-12 science education system needs strong connections with NASA's scientific, engineering and technological enterprises if it is going to play sufficient role in preparing the science and engineering workforce required to implement and achieve the Exploration Vision.	Correlate NASA's activities, enterprise-wide, with National Science Standards (e.g. National Science Education Standards of the NRC, and Benchmarks for Scientific Literacy, Project 2061) to develop a roadmap for infusing NASA resources into the formal K-12 system. Middle School presents a particular opportunity due to level of concepts mastered and more flexible curricula relative to High School. Develop templates for products, programs and professional development that, combined with the roadmap, effectively connect NASA's ongoing, authentic activities to classrooms for educators and learners.
Not enough undergraduates are opting for physics-based careers in particular and science and engineering careers in general.	Extend focus from K-12 to K-16 to integrate cutting edge SSSC topics (in addition to other relevant NASA content) into undergraduate physics courses.
Broad dissemination is required to achieve impact. Requiring individual PIs and Missions to create their own dissemination channels can be burdensome and lessen impact.	Expand existing, and develop new centrally supported channels for dissemination that mission and research-based E/PO can use to reach full range of audiences.
E/PO investments are not maximized due to lack of sustained support and dissemination.	Make sustained investment over time in Web-based dissemination of NASA materials: use of best-practice templates to create the materials will facilitate maintaining currency.
Outreach, not advertisement, is required in order to keep the public informed and engaged at the level required if NASA is to make progress towards achieving the Exploration Vision, particularly over the longer term.	Improve coordination between Public Affairs and Outreach and Education to conduct timely outreach that educates the public about NASA's activities and achievements, with appropriate emphasis on risk.

Provide a consistent and coherent set of education resources and professional development for formal and informal science education that derives from across the NASA enterprise. NASA needs to centralize its educational outreach to better support the capacity of education and public outreach partners to take advantage of SSSC science to engage their audiences. Educators in the K-12 arena require standards-based educational resources coupled with high-quality professional development offerings in order to tap ongoing NASA missions and take advantage of the constant stream of fresh, current, authentic scientific discovery and engineering activities. The creation of such resources (e.g. an informational website, an animated simulation, a set of data visualizations, a teaching guide, a set of standards-based curriculum activities, a professional development seminar, online course or videoconference, an interactive module, a poster, a set of opportunities to interact online and by video with scientists, engineers and technicians, an opportunity for student research, regular updates, etc.), coupled with appropriate professional development, will ensure that educators always have NASA in their tool-kit for effective science education. Partnership with professional organizations such as the National Science Teachers Association has proven effective for NASA, and should be expanded.

SSSC and other NASA missions and activities likewise provide wonderful springboards for learning in the informal setting. But educators and exhibit planners in the informal settings typically find each NASA opportunity requires a significant effort, simply to ramp up, since there is little consistency in what NASA produces, from center to center, from mission to mission. It would be tremendously helpful to know that for each NASA activity, there will be a standard set of resources (e.g., an informational website, an annotated simulation, a set of opportunities to interact online and by video conferencing with scientists, engineers and technicians, activities for out-of-school settings, regular updates, etc.) with common interfaces and similar formats that are fairly constant from activity to activity. Professional development is also required for informal educators; and current partnership efforts with professional organizations such as the Association of Science and Technology Centers have proven effective, and should be expanded.

It is understood that flexibility is essential - unique opportunities and requirements of each activity should be exploited, technologies will evolve, and evaluation inform revision – however, the ability to count on a standard package would likely reduce the learning curve for users and increase the usability and use of the resources. SECEF is a good example of the value of a coordinated national effort to develop and support E/PO activities; emphasis on standardized packages will strengthen this approach.

Promote and support the integration of the SSSC-related content more fully into standards-based K-12 science curricula. National science education standards provide direct opportunity to take advantage of SSSC science specifically and NASA science in general to improve science education on a national level. In this era of standards-based curriculum and high stakes testing, what gets taught is what is required in the curriculum and thus assessed on tests. State science curriculum standards generally map to these national standards, and thus tremendous opportunity exists for current SSSC science content to enrich and infuse these curricula. Influential science education standards such as the National Science Education Standards (National Research Council) and the 2061 Benchmarks for Science Literacy (AAAS) place substantial emphasis on SSSC related science concepts from the earliest grades through high school. The 2061 Benchmarks, for example, posit that in order to achieve scientific literacy students in grades K-2 master concepts such as ‘The Sun can be seen only in the daytime, but the moon can be seen sometimes in day and sometimes in night’ (4A/2); students in grades 3-5 further expand this understanding to ‘Stars are like the sun, some being smaller and some larger, but so far away they look like points of light’ (4A/5); in grades 6-8 they learn that ‘The Sun is a medium-sized star located near the edge of a disc-shaped galaxy of stars, ….’ (4A/1), and that ‘Telescopes reveal that the Sun has dark spots’ (10A/2); and by high school, that ‘Increasingly sophisticated technology is used to learn about the universe. Visual, radio, and X-ray telescopes collect information from across the entire spectrum of electromagnetic waves; ….' (4A/3). This progression of understanding highlights the role of understanding the Sun at many levels in developing scientific literacy. SSSC scientific research provides vivid, authentic examples to promote student mastery of these concepts.

The entire NASA enterprise could, for example, be mapped to the Benchmarks for Scientific Literacy, and/or the National Science Education Standards. The result would be a roadmap in itself for integrating NASA science and engineering activities into science curricula across the nation.

Extend focus to higher education in order to ensure adequate numbers of trained scientists and engineers for the SSSC community (and the rest of NASA) to achieve the Exploration Vision. The field of solar and space physics is in need of a national effort that relates the exciting applications in our field to specific curricular needs of introductory physics and astronomy (of which there are substantial enrollments at just about every college in the nation). And, in general, the excitement of space science should be utilized to entrain and encourage more undergraduates through physics, math and engineering programs at the university level. This will compliment current programs that are geared towards providing early research experiences (NSF's REU program, for example) which are very important for attracting non-traditional students into the workforce. Attention needs to be paid to how the space physics workforce is developed – where do students come from and why – in order to ensure sufficient numbers for a healthy scientific community able to achieve NASA's goals.

Enhance existing and create new distribution channels for E/PO efforts: products, programs, and messages. It is not realistic to make individual SSSC PIs responsible for building and/or sustaining their own dissemination relationships. This is not to say that individual PIs should not be encouraged to go into classrooms, make public presentations, appear in the media, etc. We recommend that NASA develop a spectrum of dissemination options that are supported and sustained centrally. In addition, NASA should support best practice use of World Wide Web for keeping products current and leveraging development efforts over time.

Emphasize unique learning opportunities that SSSC-related content can provide, in particular, focused on the visualization of data, essential for advancing science learning and the nation's scientific capacity. Expand efforts already underway to create high-production value media programs around the scientific assets of NASA, including Sun-Earth System. Fully digital space shows; large-format media projections, television productions, etc. are powerful vehicles for promoting public understanding of complex phenomena and teaching students of all ages critical skills for 21st century science involving collecting, analyzing, visualizing and communicating data and constructing, manipulating and interpreting scientific models and simulations. Increased efforts, taking advantage of partnerships with media production groups and distributers, will contribute substantially to achieving greater impact for E/PO programs.

Focus on innovative external partnerships to create programs that reach broadest range of public. Through leveraging partnerships with informal science learning centers (museums, planetaria, science centers, zoos); national parks; community groups (Girl Scouts), publishers and the media, SSSC science can be more widely disseminated by taking advantage of existing channels. For example, NASA has connected very effectively with the National Parks to support content on the aurora and noctilucent clouds for summer programs in Alaska to information about the Sun supporting educational programs at National Parks in the southwest. Programs such as these provide amplified impact by enhancing the capacity of established channels to engage, excite and educate the public around science and engineering content. New avenues should also be explored, for example, products developed with the gaming industry could engage the public, young and old, in the Exploration Vision.

To maximize impact of SSSC science for E/PO, efforts should take advantage of opportunities that exist at the intersection of the "formal" education and "informal" education sectors. Too often in education policy and strategy, schools and museums are viewed independent of one another with isolated objectives and strands of efforts. While there are clear differences between the two, substantial connections and overlaps exist. Many informal science education institutions already operate at the intersection of the two sectors – offering substantive professional development for teachers, providing learning experiences and field trips for classes, delivering afterschool services and developing and distributing curriculum materials and resources. A key strength of these institutions is local knowledge. The formal education landscape is highly variable, and this local knowledge is key to successful connections between science and engineering-rich agencies, such as NASA, and science and engineering education efforts in the formal setting. NASA Education and Public Outreach should take advantage of the existing connections and overlap between the formal and informal education arenas.

Develop better coordination with Public Affairs is required to maximize E/PO efforts. Consistent messaging is essential to effective communication, and effective communication is key to strong E/PO. More substantial overlap should occur between Public Outreach and Public Affairs (PA). The activities are distinct: Public Outreach from SSSC covers a broad range of topics and targets the public directly, and Public Affairs communicates specifically new and current discoveries to the media for dissemination to the public. However the visual and editorial resources required by both are very similar, and thus we recommend that Public Affairs team up with the E/PO group early in order to develop the same core messages and visual assets. This will facilitate getting better media coverage of scientific results and publicizing exciting E/PO events. It will also strengthen education programs because they can also take advantage of the visual and editorial assets developed for Public Affairs and Public Outreach.

E/PO efforts need to focus on outreach, not advertisement. While it is important to raise public awareness of SSSC missions and activities, it is essential to invest E/PO funds in products and programs that go beyond advertisement and truly engage and inform. Thus we strongly discourage the use of E/PO funds for lanyards, pins, etc., that are solely designed to advertise a mission.

Educate the public via outreach through informal and formal channels about the risks inherent in the exploration of space. As NASA pursues Return to Flight and the Exploration Vision, it will be very important for the public to be aware of the risks associated with these activities. In the event that accidents occur that result in tragic loss of life or even setbacks in mission activities, the public will be best able to respond appropriately if they were aware up front of the risks involved.

Shift in Management and Implementation of SMD E/PO Efforts

It can't be stressed too highly the impact NASA has had through commitment of substantial funds for E/PO efforts over the past decade or so. In addition, the value of having the scientific community intimately involved in the development and implementation of E/PO products and programs can't be over emphasized. Thus we strongly advocate maintaining the established commitment of funds for E/PO.

At the smaller scale NASA should continue to use the model of supplements for which individual PIs can apply to support E/PO activities that stem from their scientific research and mission activities. Rather than rely on the PIs to invent their own E/PO activities, however, we recommend that the allocation of E/PO funds be linked to a portfolio of approved E/PO program and product templates from which the PI can select; and require dissemination activities through one or more of NASA's approved and maintained channels as appropriate. In addition, E/PO activities in the near term should map to one of the 5 themes articulated above. Themes will be modified and new themes developed as part of future SSSC strategic planning activities.

At the mission scale – we recommend that each mission select from a range of approved product and program suites, and identify E/PO theme(s) that their activities map to. In addition, mission PIs should be required to utilize appropriate dissemination strategies and channels. While individual PIs with particular interest and commitment to developing new types of E/PO should be encouraged and supported, as a general case, do not burden PIs with inventing E/PO programs as they are putting their mission proposals together. In essence, science proposals funded by the Science Mission Directorate should be selected on the basis of their scientific merit. Funding for E/PO derived from these scientific missions and programs should then be set at agency approved levels. The E/PO funds should then be allocated to selections from the portfolio of approved program and product templates and/or competed, if existing program and product templates are not sufficient.

The portfolio of approved product and program suites should be developed using existing successful E/PO efforts as models, as well as taking advantage of best practices in formal and informal education. It is very important that these be developed through collaboration between the Science Directorate and the Office of Education. It also very important that PIs funded by the Science Directorate play a significant role in the choice of allocation of their E/PO funds to the products and program suites approved by the Science Mission Directorate and developed in collaboration with the Office of Education.

Sustained public engagement with, and support of, the Exploration Vision will be essential to NASA's success over the next 30 years. The SSSC community is excited to collaborate in the E/PO efforts designed to bring the public along on the Vision for Space Exploration. Progress in SSSC science will not only enable the safe and productive transit and landing of human and robotic explorers on other planets and planetary bodies in our Solar System; but will also advance our capacity to mitigate hazardous space weather impacts and global climate change at Earth; and, continue to open new frontiers of scientific discovery about the Earth, the Solar System and the Universe.

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F. External Cost Drivers Beyond Our Control

Scientists and engineers working on Sun-Solar System Connection science have overcome many of the problems of building, flying, and operating space missions. But our science is affected by factors beyond the control of the community. Each is founded on rational decisions made by groups in the larger society which we work within. Like Reinhold Niebuhr, we need "*the serenity to accept the things [we] cannot change, the courage to change the things I can, and the wisdom to know the difference.*"

SPACE LAUNCH COST IN THE FREE MARKET. The single largest cost in most space missions is the launch vehicle. Unlike other technologies, the cost to orbit a kilogram has been nearly constant over the past decade. Why is the cost per mass so expensive? Space launchers are the most difficult challenges in engineering and manufacture because the forces and energies present in a launch vehicle are so high that they prevent graceful failures. From 1988 to 1999, 4% of launches failed in ways that required their destruction to insure public safety; as an Aeronautics and Space Engineering Board report states "*Destruct commands are often superfluous because vehicles explode or break up because of dynamic forces*." In the early years of spaceflight, NASA solved this problem by building duplicate satellites, so that one might succeed if another failed. Today the response of the users has been to emphasize reliability of a small number of satellites.

The commercial space market provides about half of the global demand for launch vehicles. The 2004 FAA/COMSTAC forecast of commercial demand shows that the launch rate is static at ~22 per year from 2000 until 2013. The principal change has been the demand for very large satellites, with the average mass per satellite growing from 2,400 kg in 1993-94 to 4,100 kg in 2003-04. The recent development of EELVs by the DoD suggests that their needs are similar to those of the commercial market. Some of the other Federal space activities, including NASA, also need large spacecraft and launchers. Taken together, the manufacturers of space launchers have good reason to focus on larger vehicles. The constant, small numbers of launches prevents economies of scale. To recoup the high development costs of new launchers, it is desirable to stop the production of older, smaller vehicles. Opportunity for small, simple, inexpensive, or risky payloads is absent when only large, expensive vehicles are available. Only large, expensive spacecraft make economic sense.

Yet, many NASA science missions can be accomplished with much smaller, less costly spacecraft. The SMEX, MIDEX, Discovery, ESSP, and New Millenium mission lines are all highly productive and depend on smaller vehicles.

PUBLIC TRUST AND RISK TOLERANCE. NASA provides the visible demonstration of the value of American technological society to solving grand problems. The inspiration provided by a great success such as the Mars Rovers is matched by the disappointment and concern attached to failures of other missions. Success and failure are visible and owned by the American public.

Personal freedom is one foundation of American society. We accord individuals the right to pursue activities that have significant risk of failure, even injury or death, as a price of that freedom. These private risks, taken voluntarily, are accepted. Risk in systems supported or controlled by tax funds is not accepted. Public safety and fiscal responsibility require detailed investigation to determine causality and future improvement. Examples include airline or other controlled transportation accidents, military accidents, and NASA accidents.

NASA missions are growing in size, cost, and complexity. Growing complexity drives a compounding of levels of risk management, including detailed process control, frequent reviews, and larger requirements on project management. Risk management seeks to minimize avoidable failures which impose delay and unplanned costs on all missions because they share common technologies independent of their science focus. As with other complex aspects of our society, the cost of risk management is an increasing fraction of the total.

Yet, risk is a critical part of the process of learning to succeed. NASA fosters future success by offering broad range of projects and missions to permit new generations to learn through trial and error, and help the best progress to larger projects. The desire to minimize risk must be tempered by a desire to maximize success.

NATIONAL SECURITY. Space technology provides unique contributions to national security, in reconnaissance, navigation, and communication (and space weather effects on such systems). American technological advantages over potential adversaries drives restrictions on civilian space interactions with foreign collaborators. Recent increases in these restrictions, founded in the International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR), apply even to interactions with friendly nations. NASA has accorded Principal Investigators (PI) freedom to involve foreign collaborators. The cost of these positive foreign interactions is increasing to insure the required compliance with ITAR/EAR restrictions. One result is decreased opportunities for the cost-sharing of space missions.

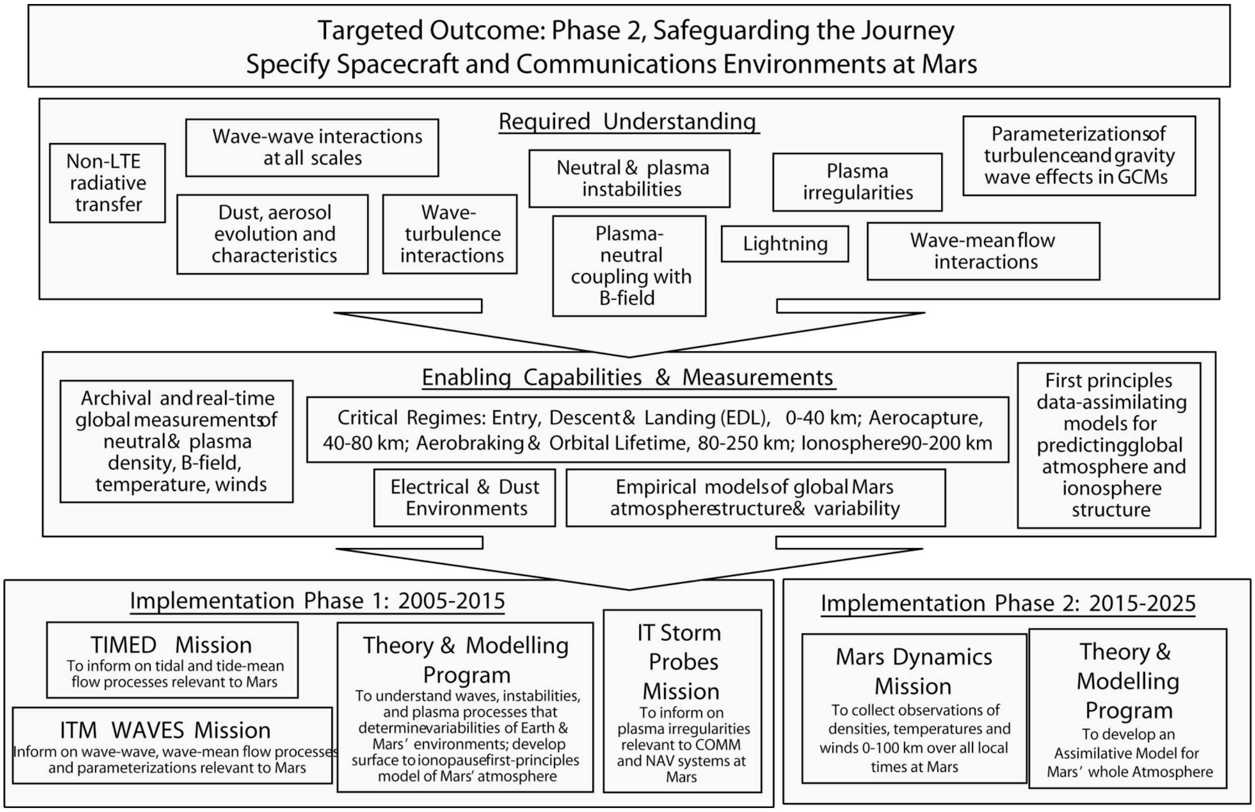
Yet, foreign contributions, such as the Huygens lander on the Cassini mission, have improved the quality of many science missions. Strengthening the technical teamwork between the U.S. and our partners permits activities that could not be achieved separately.

NASA AND EXTERNAL FACTORS. These problems are opportunities for NASA leadership. Fiscal responsibility, scientific and technological opportunities are strong arguments for working to maintain a range of launch vehicles, both large and small. This is a Capability important to NASA.

The public and future scientists are inspired by spaceflight because it challenges us to advance the limits of our abilities. Engaging the public in the challenges and inherent risks of pioneering spaceflight and exploration is an opportunity for E/PO on these issues in modern systems. NASA's work with its communities to develop the most cost-efficient methods for appropriate risk management of complex space projects is a Capability that can improve many areas of our technical society and economy.

Foreign collaborations add value that advances America's space goals. Aiding its projects to achieve cost-effective compliance with ITAR rules is a Capability important to NASA. Continued dialog and negotiation between NASA and the other relevant agencies to develop and clarify more appropriate rules for space research missions will enhance those agencies' Capability for dealing with other critical technical issues.

G. Example Requirements Flow Down



H. Candidate Mission Reference List

SSSC utilizes several mission resources. Strategic fundamental science missions are executed as **Solar-Terrestrial Probes (STP)**, The **Living With A Star (LWS)** mission line is also strategic, dedicated to research on understanding and mitigating effects of space weather. **Explorer (EXP)** missions are smaller than the others and present opportunities for open competition to address scientific investigations that are relevant and timely. Some missions receive external **(EXT)** funding, either from other parts of NASA, other agencies, or other national entities. Below, we list & define acronyms for SSSC mission candidates, and categorize them, to the degree possible at this time, according to these mission lines.

Acronym	**Mission Name**	**ProgramLine**
AAMP	Auroral Acceleration Multi-Probe	STP
AIM	Aeronomy of Ice in the Mesosphere	EXP
DBC	Dayside Boundary Constellation	STP
FS	Far-side Sentinals	LWS
GEC	Geospace Electrodynamics Cluster	STP
GEMINI	GEospace Magnetosphere-Ionosphere Neutral Imagers	STP
	Heliostorm	STP

HIGO	Heliospheric Imager and Galactic Observer	STP
IHS	Inner Heliospheric Sentinals	LWS
IP	Interstellar Probe	STP
ITImager	Ionosphere-Thermosphere Imager	LWS
ITMC	Ionosphere-Thermosphere-Mesosphere Coupler	STP
ITMW	Ionosphere-Thermosphere-Mesosphere Waves	STP
ITSP	Ionosphere-Thermosphere Storm Probes	LWS
JPO	Jupiter Polar Orbiter	TBD
	L1 Earth-Sun	TBD
LRO	Lunar Reconnaissance Orbiter	EXT
	Mars Aeronomy/Mars Dynamics	TBD
MC	Magnetospheric Constellation	STP
MSL	Mars Science Laboratory	EXT
MMS	Magnetospheric MuliScale	STP
MTRAP	Magnetic TRAnsition region Probe	STP
NO	Neptune Orbiter	TBD
Na	Pluto/Kuiper	TBD
RAM	Reconnection and Micro-scale	STP
RBSP	Radiation Belt Storm Probes	LWS
SCOPE	Solar Connection Observatory for Planetary Environments	EXT
SECIP	Sun-Earth Coupling by Energetic Particles	STP
SHIELDS	Solar Heliospheric & Interplanetary Environment Lookout for Deep Space	TBD
SI	Stellar Imager	STP
SDO	Solar Dynamics Observatory	LWS
	Solar-B	EXT
Na	Solar Orbiter	EXT
SP	Solar probe	TBD
Na	Solar Sail Demo	TBD
SPI	Solar Polar Imager	STP
STEREO	Solar-TErrestrial RElations Observatory	STP
SWB	Solar Wind Buoys	TBD
TE	Titan Explorer	EXT
Na	Telemachus	STP
THEMIS	Time History of Events and Macroscale Interactions during Substorms	EXP
VAP	Venus Aeronomy Probe	TBD

I. Mission Descriptions

Near-Term Missions

Aeronomy of Ice in the Mesosphere (AIM)

The primary goal of the Aeronomy of Ice in the Mesosphere (AIM) mission is to resolve why Polar Mesospheric Clouds (PMCs) form and why they vary. In addition, AIM will determine the mesospheric response to solar energy deposition and coupling among atmospheric regions. AIM will measure PMCs and the thermal, chemical and dynamical environment of the upper atmosphere. This will allow the connection to be made between the clouds and the meteorology of the polar mesosphere as well as to examine how this region of the atmosphere responds to solar forcings. These connections are important because the significant observed variability in the yearly number of PMCs, has been suggested as an indicator of global change. Confounding our ability to understand PMCs as a global change indicator are fundamental limitations in our understanding of how these clouds nucleate, the environment in which nucleation occurs, and how the mesosphere responds to both lower atmospheric and extraterrestrial forcing. PMCs are significantly driven by variations in solar irradiance which through photolysis alters the amount of available water vapor to form clouds; however, there remain unexplained time lags between the solar forcings and the response in cloud formation. The simplest models of PMC formation suggest that super-saturated conditions must be present before nucleation occurs. However even this hypothesis remains untested because we have no comprehensive knowledge of the chemical/ thermal environment in which PMCs form. This environment is known to undergo significant variation in composition and structure in response to solar photon and particle energy inputs.

AIM is a critical mission for the SSSC community because it will examine the relative contributions of solar and anthropogenic effects that cause change in the upper atmosphere and it will examine long term change. AIM is also important because it will make key observations of solar energetic particle induced effects on upper atmospheric composition, in particular of odd-nitrogen compounds and ozone. The body of data collected by AIM will provide the basis for a rigorous study of PMCs that can be reliably used to study past PMC changes, present trends and their relationship to global change as well as critical knowledge regarding the response of the upper atmosphere to solar variability. In the end, AIM will provide the basis for the study of long-term variability in the Earth's upper atmosphere and climate.

AIM is a top priority in view of current heightened scientific and public interest in PMCs and the immediate need to understand how the upper atmosphere responds to variable solar energy inputs such as solar storm events. PMCs attained the highest degree of U.S. public awareness in history, with the remarkable sighting on June 22-23, 1999 of a large PMC at locations (Colorado and Utah) where they have never before been seen. Other low latitude PMCs have also been seen since this first observation. While PMCs are often observed in the polar summer mesosphere, the sudden occurrences of such dramatic low latitude displays were unexpected. Dozens of news accounts have appeared in the media. The fact that people in highly populated areas can now view NLCs coupled with their potential relationship to solar variability and global change, highlights the importance of understanding their formation. In addition, the largest odd nitrogen input to the upper stratosphere due to energetic particles ever observed occurred in April, 2004.

Geospace Electrodynamic Connections (GEC)

GEC will determine the fundamental processes of how the ionosphere and magnetosphere are coupled. The upper atmosphere is the final destination of the chains of fields, particles and energy that start at the Sun, transit the heliosphere, and are modified by the magnetosphere and upper atmosphere.

We understand little about how these chains affect and in turn are dependent upon the upper atmosphere due to several factors: first, the energy inputs vary rapidly in space and time; second, we have only sparse measurements of the low altitude atmospheric transition region where the energy dissipation is greatest; and third, the altitude transition from collision-dominated to collision-free phenomena is complex. To transform and inform our understanding of this fundamental question a formation of 3-4 spacecraft must be sent to resolve the spatial structures and time variations, repeatedly and systematically, into the depths of the atmosphere to this transition region: 130 to 180 km. The spacecraft must have complete instrument packages that measure both the magnetosphere energy/momentum inputs at high latitudes and the atmosphere-ionosphere responses. GEC will transform our understanding of the chain of events from the sun to the atmosphere by providing for the first time, comprehensive, collocated, simultaneous atmospheric measurements, the models with which to interpret them, and context setting measurements of the Sun, heliosphere, and magnetosphere. These questions cannot be addressed without actually making the in situ observations. GEC does this using proven technologies, such as formation flying, to unravel the spatial and temporal coupling of the transition region phenomena in a reconfigurable observatory.

GEC will transform our understanding of fundamental processes in the upper atmosphere. It will also enable practical applications relevant to Protecting our Home in Space, and the Outward Journey. During magnetic storms, energy and momentum are transferred from the magnetosphere to the upper atmosphere, resulting in dramatic global changes of temperature, neutral density, composition, winds, and electron density. At the Earth, these changes affect satellite orbits, spacecraft maneuvers (such as docking), and degrade predictions of orbital debris impacts on manned spacecraft such as the Shuttle, Space-Station, and the future Crew Exploration Vehicle. The ionospheric changes can lead to outages for radio-based systems, so that communications with satellites, astronauts and spacecraft within and outside Geospace can be completely disrupted for many hours. Dipping the spacecraft from the collisionless to the collisional regime provides an analog for aerobraking and aerocapture operations at Mars.

The GEC mission is the highest priority for the Solar Terrestrial Probe line because the fundamental science questions it will address are compelling and urgent. Under current NASA funding guidelines, it is planned for launch in 2017, with a two -year prime mission lifetime. It is possible that GEC will overlap with the ITSP mission, with corresponding synergies that are discussed under the ITSP description. However, each mission provides unique measurements and insights, and neither one should be delayed for the sake of overlap.

Farside Sentinel

Farside Sentinel, a mission with a spacecraft placed at 1 AU viewing the far side of the Sun, will provide new knowledge about the solar dynamo, solar activity, and the dynamic space environment in general. It contains both remote sensing and in situ instruments. Remote sensing instruments include a magnetograph-Doppler imager and a radio science package for coronal sounding. Its location at about 180 degrees from Earth allows, in conjunction with similar observations from near Earth, helioseismological measurements of the deep interior flows that are thought to drive the dynamo. The magnetograph will provide more longitudinal coverage of the Sun so that the evolution of solar magnetic fields and active regions can be observed for longer times. Farside Sentinel also provides an additional in situ observation post for the space environment. The in situ instrument package would be similar to that on the STEREO spacecraft. This mission provides information crucial for understanding fundamental processes (Objective F) and for developing the capability to predict the space environment. Farside will aid predictions of space weather and provide inputs for SWB, MARS, and high-latitude solar observatories. While it would be advantages to have this (or the SHIELDS) mission earlier, it was placed in Phase 3 because it was considered lower priority.

HELIOSTORM

The Heliostorm mission would measure the solar wind and heliosphere state "upstream" of the Earth and Moon. Through the use of breakthrough solar sail technology, it would fly 50% further from the Earth (farther upstream) than the current ACE measurement at the Earth-Sun L1. A set of in-situ measurements then would provide 50% greater warning time (compared to ACE) of CMEs and shock-accelerated energetic particles. In conjunction with other assets outside the Earth's magnetosphere, the mission would determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes.

Heliostorm safeguards our outward journey by providing an input that is absolutely vital to the prediction of space weather in cislunar space. Astronauts on the lunar surface will benefit greatly as the enhanced warning time will permit reaction to actual upstream conditions measured remotely by Heliostorm. The solar wind input to the Earth is required by all models of the Earth's magnetosphere, and would be provided by Heliostorm or a conventional L1 monitor.

Heliostorm could be flown 5-6 years after a successful Solar Sail Flight Validation (Sail Demo). Heliostorm (or a conventional L1 monitor) must be flown in time to replace the current ACE/Wind configuration. This suggests a launch in the 2016-2020 timeframe.

Inner Heliospheric Sentinels

How do things evolve and interact as they travel from the Sun to Earth? The four Inner Heliospheric Sentinel spacecraft flying in various formations will detect how structures change in space and time during the transit. IHS investigations will discover, model, and understand the connection between solar phenomena and geospace disturbances.

Interactions in interplanetary space make the linkage between point sampled 1 AU measurements and their solar sources difficult or impossible. IHS science is important to understanding which disturbance will be geoeffective and for developing predictive capability. The interactions relate to particle acceleration, the drivers of space weather and characterization of the extreme conditions near Earth and throughout the heliosphere.

Most space weather evolves as it passes through the inner heliosphere. Understanding this influential region of space is required for safe and productive use of space. IHS should fly in conjunction with SDO and will contribute to understanding gained by the Geospace Storm Probe missions. In an extended mission they will provide essential information about material that eventually reaches SWB or other spacecraft at 1 AU and beyond

Ionosphere-Thermosphere Storm Probes (ITSP)

The ITSP mission investigates the spatial and temporal variability of the ionosphere at mid-latitudes. ITSP combines imaging and *in-situ* measurements of the I-T system, and physics based models to inform our understanding. Two LEO satellites, in different local time orbits are required to determine how electric fields, thermospheric winds, and composition vary with local time, and generate dramatic changes of electron density in the main ionospheric layer during storms. An IT imager will fly as a Mission Of Opportunity on another spacecraft to support the LEO measurements by observing global composition changes.

Since before the Space Age we have collected ionospheric data. To meet the needs of tomorrow and to go beyond an understanding of the climatalogical behavior of the ionosphere we need to make simultaneous, collocated comprehensive measurements of the global behavior of the IT system. The scientific questions addressed by ITSP have direct relevance to the Vision for Space Exploration and to the needs of society. When we prepare to go to Mars, we must be able to land with precision and communicate with assurance. ITSP informs the design of systems for precision navigation and communication without requiring that we build at Mars the equivalent of the Earth’s network of ionospheric observatories. The FAA must develop a GPS-based robust system for automated landings at airports (Wide Area Augmentation System - WAAS). Under disturbed conditions GPS location errors of meters are not uncommon: but we don’t know under what conditions these errors are likely to occur. The FAA needs the ionosphere to be better characterized so that WAAS can become operationally reliable and available. ITSP will allow us to characterize, understand, and predict plasma density gradients that degrade augmented GPS systems, and lead to the mid-latitude ionospheric irregularities which produce scintillation of radio signals.

The ITSP mission is the highest priority in the LWS line because of the urgent need for understanding the internal and external couplings that drive the mid-latitude ionosphere. ITSP was designed to overlap with the SDO and RBSP missions flying in the 2008-2015 timeframe. The EVE instrument on SDO was assigned to provide solar EUV irradiance measurements to support the I-T science of ITSP specifically to understand the temporal variability of the source term for the ionosphere. The RBSP mission will measure electric fields and energetic particles in the inner magnetosphere that map down to the mid-latitude ionosphere, with dramatic consequences for positive-phase ionospheric storms that develop in the afternoon and evening sectors. The current schedule places ITSP at solar maximum and in the declining phase of the solar cycle – times when the ionosphere is both enhanced and disturbed. ITSP will fly during the phase of the solar cycle that is the most stressing both from the standpoint of technical systems and models. ITSP results will be available in time to guide the concept of operations for precision landing on Mars and communications (surface-surface and surface-space).

Another geospace mission (GEC) was selected as the top priority in the Solar Terrestrial Probe line. Under current NASA funding guidelines, GEC would launch in a similar timeframe (2017 with a two year lifetime) to ITSP, so the missions would potentially overlap. This was not originally planned, but various factors affecting NASA budgets and delays in the ITSP and LWS lines led to the present situation. The GEC mission is focused on very different scientific objectives in a different altitude and latitude regime from ITSP. Each mission provides scientific insight that is unique. An overlap in the mission timeframes provides synergistic opportunities because GEC measures the high latitude drivers that contribute to the middle and low latitude response measured by ITSP. However, because of the urgency of each of these missions, each should fly as early as funding permits, regardless of any loss of overlap with the other.

L1-Earth-Sun

The L1 mission will provide the first comprehensive and continuous observation of the Earth’s whole dayside atmosphere, together with measurements of the contributions to the critical solar spectral irradiance that drive the upper atmosphere. Changes in solar UV brightness and spectrum affect the chemistry, dynamics and temperature of the Earth's outer atmosphere, affecting satellite drag and indirectly influencing the amount of energy absorbed by land and oceans. UV absorption leads to important processes including photoionization of N_2, O_2, NO, and O at wavelengths below 1300 Å, and is the main source of energy for ionization and heating of the ionosphere. Knowledge of the solar spectral irradiance is critical for understanding climate variability and for isolating external variations from human made and innate climate variability. Understanding the Sun's EUV spectral irradiance and variability requires not only irradiance time series but also spatially resolved radiance observations of solar features at all temperatures/formation heights simultaneously, to compare with radiative transfer models of the solar surface.

The Earth-viewing portion of the mission consists of a combination of spectrometers in an extended wavelength range (58 nm to 2.4 mm), with high spatial resolution on the entire sunlit Earth disk. The solar portion of the mission consists of a UV/soft x-ray irradiance spectrometer, an imaging bolometer, and a UV/EUV imaging spectrograph to explain the irradiance phenomena that affect Earth's atmosphere by providing identification and realistic assessment of the contributions of evolving solar activity features to total spectral irradiance. The mission also includes magnetometer capable of high time resolution measurement of magnetic field fluctuations and shocks, and two energetic particle analyzers capable of measuring energy resolved charged particle spectra.

By observing simultaneously the Earth, the Sun, and the solar wind, the L1-Earth-Sun mission will enable the first detailed exploration of the couplings within the Earth-Sun system. It fulfills a fundamental and critical need in the S3C Strategic plan with cross-cutting synergistic objectives relevant to understanding fundamental processes which influence Earth's climate as well as strong relevance to the Vision for Exploration by improving our understanding necessary for solar activity prediction and its impact on the Earth.

The L1-Earth-Sun mission should fly in the early part of Phase 2 in order to maximize overlap with SDO and GEC. SDO provides complimentary information regarding solar energy deposition while GEC provides in situ observations of the Earth's upper atmosphere that strongly compliment and partially validate the L1-Earth-Sun remote observations. Flying L1-Earth-Sun in early Phase 2 also permits the timely replacement of key existing assets at L1.

L1-Mission

In situ observations from the Earth-Sun L1 point are essential to understanding geospace and provide about one hour of warning of disturbances traveling toward Earth in the solar wind. The most important quantities are particles and field detection. Additional capabilities can include radio sensing, composition and high-energy particle detection, and even solar observations, though these can often be accomplished from other vantage points.

Without upstream information the state of the magnetosphere cannot be understood. Models of propagation in the inner heliosphere need a reference at 1 AU against which to test their models. Spatial variations in structures around L1 is not well understood. There needs to be data from L1 at all times to provide adequate warning for many operational users in addition to NASA scientists.

The timing of this mission depends upon future assets launched by NASA and other agencies and the continued functioning of existing spacecraft. The existing Great Observatory provides L1 observations and some future mission must do the same. Partnerships may be the preferred method for satisfying the need for observations from L1. The possible flight of Heliostorm, an Earth Science L1 mission, or collaboration with the IH Sentinels or SWB missions may provide additional options.

Magnetospheric Multi-Scale

MMS will determine the fundamental physical properties of magnetic reconnection. It is a four spacecraft mission designed to study magnetic reconnection, charged particle acceleration, and turbulence (cross-scale coupling) in key boundary regions of the Earth's magnetosphere. The primary goal of the mission is to use high time resolution, *in situ* plasma and fields measurements to determine the micro-scale processes in the exceedingly small (perhaps <100 km thick) diffusion region, where the electrons in a plasma become decoupled from the magnetic field, and the field reconnects. The close spacecraft spacing will also enable exploration of the cross-scale coupling of plasma turbulence in the Earth's magnetosheath, at the magnetopause, and in the magnetotail. Finally, charged particle acceleration processes associated with magnetic reconnection, turbulence, and electric fields in the outer magnetosphere will be determined using direct measure of the plasma and waves that cause the acceleration.

Magnetic reconnection is a primary source of energy release and particle acceleration in plasmas.

No mission has ever been properly instrumented and configured to measure the small-scale features of reconnection in space. Thus, we know little about this fundamental process that drives much of the activity on the Sun, near Earth, and throughout the Solar System.

MMS was recognized as by the Decadal Survey report as the highest priority mission for the Solar-Terrestrial Probes strategic line. A SWRI-led team successfully proposed to build and operate this mission, and they are just beginning Phase B development.

Radiation Belt Storm Probes (RBSP)

The RBSP mission focus is to understand the variability and extremes of energetic radiation belt ions and electrons by identifying and evaluating their acceleration processes and transport mechanisms plus identifying and characterizing their sources and losses. These particle populations respond to interplanetary structure and environment changes in the form of shocks, CMEs. SEPs and changes in the solar wind and interplanetary magnetic fields. Those responses are generally denoted as magnetic storms and substorms and ultimately involve the whole of geospace from the upper atmosphere to the boundary with the solar wind. The RBSP instruments provide comprehensive measurements of the particle phase space densities plus the local AC/DC magnetic and electric fields in the inner magnetosphere where the intense radiation belts reside. RBSP provides one link in the chain of evidence that tracks the Geospace response to solar and interplanetary sources and variability. ACE, TWINS, SDO,MMS, ITSP and IHSentinels will fill in many of the other links. Flying together, as we hope they will, would provide a nearly complete picture of geospace, its the external environment and the its responses to solar variability and evolving interplanetary plasma and field structures.

RBSP consist of two small satellites in “chasing” elliptical orbits with low perigees, ~ 5.5 R_E , geocentric, apogees and slightly different orbital periods. The different periods generate an orbital evolution that provides both variable radial separations in the same local time frame and local time separations at a range of constant radial distances to separate space-time effects in the radial transport and azimuthal drifts of the particles.

RBSP is important to objectives H and J because it provides the observations needed to characterize and develop models of the near Earth space weather. Its data will form the basis for specification of the near Earth radiation environment and its variability on a time scale that meets the needs of the Exploration Visions early operations near Earth. These data will provide a measure of the magnetospheric energy inputs to the ionosphere and atmosphere important to space station and crew vehicle communications, reentry and atmospheric drag induced orbit variations. In addition, RBSP observations will also provide new knowledge on the dynamics and extremes of the radiation belts that are important to all technological systems that fly in and through geospace. This includes many platforms that are important to life and society as we rely ever more on space platforms to link us together through communications, to provide Earth resource data and to provide entertainment streams. It is also very important that we understand the space weather in geospace because it can impact the many US space assets play a role in our national security. Without that security, there will be no other missions.
The Solar Sail Flight Validation or "Sail Demo" would validate the processes and analytical models required to make solar sails a practical propulsive option for science missions. The Sail Demo would: deploy in a near-Earth orbit, a solar sail that is > 40 m in edge length; correlate structural performance with models; validate its attitude control; and measure acceleration from the sail.

Solar-B

Solar-B will reveal the mechanisms of solar variability and study the origins of space weather and global change. NASA is a 1/3 partner with the Japanese space agency (JAXA) on this mission to investigate the detailed interactions between the Sun's magnetic field and the corona. High resolution observations of active region on the photosphere together with an X-ray telescope and imaging spectrograph will help understand the creation and destruction of magnetic fields, variations in solar luminosity, generation of UV and X-radiation, and the dynamics of the solar atmosphere.

Solar B addresses most of the expected achievements in Phase 1: reconnection, the mechanisms of particle acceleration near the Sun, the origins of solar disturbances, understanding of the sources of irradiance variations, causes of the extremes in the local environment, and prediction of space weather. Many Phase 2 topics are also covered.

Solar B complements SDO, STEREO, and SOHO by providing high resolution imaging and understanding of detailed mechanisms of variability. The essential next step in understanding the origins of solar activity requires the high resolution data from Solar B.

Solar Dynamics Observatory (SDO)

SDO will help us to understand the mechanisms of solar variability by observing how the Sun's magnetic field is generated and structured and how this stored magnetic energy is released into the heliosphere and geospace. SDO's goals are to understand the solar cycle, the transfer of energy through the solar atmosphere, and the variable radiation output of the Sun. SDO measures subsurface flows, photospheric magnetic fields, high-temperature solar atmospheric structures, and the extreme ultraviolet spectral irradiance that affects Earth's atmosphere.

Solar magnetism drives the variability that causes most space weather. Helioseismology measures the internal causes of activity. Photospheric and coronal observations trace the evolution of magnetic field structures and the origins of disturbances. The upper atmosphere is highly sensitive to solar EUV variability. SDO's investigations are essential to many phase 1 and 2 achievements relevant to all three SSSC Objectives.

SDO needs to fly immediately to provide crucial understanding of solar activity, the solar cycle, and the inputs to geospace. Predictive modeling cannot improve without the improved data SDO will provide. SDO is an essential replacement for the aging SOHO spacecraft.

Solar Sail Demo

Because of the inability to fully validate this technology on the ground, the application of solar sails to a strategic science mission absolutely requires a prior successful flight validation. Such a Sail Demo (40-m edge length, 25 g/m^2) could be readily scaled then to fit the needs of the Heliostorm mission (100-m edge length, 14 g/m^2). Once a mission in the class of Heliostorm has flown, further scale-up could be accomplished for Solar Polar Imager (160-m edge length, 12 g/m^2). A further, third generation solar sail would be required for a visionary mission such as Interstellar Probe.

The flight of a Sail Demo must precede the first strategic launch by 5-6 years. A Sail Demo mission in mid-2010 would permit the flight of Heliostorm in 2016 or thereafter. Approximately 5 years would then be needed after Heliostorm to enable the scale-up to Solar Polar Imager.

Solar Orbiter

Solar orbiter is a European Space Agency (ESA) mission with U.S. participation that will fly as close as 45 solar radii to the Sun in order to study the solar atmosphere with unprecedented spatial resolution (~100 km pixel size). Its science goals are to characterize the properties and dynamics of the inner solar wind, to understand the polar magnetic fields using helioseismology, to identify links between activity on the Sun’s surface and coronal disturbances using co-rotating passes, and to fully characterize coronal regions from high inclination orbits. Using Venus gravity assists, the orbital inclination will shift over time providing the first high latitude views of the solar poles. Solar Orbiter will provide key components to NASA's LWS program by understanding the causes of Space Weather and thus will answer science questions of Objective H. It will also provide data to increase our fundamental understanding of particle acceleration and the role of the solar dynamo in structuring the solar magnetic field (Objective F). Both science areas are essential in developing a short and long term predictive capability for the Exploration Vision (Objective J). Solar Orbiter is positioned to fly in the 2015-2025 (Phase 2) time frame which will coincide with Inner Helisopheric Sentinels to continue the system science of our Great Solar Observatory.

SOLAR PROBE

Solar Probe is the first flight into the Sun's corona, only 3 solar radii above the solar surface. Solar Probe's instruments measure plasma, magnetic fields and waves, energetic particles, and dust that it encounters. They also image coronal structure surrounding Probe's orbit and in polar structures at the coronal base. Probe makes two passes into the corona, separated by 4.5 years, exploring why the corona changes its whole form over the solar cycle.

The corona is heated to millions of degrees by poorly understood processes governed by its magnetic field. The UV radiation from the hot solar atmosphere affects the chemistry of the atmospheres of the Earth and other planets. The boundary where the corona accelerates to the solar wind governs the heliosphere and its interactions with the planets and the interstellar medium. That boundary is also critical to the release of solar disturbances that travel throughout the solar system, to the Earth and other planets, producing energetic particle events and magnetospheric storms. Probe will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity. Accurate prediction of events that disturb the Earth's human systems and deepspace explorers require this understanding.

One factor sets the placement of Solar Probe in the Roadmap: Probe is the most technically challenging mission attempted. It must function in the cold and intense particle radiation of its orbit-shaping flyby at Jupiter, and in the heat and high-speed dust impacts of the solar corona. The path to meet the technical challenges is now well defined and Solar Probe is ready for a mission start. Probe can only be achieved with specific budget augmentation because the work to ensure surviving its difficult environment keeps it more costly than any line mission.

STEREO

The Solar-Terrestrial Relations Observatory (STEREO), to be launched in 2006, will describe the 3-D structure and evolution of coronal mass ejections (CMEs) from their eruption on the Sun through the inner heliosphere to Earth's orbit. The mission will employ remote sensing and in situ measurements from two spacecraft drifting in opposite directions away from the Earth at 1 AU to triangulate CME-driven shocks, detect preceding shock-accelerated particles, and analyze in situ CME and solar ejecta signatures, including heavy ion mass and charge states. In addition, as the spacecraft reach large separations, one spacecraft will observe the propagation of CMEs that will be directly sampled by the second spacecraft to provide a definitive determination of the relation between the white light and in situ features of a CME. The instrumentation package on each spacecraft includes a coronal and heliospheric imaging package (with an EUV imager, two coronagraphs, and heliospheric imager)s, a set of radio wave receivers, and an array of in situ measurements for measuring the solar wind, energetic particles, and interplanetary magnetic fields. This mission will provide not only fundamental knowledge about the 3D structure and propagation of CMEs, but also provide important information on CME-shock-accelerated particles, constributing to the characterization of the space environment. This mission is a high priority for SSSC science because of the central role of CMEs in determining "space weather."

TIME HISTORY OF EVENTS AND MACROSCALE INTERACTIONS DURING SUBSTORMS (THEMIS)

THEMIS is a MIDEX Explorer mission that addresses the spatial and temporal development of magnetospheric substorms. The mission consists of 5 identical spacecraft and a array of ground-based all-sky cameras. The cameras are a mission-critical element of THEMIS, providing a global context for the in situ measurements and also detecting auroral substorm onset for mission operations decisions. When the spacecraft are on the dayside, it will address the question of solar wind control of the magnetosphere and the coupling of energy across the various dayside boundaries.

THEMIS addresses the issue of onset and evolution of the substorm instability, an explosive yet fundamental mode of the magnetosphere. This was identified by the National Research Council as one of five main strategic questions in space physics.

The mission was selected in the last MIDEX proposal solicitation and is currently in Phase C/D development.

The Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS)

TWINS provides stereoscopic viewing of the magnetosphere by imaging charge exchanged energetic neutral atoms (ENAs) over a broad energy range (~1-100 keV) using identical instruments on two widely spaced high-altitude, high-inclination spacecraft. TWINS will enable a 3-dimensional visualization of large scale structures and ion dynamics within the magnetosphere. The TWINS instrumentation is essentially the same as the MENA instrument on the IMAGE mission and provides a 4°x 4° angular resolution and 1-minute time resolution ENA image. In addition, a simple Lyman-alpha imager is used to monitor the geocorona. The first TWINS spacecraft may overlap with the IMAGE mission, providing an early (2005-2006) opportunity for magnetospheric stereo imaging that could evolve into three spacecraft imaging with the launch of the second TWINS in 2006.

TWINS will provide a 3D view of the ring current ions in the magnetosphere. These ions carry much of the energy and most of the mass into and through geospace. Different from in situ observations, TWINS will provide a dynamic picture of the whole geospace system with a cadence that resolves the radial and azimuthal ion motions. The in situ measurements provided by RBSP, MMS and ITSP, are truth data that can be used to further validate the necessary inversion process that will be applied to the TWINS data to obtain 3D ion flux distributions. These TWINS distributions will provide a global geospace input for space weather models. The 3D ion distributions will enable inferring the inner geospace currents and electric fields which penetrate to low altitudes and high latitudes where they couple energy into the ionosphere-thermosphere system partially driving its space weather.

While TWINS is not a subject of the current roadmap, except as a mission of opportunity element of the Great Observatory, it does support many of the objectives H and J, as can be seen in the discussion above. TWINS value is greatly enhanced if it is flying simultaneously with RBSP, ITSP and MMS. While those missions are to be launched in the next decade, it should be noted that the first of the current sister platforms in the TWINS orbits have been flying since 1994 and will probably be operated for years to come. Thus we expect the TWINS instruments, if they survive, could be operating out through 2015 or so.

Candidate Missions for Phase 2 and Phase 3

Aeronomy and Dynamics at Mars (ADAM)

Aeronomy and Dynamics at Mars (ADAM) will determine the direct, dynamic coupling of a dusty atmosphere with the solar wind. It is a single spacecraft that will orbit Mars, taking in situ and remote sensing data of the upper atmosphere, ionosphere, and solar wind. Instruments will measure the composition, thermal profile, and circulation in the Martian upper atmosphere. Mars Aeronomy will determine the sources and sinks of ionospheric plasma, its coupling to other regions of the atmosphere, and its to the solar wind.

The dynamics, evolution, and fate of the Mars upper atmosphere addresses fundamental science questions as well as providing pertinent information for manned flights to Mars. Aerobraking and aerocapture require a detailed knowledge of the Martian upper atmosphere, as well as an understanding of how and why the atmosphere varies, for hazard prediction and risk mitigation.

This is a high priority mission with direct relevance to the manned flight component of the Vision for Space Exploration. It should be flown as soon as possible in order to allow time for the scientific investigations of the Mars upper atmosphere to progress to a point of transferring the lessons learned from ADAM to the manned flight program with sufficient lead time to impact mission development. Therefore, it should be a Phase 1 or early Phase 2 mission.

Auroral Acceleration Multiprobe

One of the key goals of Objective F is providing the detailed understanding of the processes that accelerate particles to high energies that will be necessary to predict fluxes of high energy particles throughout the solar system. This predictive capability is the goal of RFA J.3. In addition, by providing a better understanding of energetic particles in the Earth's space environment, AAMP is also important to Objective H because it will enable mitigation of impacts on space assets, and, by quantifying the auroral input to the ionosphere/thermosphere, it will improve models of lower latitude composition and variability of the ionosphere, which affect communications/navigation activities. The Auroral Acceleration Multi-Probe (AAMP) mission is designed to provide this understanding by making extremely high time resolution measurements of particle distributions and 3d electric and magnetic fields in situ within the Earth's auroral acceleration region. The auroral acceleration region provides a unique laboratory for the study of acceleration processes, both because it reveals many of the critical processes and because it is readily accessible to measurement. Our basic understanding of particle acceleration in parallel electric fields and kinetic Alfven waves, as well as the structures that support parallel fields, have come from in situ auroral observations. To make the progress required for a predictive understanding requires simultaneous measurements both along and perpendicular to magnetic fields. The AAMP four satellite mission is designed to provide the needed conjunctions through a careful orbit strategy. The AAMP mission will determine how are parallel potential drops distributed and supported in a collisionless plasma; how the coupling of the dense cold ionospheric plasma to hot magnetosheric plasma leads to parallel electric fields; what the role of wave micro- and macro-physics is in auroral acceleration; and how magnetosphere-ionosphere coupling influences acceleration on various scales.

The fundamental understanding of acceleration processes is critical to the NASA SSSC goals and, thus, the mission should be flown as soon as possible. Its placement in the mission queue indicates the need to inform activities that occur in the intermediate time frame.

Dayside Boundary Constellation

DBC will determine the global topology of magnetic reconnection at the magnetopause. It is a network of ~30 Sun-pointing, spinning, small spacecraft, separated by ~1 R_E, that skim both the dawn and dusk sides of the dayside magnetopause. The multi-spacecraft provide simultaneous comprehensive observations of boundary phenomena including turbulence over a wide range of latitudes and local times. Three spacecraft are boosted to have apogee outside the bow shock to provide continuous monitoring of the foreshock-preconditioned solar wind input.

This mission addresses critical unresolved questions about the transfer of energy across the magnetopause boundary. It also will robustly measure the global magnetic field topology on the Earth's dayside magnetopause, something which has not been done before.

MagCon is a precursor mission to DBC, as it will have a constellation of spacecraft in the magnetospheric equatorial plane. Therefore, DBC should be in the Phase 3 mission queue.

DOPPLER

The DOPPLER mission enables improved nowcasting and forecasting of solar activity by providing improved understanding of the physical processes and mechanisms of energy storage and release on the Sun. Measurements of motions and changes in nonthermal velocity distributions in the lower corona and chromosphere are crucial to understanding and separating various models of CME initiation and onset. Depending upon the specific physical process, Dopplergrams and other derived data products are likely to be the most reliable indicators that a specific region is about to erupt. Even without advance warnings, the reliable characterization of near disk-center CME liftoff by means of Doppler imaging would represent a significant improvement in space weather modeling capability. DOPPLER consists of a suite of small, lightweight, moderate resolution spectral imagers (UV/EUV imaging spectrograph, 2 EUV imagers, and a Magnetograph) to detect, observe and study remotely all of the relevant signatures of solar activity responsible for space weather events and disturbances. DOPPLER addresses issues directly relevant to supporting the Vision for Exploration by enabling improved nowcasting and future forecasting of solar activity by identifying and developing new precursor signatures of CME initiation and onset, flare eruption, and flare initiated SPEs.

The DOPPLER mission should fly in the early part of Phase 2 (2015-2020), with overlap with SDO to identify and develop new solar activity precursor signatures necessary to protect astronauts during surface EVAs on the Moon (late Phase 2). The small, lightweight instrumentation developed by DOPPLER would then be available for Phase 3 missions required to provide nowcasting and forecasting capability at Mars and beyond.

Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)

GEMINI is a mission that will provide the first 3-dimensional observations of the global Geospace dynamics in response to external solar drivers and internal coupling. Stereoscopic views of the radiation belt associated ring current and thermal ions of the plasmasphere, simultaneous images of the aurora in both hemispheres, and coordinated ground based observations are used to determine the coupling dynamics between the ionosphere, ring current, and plasmasphere and to discover the important feedback and dissipative mechanisms between these regions. The power of GEMINI is that imaging this complex coupled system to unravel its macro-scale interactions simultaneously provides the global context for correct interpretation of in-situ observations. It is to magnetospheric space-weather what the Solar Terrestrial Relations Observatory is to the solar-wind observations. The discoveries from this mission are applicable to understanding fundamental processes at work not only in Geospace but other magnetized planetary systems and thus are important to Objective F. Global Geospace observations are needed to provide the system level context for nowcasting and prediction of the plasma environment where exploration activities are occurring within Geospace. In addition, these results are significantly augmented when coupled with inner heliospheric and solar disk observations. The conjugate auroral observations are essentially the “footprints” of the magnetosphere and therefore provide the magnetospheric configuration to distances beyond the lunar orbit. For these reasons GEMINI is important to Objective J. Operating GEMINI in conjunction with the RBSP and ITSP missions is ideal as documented in the LWS Geospace definition report. However, even without mission overlap, the system level understanding of the coupling between regions in Geospace that creates, evolves and annihilates radiation belts and how that induces and impacts ionospheric variability is extremely significant to operational space based assets that society has become so dependent on. As such, GEMINI is important to objective H.

Heliostorm

The Heliostorm mission would measure the solar wind and heliosphere state "upstream" of the Earth and Moon. Through the use of breakthrough solar sail technology, it would fly 50% further from the Earth (farther upstream) than the current ACE measurement at the Earth-Sun L1. A set of in-situ measurements then would provide 50% greater warning time (compared to ACE) of CMEs and shock-accelerated energetic particles. In conjunction with other assets outside the Earth's magnetosphere, the mission would determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes.

Heliostorm safeguards our outward journey by providing an input that is absolutely vital to the prediction of space weather in cislunar space. Astronauts on the lunar surface will benefit greatly as the enhanced warning time will permit reaction to actual upstream conditions measured remotely by Heliostorm. The solar wind input to the Earth is required by all models of the Earth's magnetosphere, and would be provided by Heliostorm or a conventional L1 monitor.

Heliostorm could be flown 5-6 years after a successful Solar Sail Flight Validation (Sail Demo). Heliostorm (or a conventional L1 monitor) must be flown in time to replace the current ACE/Wind configuration. This suggests a launch in the 2016-2020 timeframe.

Inner Magnetospheric Constellation

IMC will determine the interaction among the radiation belts, ring current, plasmasphere, and outer magnetosphere. It is multiple spacecraft in at least two ecliptic plane “petal” orbits. Large day/night and dawn/dusk asymmetries exist in the inner magnetosphere and complicate the global specification of particles and fields. Through simultaneous measure of radial and longitudinal variations in the radiation belts, the temporal and spatial asymmetries will be resolved.

The in-situ measurements from these multiple positions allow the construction of comprehensive “weather maps” of the inner magnetosphere (1.5-12 Earth radii) that evolve in response to Sun-induced disturbances. This spacecraft fleet focuses on detailed specification of the orbital environment of most spacecraft and manned missions, to determine in detail the origin and evolution of particle populations and their interaction with the evolving electro-magnetic field during magnetic storms.

These observations extend the radiation belt storm probe results by making simultaneous maps of the radial as well as the longitudinal variations in the radiation belts. It should fly after RBSP, and probably after GEMINI, putting it into Phase 3 of the mission queue.

Ionosphere Thermosphere Mesosphere (ITM) Waves

Gravity and planetary waves play a key role in the upper atmosphere by redistributing energy across geographic and altitude regions. They affect the global circulation and the vertical transport of energy and chemically reactive species. ITM-Waves seeks to understand the sources and sinks of gravity waves, including how they interact with each other, with the neutral and ionized constituents of the atmosphere, and with tides and the zonal mean circulation.

ITM-Waves is an important mission for SSSC because the wave processes it studies are fundamental to the coupling between distinct altitude regions, and to the overall dynamics of the Earth’s atmosphere. These processes play a key role in the response of the atmosphere to solar storms. Gravity waves are also thought to be a critical factor in preconditioning the ionosphere by contributing to the initial conditions necessary for plasma instabilities to form near the magnetic equator, and perhaps also at mid-latitudes. These unstable conditions can result in the formation of large-scale depletions in the plasma density, coupled with small-scale irregularity formation and severe radio wave disruptions. The ITM-Waves mission is designed to provide global characterization of the wave processes that lead to these disruptions, and will thereby enable further development of the theory and models necessary for comprehensive understanding of the phenomena. Insight into these phenomena in geospace may help to mitigate issues related to aero-braking and aero-capture in the Martian atmosphere, so ITM-Waves is pertinent to exploration mission requirements.

ITM-Waves should follow GEC and ITSP as closely as possible in time because these two missions provide key information on how the atmosphere responds to solar energy, storms, and substorms. Together the three missions are synergistic in that they address the overall goal of understanding the Earth's response to solar energy. If possible, ITM-Waves should overlap in time with the Mars Dynamics mission because additional synergies would be created by studying the responses of both atmospheres to simultaneous solar forcing.

Interstellar Probe

Interstellar Probe is the first mission that will leave our heliosphere and directly sample and analyze the interstellar medium. It is a single spacecraft that will use an advanced in-space propulsion system such as a solar sail or nuclear electric propulsion to reach the upstream interstellar medium at a distance of 200 AU within about 15-20 years. This spacecraft will carry the first payload specifically designed to directly determine the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields. On its way, it will provide only the second opportunity after Voyager to directly observe the thick region of interaction between the solar wind and the interstellar medium, from the termination shock to the heliopause and beyond. This region plays a central role modulating the Galactic Cosmic Ray flux and in the creation of the anomalous component and understanding this modulation will help increase the productive and safety of human explorers. Additional advanced instrumentation used en route could determine the nature and chemical evolution of organic molecules in the outer solar system and interstellar medium and measure the cosmic infrared background (CIRB) radiation normally hidden by the Zodiacal dust.

Because this mission is enabled by advanced propulsion, it has been place in Phase 3. The Solar Polar Imager mission would provide a technology demonstration of the solar sail propulsion system needed for Interstellar Probe. It is expected that additional resources would be needed for this mission because of its 15+ year lifetime coupled with the need for advanced propulsion.

Io Electrodynamics

IE will investigate the magnetic coupling and energy conversion process in a unique magnetized plasma situation, while determining the role of Io in Jovian radio emissions. The spinning spacecraft will be placed in an elliptical Io-resonant orbit that provides repeated encounters with the Io flux tubes. A radiation hardened payload of fields and particles instrumentation will complement a UV imager for context observations.

The timing of IE is non-critical relative to the other SSSC missions, but the mission is complementary to other missions that support Exploration of the terrestrial planets, for comparative purposes.

Jupiter Polar Orbiter

JPO will conduct a comparative test of magnetospheric models in a case where planetary rotation is dominant over the solar wind interaction in powering the system.

JPO places a spinning radiation hardened spacecraft in polar elliptical orbit around Jupiter at 75°

inclination. The payload includes fields and particles instruments, planetary imagery and radio science. Measurements will be made of the Jovian auroral acceleration regions and radiation belts, the polar magnetic field and plasma waves. Radio occultations of the ionosphere and atmosphere will determine their characteristics.

JPO timing relative to other missions is non-critical but the mission is highly complementary to other missions that support Exploration of the terrestrial planets, for comparative purposes.

L1 Solar-Climate Explorer

L1SCE examines the mechanisms that potentially link solar variability to changes in Earth's climate via solar irradiance or Earth albedo variations, energetic particle precipitation.

L1SCE measures the spatial, spectral, and temporal variation in the Earth's albedo, while simultaneously measuring the solar photon, electromagnetic, and particle flux incident upon Earth. A platform in Earth-Sun L1 halo orbit provides continuous viewing in both directions for >3 yrs. The payload includes multi-wavelength imaging spectro-radiometer, solar irradiance, in-situ plasma, magnetic field, and energetic particles instruments.

This mission is needed as soon as possible to complement other missions. It represents an interdisciplinary partnership between Sun-Solar System Connections and Earth Science.

Magnetospheric Constellation

Magnetospheric Constellation (MagCon, or MC) will employ a constellation of ~36 spacecraft to describe the temporal and spatial structure of complex processes occurring throughout vast regions of the Earth's magnetosphere. *In situ* plasma, magnetic field, and energetic particle observations, and possibly imaging, will be used to distinguish between nonlinear internal dynamics of the magnetosphere and global responses to varying solar wind conditions. The data will be provided on spatial and temporal scales sufficient to enable close cooperation with state-of-the-art numerical simulations capable of describing where magnetic flux, mass transport, energy conversion, and dissipation occur. By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

Understanding the mass and energy flow in the magnetotail and throughout the rest of the magnetosphere is an unresolved issue of fundamental importance. With the flight of the New Millennium ST-5 mission, many of the technological obstacles of this mission have been addressed. It should be the next STP mission after GEC, which puts it in the Phase 2 mission queue.

Magnetosphere-Ionosphere Observatory (MIO)

MIO will determine the processes that drive auroral arcs. It is a tight cluster of satellites in geosynchronous orbit that are magnetically connected to a ground-based observatory, with a satellite-based electron beam establishing the precise connection to the ionosphere. One of the longest standing problems in magnetosphere-ionosphere coupling is the fundamental question how large-scale processes in the magnetosphere (with spatial scales of many thousands of kilometers) effectively couple to the ionosphere to produce very narrow auroral arcs (with scales less than 1 km). The MIO spacecraft cluster will perform the local gradient measurements required to identify the causal mechanism for generating auroral arcs.

The MIO mission examines the still unresolved relationship between magnetospheric dynamics and auroral arc features. The electron beam explicitly addresses the ambiguities of ionosphere-magnetosphere connectivity. It addresses fundamental scientific questions that are of direct relevance to life and society.

Conceivably, MIO could fly at any time. However, it did not make it in to the mission phasing diagram within the available resources. Therefore, it is part of the Phase 4 mission queue.

Mars Atmospheric Reconaissance Survey (MARS)

The Mars Atmospheric Reconaissance Survey (MARS) mission will provide a robust assessment of the upper atmosphere of Mars to enable safe human space flight to that planet. It will consist of a comprehensive package of in situ and remote sensing instruments to quantify the dynamics and chemistry throughout the Mars atmosphere. It could be one or several spacecraft, depending on what is thought to be needed to resolve the remaining questions about the Mars space environment.

This mission will provide as complete a set of measurements as possible to answer any remaining questions about the Mars upper atmosphere and its interaction with the solar wind before manned flights to Mars begin.

It should fly after ADAM, but before astronauts go to Mars. Therefore, it is part of the Phase 3 mission queue.

MTRAP Mission Description

The primary objective of MTRAP is to measure the build up and release of magnetic energy in the solar atmosphere. MTRAP will measure the vector magnetic field from the photosphere to the magnetic transition region, where the solar atmosphere changes from being plasma to magnetic field dominated. MTRAP will also obtain simultaneous plasma diagnostics of the magnetic transition region with UV/EUV imaging spectrograph neasurements. MTRAP has two orders of magnitude greater collecting area and one order of magnitude improvement in angular resolution over Solar-B and will greatly improve our ability to follow rapid changes in the magnetic field geometry. MTRAP is centered around a very large solar optical telescope with a 6m aperture, providing over 100 times the collecting area and 10 times the angular resolution (0.05 arcseconds) of Solar-B.

MTRAP addresses fundamentally important questions and issues related understanding magnetic reconnection and micro-scale instabilities in the chromosphere/corona interface on the Sun.

MTRAP should fly early in Phase 3 of the STP line (2025-2035), benefiting from knowledge learned from Solar-B and SDO.

RAM Mission Description

The Reconnection and Microscale (RAM) mission is a next generation, high resolution mission focused on understanding the basic small-scale processes in hot magnetized plasmas that are ubiquitous throughout the universe. In hot magnetized plasmas the physical processes governing the dynamics take place on remarkably small spatial and temporal scales. RAM addresses several fundamental questions such as what are the mechanisms and magnetic topology that lead to reconnection, what micro-scale instabilities lead to global effects and how do magnetic stresses form and release in the solar corona? RAM includes a 0.02 arcsec/pixel EUV imaging telescope, a 0.1 arcsec/pixel UV/EUV imaging spectrograph, and a small x-ray calorimeter to perform simultaneous high resolution imaging and imaging spectroscopy to understand the small scale dynamic processes and mechanisms of reconnection on the

Sun.

RAM addresses fundamentally important questions and issues related understanding magnetic reconnection and micro-scale instabilities on the Sun.

RAM should fly as one of the first missions in Phase 3 of the STP line (2020-2025), benefiting from knowledge learned from Solar-B and SDO.

SHIELDS

Solar Heliospheric and Interplanetary Environment Lookout in Deep Space (SHIELDS) is a new mission concept developed specifically in response to the Vision for Exploration to help ensure the safety and productivity of human and robotic explorers. This mission places two spacecraft in fixed locations 120 from Earth in order to view the entire solar surface and to determine the direction of propagation of CMEs anywhere in the inner heliosphere. Remote sensing instruments include coronagraphs (for observing CME onset and propagation), magnetographs (to observes evolution of the surface magnetic fields and active regions) and EUV telescopes (to observe flare activity). Observations of the entire solar surface should help enable the predictability of longer periods that are “all clear”of solar activity (Objective J). The spacecraft would also carry in situ instruments similar to those on STEREO and FARSIDE to observe the CMEs and associated solar energetic particles, also in support of Objective J. This mission could replace the Farside Sentinel by providing the farside views of the Sun. To provide the helioseismology nneded to understand the dynamo and origins of solar activity (Objective F), a Doppler-magnetograph would also be needed. This would be a more costly mission than Farside since it uses two spacecraft, and, at some point the community will decide which of the two to pursue. Like Farside, this mission has been place in Phase 3. It will support RAM, SWB, MARS, high latitude solar observations, and provide inputs for studies of impacts on planets other than Earth.

Solar Connection Observatory for Planetary Environments (SCOPE)

The SCOPE mission will compare the global effects of external and internal driving mechanisms on planet and comet near-space environments through observations of auroral, airglow, coronal, and/or internal plasma emissions. It will differentiate features of Jupiter’s (and other giant planets’) auroral emissions due to internal processes (rotation and internal plasma sources) from those due to solar wind interactions and will measure the response of ionosphere-solar wind coupling to changes in solar activity in planetary systems without magnetospheres (Mars, Venus, Comets). The mission will also refine and expand our knowledge of Earth’s global geospace response by extending auroral observations into new domains of spatial and spectral resolution. A key result will be a data base that can be used to directly compare the terrestrial solar interaction with those of superior (Mars-Neptune) planets from opposition campaigns that monitor both systems along the same Sun-planet line. The data base will also allow mapping of the opacity and velocity structure of interplanetary hydrogen and study of the transition region between the heliosphere and LISM

Measurements will be made using dual meter-class telescopes (EUV & UV) covering bandpasses from 55 – 31 nm. The instruments will provide Hubble Space Telescope (HST) - class performance for UV observations and the highest sensitivity and spatial resolution yet achieved below 120 nm. High spectral resolution (R<105) measurements of diffuse emissions will be made with 50 times the etendue of HST-STIS permitting inner solar system observations of Venus, Mercury, and comets to within ~0.35 AU of the Sun, L1-halo orbit for observations for uninterrupted measurements of the Earth’s North or South polar regions and a remote perspective on planets giving full hemisphere studies up to rotational poles. The potential operational lifetime is 5+ years.

SCOPE measurements will provide: global imaging of auroral emissions, upper atmospheric circulation, exospheres and near-space plasma distributions; imaging spectroscopy of UV ion-neutral emissions and atmospheric absorption features; narrow-field spectroscopy of planetary (auroral-dayglow-coronal) H Ly-α profiles; wide-field line profile measurements of diffuse H Ly-α emission from the interplanetary medium (IPM), comets, geocorona,and the heliopause; pencil-beam measurement of heliopause and LISM dynamics from H Ly-α and H Ly-β line-of-sight absorption spectroscopy; high speed photon counting detectors for precision time resolution; coordinated observations of planetary targets, the IPM and heliopause with existing in situ space probes; cross-cutting techniques for characterizing auroral emissions in planetary magnetospheres, such as the development of auroral indices as a function of precipitating species at each of the planets (e.g. hemispheric power, auroral oval location, auroral oval size).

SCOPE is important because it will provide fundamental science observations and understanding of key planetary and interplanetary processes that are critical to the exploration vision and the overarching goals of the SSSC program. SCOPE should be launched as soon as possible in Phase 4 when our understanding of more basic planetary processes has matured.

Solar Energetic Particle Mission (SEPM)

SEPM – the Solar Energetic Particle Mission will determine how, when, and where solar energetic particles (SEPs) are accelerated. SEPM will also help determine how the solar wind is accelerated. A large aperture UV coronagraph-spectrometer and a large aperture visible light coronagraph-polarimeter will observe the corona from 1.15 to 10 solar radii. SEPM instrumentation will be about 100 times more sensitive than current coronagraphs. New diagnostics will determine velocity distributions for electrons and minor ions and derive magnetic field strengths in coronal streamers and coronal mass ejections (CMEs). SEPM will measure critical plasma parameters in pre- and post-shock CME plasmas including suprathermal seed particle populations and it will characterize upstream turbulence which is believed to play a critical role in particle acceleration.

When combined with an integrated theory and modeling program, SEPM measurements will be used to significantly advance our fundamental understanding of energetic particle acceleration (Objective F). Ultimately this understanding will be used to develop a predictive capability for the flux, energy spectrum, and composition of SEP's – thus enabling the Exploration Vision (Objective J) and providing information about the solar sources of Space Weather that affect our home planet (Objective H). Ideally the remote sensing SEPM spacecraft should fly in concert with a near-Sun spacecraft (e.g. Inner Heliospheric Sentinels or Solar Orbiter) that will detect energetic particles before significant scattering in the interplanetary medium. SEPM should start as early as possible during a period of high solar activity to inform the development of SEP hazard prediction before human explorers return to the moon.

The possible combination of the SEPM and Doppler missions promises a powerful tool for understanding the physical processes of solar energetic particle acceleration and relating SEPs to flares on the disk and to coronal mass ejections that propagate out into interplanetary space. The identification of early signatures to determine which SEP events are the most dangerous will be useful for developing a predictive capability for the Exploration Vision. The UV/EUV imaging spectrograph will determine flow velocities and energy release signatures on the solar disk.

Solar Polar Imager

Solar Polar Imager will provide critical missing observations need to understand the solar cycle and the origins of solar activity. It is a single spacecraft mission that uses a solar sail to achieve a final 0.48 AU circular orbit with a 75° inclination to the ecliptic. The spacecraft carries a magnetograph -Doppler imager for high-resolution helioseismology and surface magnetic field measurements of the polar regions, a coronagraph for polar views of the corona and CMEs, and *in situ* particles and fields instrumentation for solar wind and energetic particle observations. Other instruments, such as a solar irradiance monitor and a

UV spectrometer and a heliospheric imager could also be included.

This mission is necessary to understand the solar dynamo because the polar orbit enables us to measure the convective surface, subsurface and deep interior flows that control the solar dynamo and to observe the correlation between the flows and solar magnetic field activity and evolution. The rapid four-month polar orbit also allows us to observe the relationship between solar activity and solar wind structure and energetic particles at all latitudes, crucial for characterizing the near-Sun source region of the space environment. In addition, the polar magnetic field measurements are needed to provide the solar surface boundary conditions for the global MHD models used for space weather prediction.

Because this mission requires a solar sail to achieve the near-polar orbit, it has been placed after the Heliostorm mission that will be the first science mission utilizing solar sail propulsion. The Telemachus mission can also address the goal of characterizing the space environment at all latitudes and give some information on the magnetic fields and flows in thepolar regions. Thus at some point, the community may choose between Solar Polar Imager and Telemachus, based in part on the maturity of the solar sail propulsion technology.

Solar Weather Buoys (SWBs)

The initial function of SWBs is to answer definitively the yet un-resolved basic scientific question: what is the spatial longitudinal extent and evolution of the major Solar Energetic Particle (SEP) and Coronal Mass Ejection events that occur during the maximum of the solar cycle? Their complementary function is to give prompt and unambiguous warning of the injection of biologically damaging doses of high-energy particle radiation for astronauts exposed on the surface of the Moon or in transit to the surface of Mars. SWBs are ~15 small spacecraft distributed every ~20° in ecliptic longitude around the Sun at 0.9 AU, identically instrumented with plasma, magnetic field, energetic particle, and hard xray detectors.

SWBs will attack the fundamental problem (F.2) of bringing our understanding of the acceleration and propagation of SEPs and CMEs from the Sun to 1 AU up to the level of prediction. In its complementary role, it will safeguard our outward journey (J.2) to the surfaces of the Moon and Mars.

By launching in 2022, the 5-year deployment phase will be completed in time to catch the rise-to-maximum phase of the solar cycle (2027-2030). During the remainder of the solar cycle (2031-2036), SWBs will paint a definitive scientific picture of how large SEPs and CMEs propagate from the inner heliosphere (being simultaneously observed by IHSentinels, Solar Orbiter, and solar imagers) to 1 AU and beyond towards Mars orbit at 1.4 AU. During this time SWBs' prompt warning capability will be honed and perfected so that they will function with high reliability at the anticipated launch time for the manned mission to Mars (2035).

Sun Earth Coupling by Energetic Particles (SECEP)

SECEP seeks to understand and quantify the impact on atmospheric composition, in particular of odd nitrogen, odd hydrogen, and ozone, by solar energetic particle precipitation (EPP). EPP is thought to be a significant source of ozone destruction through production of high altitude odd nitrogen and odd hydrogen compounds which can be transported lower in altitude where they will catalytically destroy ozone. In order to understand these processes SECEP will measure the precipitating energetic particle influx as well as the descending odd nitrogen and odd hydrogen compounds and ozone densities. Other relevant parameters which affect these processes such as temperature and winds will also be observed.

SECEP is crucial to SSSC goals because it studies a key link between solar energy and its impact on the habitability of Earth. Dramatic effects of EPP on stratospheric and mesospheric ozone have been demonstrated by recent observations. The impact is greatly magnified by the long lifetime of odd nitrogen compounds at stratospheric altitudes. The decent of the odd nitrogen compounds from the ionosphere where it is created to the mesosphere and stratosphere occurs primarily in the polar night where destruction by photolysis can not occur. Therefore SECEP provides valuable fundamental science on how atmospheric regions are coupled. Because ozone plays a key role in Earth's habitability by shielding the population from harmful UV radiation, SECEP is a high priority mission. SECEP should follow GEC and ITSP closely in time because these two missions provide key information on how the atmosphere responds to solar energy and the three missions together are synergistic for the overall goal of understanding the Earth's response to solar energy and the effect on the human population.

Stellar Imager (SI)

Stellar Imager (SI) is a mission that will obtain the first direct images of surface magnetic structures in sun-like stars. The SI will develop and test a predictive dynamo model for the Sun (and Sun-like stars) by observing the patterns in surface magnetic fields throughout activity cycles on a large sample of Sun-like stars. It will image the evolving dynamo patterns on nearby stars by repeatedly observing them with ~1,000 resolution elements on their surface using UV emission to map the magnetic field. SI will image the structure and differential rotation of stellar interiors by the asteroseismic technique of acoustic imaging, achieving at least 30 resolution elements on stellar disks with 1-min. time resolution in one or more broad optical pass bands. The power of SI lies in its ability to provide information on the dependence of the dynamo on stellar properties, and enable by its population study dynamo model validation within years rather than many decades. It therefore gives solar physicists a unique 'laboratory environment' within which to vary stellar and dynamo parameters. SI addresses the goals of the Exploration Initiative by enabling improved long-term space weather forecasts throughout the heliosphere to guide vehicle design and mission planning, and forecasts of extended periods for safe construction at Moon, Mars, Earth-Moon L1, Sun-Earth L2, and LEO staging orbits. By observing planet harboring stars and their evolving environments it will also provide an improved understanding of formation of planetary systems and habitability zones of extra-solar planets. Stellar Imager provides crucially needed information for several of the SSSC Objectives by observing patterns of magnetic activity and underlying atmospheric structure of a population of stars to compare with the sun. It supports Objective F by enabling an understanding of the creation and variability of magnetic dynamos, Objective H by promoting an understanding of the causes and subsequent evolution of activity that affects Earth's space climate and environment and how the habitability of planets are affected by solar variability, and Objective J by developing the capability to predict the origin of solar activity and disturbances associated with potentially hazardous space weather. It must fly as early as possible in the Phase 3 mission window (near 2025) to provide the information critical to our planned exploration activities as humans head out through the potentially dangerous interplanetary environment whose character is controlled by the sun.

Tropical ITM Coupler (T-ITMC)

T-ITMC will explore how neutral and plasma interactions distribute energy within and between Earth's low-latitude mesosphere, thermosphere, ionosphere, and inner plasmasphere.

T-ITMC will improve our understanding of the influence of geospace on Earth (Objective H), explore the fundamental interactions between atmospheric plasmas and neutrals across scales from 1 cm to 1000 km (Objective F), and provide a fundamental database of atmospheric dynamics (winds, gravity waves, and ion drifts) that can be applied to exploration of other planets (Objective J).

It should be flown after the GEC and ITSP missions and should be reconfigured as necessary to address unanswered questions from those missions. In the event of limited flight opportunities, the importance of T-ITMC can be evaluated in light of the GEC and ITSP results.

Venus Aeronomy Probe

Venus Aeronomy Probe will study the robust upper atmosphere and solar-wind atmosphere interaction of a planet with essentially no intrinsic magnetic field. This mission will determine the processes by which solar wind energy is transmitted to the ionosphere and upper atmosphere. It will also study how charged particles are accelerated to create auroral-type emissions, how magnetic field ropes form and dissipate, how ionospheric plasma is lost, as well as other electrodynamic interactions.

The dynamics and evolution of the Venus upper atmosphere and its direct interaction with the solar wind is a critical component of the reasons why this planet digressed from habitability. Understanding the physical processes responsible for the development of the present-day Venus atmosphere is vital to understanding the evolution of planetary atmospheres in general, including that at Earth.

Because Venus is not hospitable to humans and is therefore not a manned-flight destination, this mission should be flown after one or more similar missions have gone to Mars. Therefore, it is part of the Phase 3/4 mission queue.

J. Sun-Solar System Connection Foundation Roadmap Team

External Chair: Todd Hoeksema, Stanford University
NASA Center Co-Chair: Thomas Moore, NASA/GSFC
Markus Aschwanden, Lockheed-Martin
Donald Anderson, NASA/HQ
Scott Bailey, University of Alaska
Thomas Bogdan, NCAR
Cynthia Cattell, University of Minnesota
Gregory Earle, Univ. of Texas at Dallas
Joseph Fennell, Aerospace Corp.
Jeffrey Forbes, University of Colorado
Glynn Germany, University of Alabama in Huntsville
Nat Gopalswamy, NASA/GSFC
Donald Hassler, Southwest Research Institute
Rosamond Kinzler, American Museum of Natural History
Craig Kletzing, University of Iowa
Barry LaBonte, JHU/Applied Physics Lab
Michael Liemohn, University of Michigan
Paulett Liewer, NASA/JPL
Neil Murphy, NASA/JPL
Edmond Roelof, JHU/Applied Physics Lab
James Russell, Hampton University
Leonard Strachan, Smithsonian Astro Observatory
NASA HQ Lead: Barbara Giles

K. Sun-Solar System Connection APIO-Appointed Roadmap Committee

NASA HQ Co-Chair: Al Diaz (NASA HQ Science Mission Directorate)
Center Co-chair: Franco Einaudi (NASA GSFC)
Center Co-chair: Thomas E. Moore (NASA GSFC)
External Co-chair: Timothy Killeen (National Center for Atmospheric Research)
Directorate Coordinator: Barbara Giles (NASA HQ Science Mission Directorate)
APIO Coordinator: Azita Valinia (NASA GSFC)

Committee Members:
Scott Denning (Colorado State University)
Jeffrey Forbes (Univ of Colorado)
Stephen Fuselier (Lockheed Martin)
William Gibson (Southwest Research Institute)
Don Hassler (Southwest Research Institute)
Todd Hoeksema (Stanford Univ.)
Craig Kletzing (Univ. Of Iowa)
Edward Lu (NASA/JSC)
Victor Pizzo (NOAA)
James Russell (Hampton University)
James Slavin (NASA GSFC)
Michelle Thomsen (LANL)
Warren Wiscombe (NASA GSFC)

Ex Officio members:
Donald Anderson (Science Mission Directorate)
Dick Fisher (Science Mission Directorate)
Rosamond Kinzler (American Museum of Natural History)
Mark Weyland (Space Radiation Analysis Group, JSC)
Michael Wargo (Exploration Systems Mission Directorate)
Al Shafer (Office of the Secretary of Defense)

Systems Engineers:
John Azzolini (GSFC)
Tim Van Sant (GSFC)

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
SUN-SOLAR SYSTEM CONNECTION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Sun-Solar System Connection Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on exploring the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

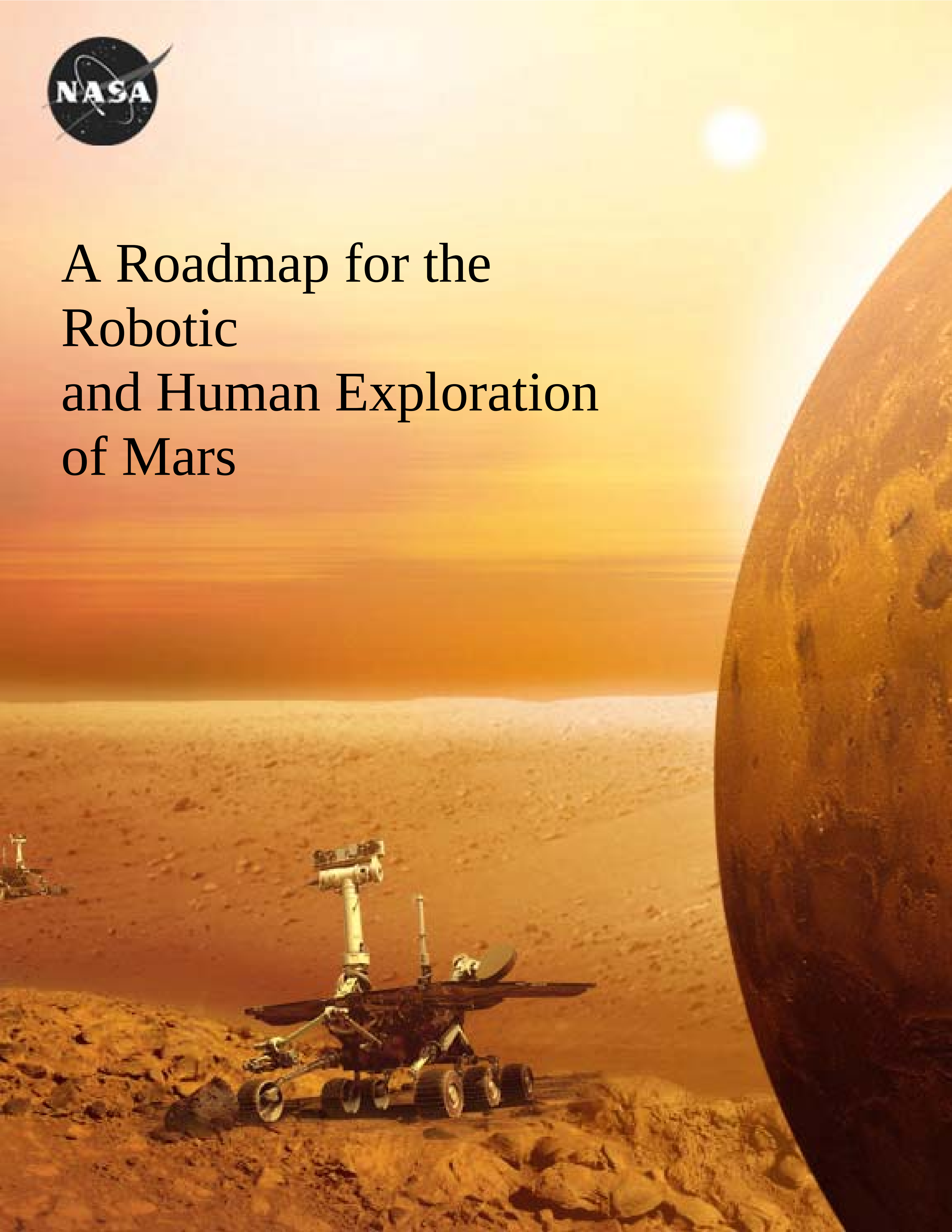
DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

A Roadmap for the Robotic and Human Exploration of Mars



About the Roadmap

In December 2004, NASA established a number of strategic roadmap teams to provide guidance and priorities for achievement of the nation's space exploration objectives. This was partly in response to the Vision for Space Exploration, as well as to the Presidential Commission on Implementation of United States Space Exploration Policy (the "Aldridge Commission"). This is the report of the team chartered to study the robotic and human exploration of Mars.

The Mars Roadmap Committee met three times – in January, February, and March 2005. All of the strategic roadmap committees were requested by NASA to terminate their activities and provide their best-effort reports by May 2005; consequently, this document has not undergone the level of detailed editing, production, and printing that would normally have been expected. Nonetheless, the Committee feels that it has reached important conclusions about the priorities for the Mars exploration program, and has created a framework for the key decisions that will one day lead to human exploration of Mars. This document articulates those priorities and recommendations.

Mars Roadmap Committee

Al Diaz, NASA HQ, Co-Chair	Chris McKay, Ames Research Center
Charles Elachi, JPL, Co-Chair	Sally Ride, University of California/San Diego
Tom Young, Lockheed Martin (retired), Co-Chair	Steve Squyres, Cornell University
Ray Arvidson, Washington University	Larry Soderblom, US Geological Survey
Bobby Braun, Georgia Institute of Technology	Peggy Whitson, Johnson Space Center
Jim Cameron, producer/writer/director	<u>Ex-Officio/Liaison:</u>
Aaron Cohen, Texas A & M	Doug Cooke, NASA HQ
Steve Dorfman, Hughes Electronics (retired)	Orlando Figueroa, NASA HQ
Linda Godwin, Johnson Space Center	Jim Garvin, NASA HQ
Noel Hinners, Lockheed Martin (retired)	Mike Hawes, NASA HQ
Kent Kresa, Northrop Grumman (retired)	Dan McCleese, Jet Propulsion Laboratory
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Laurie Leshin, Arizona State University	Firouz Naderi, Jet Propulsion Laboratory
Shannon Lucid, Johnson Space Center	Michelle Viotti, Jet Propulsion Laboratory
Paul Mahaffy, Goddard Space Flight Center	Michael Meyer, NASA SMD Coordinator, Designated Federal Official
	Judith Robey, NASA APIO Coordinator

Preface

NASA has been engaged in the scientific exploration of Mars for over forty years. During the past decade, six spacecraft - three NASA landers, two NASA orbiters, and one European orbiter - have begun to patch together the pieces of a wonderfully complex puzzle as they reveal the story of the Martian past and present. Yet we are still just in chapter one… even more riveting chapters will be read out by our robotic explorers in the next two decades.

The excitement of Mars exploration was elevated last year when the President laid out a new vision for integrated robotic and human exploration of the Moon, Mars, and beyond. Robotic science missions will extend our understanding of Mars while they lay the groundwork for human exploration - by making new discoveries, characterizing the environment, validating new capabilities, and emplacing the infrastructure that will enable safe and effective human missions.

This roadmap outlines how NASA can build on its existing robotic Mars Exploration Program to enable future human expeditions to Mars. Our existing science priorities are highly complementary to the requirements for early human exploration precursors, centered on the "Follow the Water" theme. Technology development for robotic exploration paves the way for larger-scale human missions in key areas. Augmentation of existing plans and investments with complementary measurements and technology developments represents a logical, systematic approach to implementing the Vision for Space Exploration.

Executive Summary

The Vision for Space Exploration provides new impetus and specific goals for the nation's Mars exploration program. These have been adopted as NASA's strategic objectives and constitute the charter of the Mars roadmap:

- Conduct robotic exploration of Mars
    - To search for evidence of life,
    - To understand the history of the solar system
    - To prepare for future human exploration.

- Conduct human expeditions to Mars
    - After acquiring adequate knowledge about the planet using robotic missions
    - After successfully demonstrating sustained human exploration missions to the Moon.

Observations

The development of the Vision for Space Exploration has added a new dimension to a vibrant and highly successful Mars exploration program. The existing scientific objectives of Mars exploration can be seen in light of a long-range future that will ultimately lead to human exploration of the planet, fulfilling a centuries-old dream of humankind. The goals of the present robotic Mars exploration program are well aligned with the needs of future human exploration and will enable the nation to make well-informed decisions regarding human mission capabilities, costs, risks, and priorities. New areas of emphasis should be added to the program, including:

- Precursor measurements to characterize and assess Mars' environment to ensure human safety
- Technologies responsive to the more demanding needs of human travel
- Engineering infrastructure required for human safety and mission success

Human exploration of the Moon can provide important opportunities to verify and validate systems and processes for human Mars exploration. Within a few decades, we will be prepared to undertake an integrated robotic and human exploration program for detailed study of the planet Mars, leading to a new understanding of the evolution of the solar system and the development and evolution of life.

A Phased Approach to Mars Exploration

Sustainable and effective exploration must be responsive to discoveries and resilient to unexpected changes. This has been one of the hallmarks of the highly successful robotic Mars program. The preceding years of Mars exploration position us to maintain that discovery-driven approach in the coming decades as we move toward more intensive robotic missions, human precursors, and eventually human exploration of Mars.

To facilitate program planning and development of a logical decision structure and investment portfolio, time phases of Mars exploration have been identified. The first phase (2005-2016) can be planned with some degree of specificity and serves as a near-term focus. Notional phases 2 through 4 can be defined now to provide context for goals and investments, but must remain discovery-driven and focused on key decisions. The detailed content of those later phases will be defined by and adjusted according to scientific findings, as well as by the pace of technology validation and by budgetary and programmatic factors.

First Phase at a Glance

The first phase of the roadmap extends from now (2005) through the recommended launch of the first Mars sample return mission in 2016. The primary scientific goals are the search for water and biosignatures. At the same time, those investigations will provide key information on the Mars environment that will enable decisions on human mission planning. Objectives of this period are:

Increase our understanding of Mars as a potential habitat for past and present life
- Continuation of orbital studies (MGS, Odyssey, Mars Express)
- Improved reconnaissance and site selection (Mars Recon. Orbiter)
- Water ground truth (Phoenix)
- Search for localized near-surface water and for minerals and organic compounds relevant to the search for life (Mars Science Lab)
- Launch the first Mars sample return

Pave the way for human exploration in later decades
- Architectural refinements and preliminary design of reference missions to identify architectural “swingers”
- First human precursor testbed to make environmental measurements crucial to human exploration
- Study and advance key capabilities (Entry/descent/landing, in situ resource utilization, nuclear power, etc.)
- Develop requirements flow-down for synergistic activities (lunar exploration, launch vehicles, ISS research)
- Study and down-select human exploration architectures

The Mars Science Lab (MSL) is the key mission that will establish the scientific and technical foundation for the future Mars exploration program, and is thus the single highest priority Mars exploration mission for the next 10 years. MSL will:
- Confirm and localize near-subsurface water
- Explore indications of habitability in selected environments
- Provide a comprehensive understanding of the Mars environment needed for future mission planning
- Enable informed strategic decisions on robotic science priorities and human mission architectures

MSL will demonstrate long-distance, long-duration, semi-autonomous mobility on Mars, which is a key to cost-effective future exploration. It will also utilize next-generation Entry/Descent/Landing (EDL) systems as a step toward higher-capability, human-scalable EDL.

The Committee strongly recommends that MSL should be launched no later than 2011 and preferably by 2009. Two MSL spacecraft should be launched to ensure mission success and maximize the science return. MSL is a key element of an exciting, engaging, scientifically productive robotic program leading to eventual human mission decisions.

Looking Beyond the First Phase

The subsequent phases of Mars exploration will be discovery-driven and will emphasize continued understanding of the planet and its habitability, as well as enabling well-informed decisions on future human exploration.

Phase 2: 2016 - 2025

- Continued robotic science, including analysis of the first returned Martian samples and *in situ* surface exploration
- Conduct scaleable validation tests of key capabilities (ISRU, EDL)
- Develop other major capabilities
- Establish required Earth-based facilities and infrastructure, including advanced Deep Space Network capability
- Validate human habitation and operations concepts on the Moon
- Select and validate Mars human exploration architecture
- Confirm the Mars human architecture in 2025

Phase 3: 2025 - 2035

- Emplace robotic outposts for scientific analysis and infrastructure, and verify performance of human support elements
- Build flight systems for human missions
- Demonstrate sustained human exploration on the Moon
- Conduct discovery-driven opportunistic science

Phase 4: 2035 – beyond

- Initiate human missions to Mars
- Explore Mars with a unified robotic and human system

Summary of Roadmap Achievements

The recommended phased approach to Mars exploration represents an exciting, affordable, and scientifically rewarding program that will address the key questions of planetary evolution, habitability, and life in the cosmos. At the same time it is a measured, decision-based structure that will enable the nation to make steady progress toward the long-range goal of human Mars exploration. The table below summarizes the key achievements that will be enabled by each phase of the roadmap.

Roadmap Goals	***Phase 1: 2005-2015***	***Phase 2: 2015-2025***	***Phase 3: 2025-2035***
Determine if Mars was Habitable and if Life Developed There	- Evidence of past water and aqueous processes - Habitable environments - Biosignatures	- Lab study of Mars samples - Subsurface exploration - Intensive search for life	- Intensive search for life - Discovery-driven opportunistic science
Understand the Climate of Mars	- History of water - Atmosphere chemistry and dynamics - Polar layered deposits	- Long-term climate change - Understand and predict Mars weather	- Discovery-driven opportunistic science
Understand the Geological Evolution of Mars	- High-res surface mapping - Global/local mineralogy - Surface-atmosphere interactions - Role of water	- *In situ* exploration of compelling sites - Lab study of Mars samples	- Discovery-driven opportunistic science
Prepare for Human Exploration	- Search for usable water - Environment, dust, surface characteristics - Atmosphere variability and models - Establish initial telecom infrastructure - Candidate architectures and key technologies	- Downselect architectures - Identify/explore candidate landing sites - Confirm resources - Biohazards, toxicity - Validate capabilities - Human habitation and exploration on Moon - Mars mission "dress rehearsal" - Confirm architecture	- Establish robotic outpost at preferred human site - Emplace infrastructure (Power, ISRU, comm., etc) - Develop key capabilities and build flight elements - Prepare for first human launch

Summary of Recommendations

The Mars Strategic Roadmap Committee makes the following recommendations:

<u>Scientific Recommendations</u>

- Build and fly two Mars Science Lab spacecraft
- Launch both MSL's *no later than* 2011, with a goal of launching one in 2009, and launch Mars Sample Return *no later than* 2016
- Incorporate the search for accessible water and development of water extraction techniques into Mars Exploration Program objectives
- Characterize the Mars atmosphere, both for scientific reasons and to aid in the design of EDL systems
- Upgrade our Mars science data archiving and access system to be ready for the data from future missions
- Structure an integrated program of robotic science missions and robotic human

precursor missions to achieve the desired measurements and capability advances

Programmatic Recommendations

- Develop standard product lines and reuse common products and designs whenever possible
- Expand the definition of Mars Scouts to embrace varied forms of implementation and program goals
- Build an industrial capability
- Forge partnerships with key academic units
- Increase the size of the community
- Include international components in the program
- Fully equip and utilize the International Space Station for human health research to enable human missions to Mars
- Perform system studies by industry and government and develop a Design Reference Mission to guide the human exploration plans
- Identify specific Mars mission requirements that can benefit from validation on the Moon, and levy those requirements on the human lunar exploration missions
- Form a "Super System Engineering" group to steer studies and investments

Technology/Capability Recommendations

Required:

- Hypersonic parachute to allow landing MSR-class assets at high elevations on Mars
- Human-scalable entry, descent, and landing systems capable of safely and precisely landing large masses in units of up to 40 MT
- Heavy-lift launch vehicle (~100 MT to LEO)
    - Validate on human lunar mission prior to first use for Mars
- Robust ~20-40 kW power plant for use on the surface of Mars
    - Total power required may be approx. 60-100 kW; use multiple units for flexibility and redundancy
    - Advanced high-efficiency radioisotope power is required for robotic missions
- Validation of capabilities needed for human expeditions, using appropriate venue
    - Strategically select opportunities to validate key capabilities in relevant environments
    - Includes Earth analog environments, ISS, Moon, and Mars (via robotic missions)

Possibly Required:

- ISRU for human consumables and propellant production
    - Downselect among candidate methods based on Mars environment knowledge (esp. presence of water), feasibility tests, and architecture studies
- Nuclear propulsion for Mars missions
    - If the cost benefit for Mars is established via trade studies, or if required by other overriding agency/national needs

Goals of Mars Science and Exploration

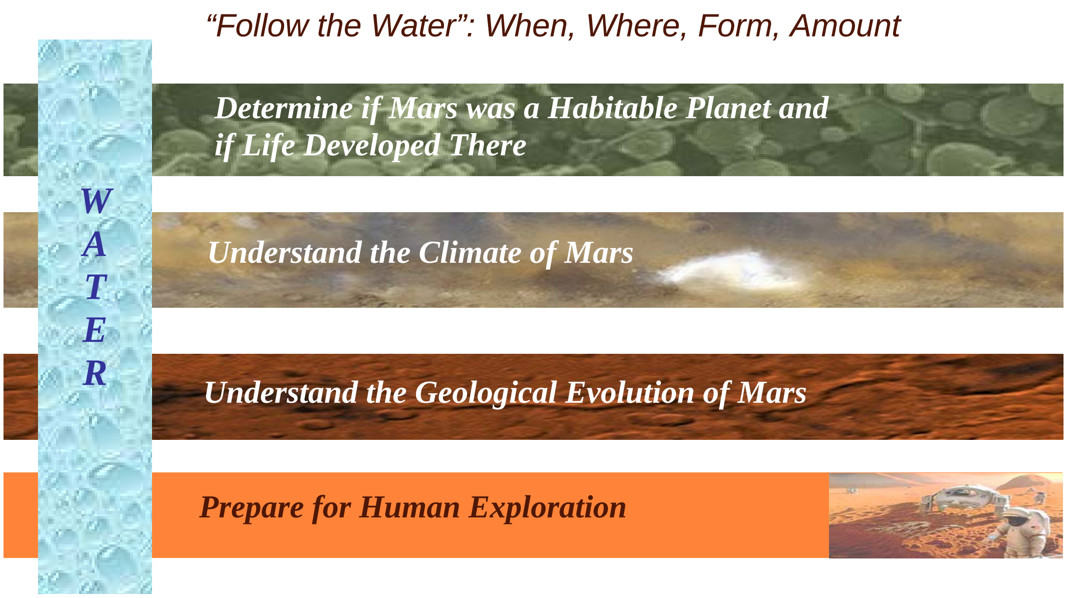
A fundamental question for humanity is whether life on Earth is unique or is abundant throughout the universe. Understanding the conditions (physical environment, energy sources, and crucial chemical components) required for life to emerge is central to this issue. The exploration of Mars offers one of the richest opportunities to address this question. The reason is fundamentally twofold. First, Mars has had a long, complicated geological evolution, with evidence for extended interaction of water with surface and subsurface materials. Second, water is believed to be a key ingredient for the development and evolution of life. We also note that understanding the evolution of Mars will undoubtedly increase our understanding of the evolution of planets, in general, and thus of the solar system.

Exploration of Mars will enable us to address questions that resonate across the scientific community and the public:

- How does life begin? What is the range of environments and chemistry that allow life to emerge and to be sustained?
- Is or was Mars a habitable planet?
- Did life develop on Mars, and if not, why not?
- What was the role of water in Mars' evolution and habitability?
- How will understanding the planetary-scale evolution of Mars contribute to a better understanding of the evolution of the solar system and planet Earth?

There is abundant evidence for interaction of liquid water and ice at the surface of Mars including dry river channel systems that cut across older terrains. Also, evidence of shorelines of past lakes and seas has been suggested by some researchers. Hydrated salts are found in association with layered deposits in the equatorial regions, including the evaporite deposits formed in shallow water and examined by the Opportunity rover in Meridiani Planum. Relatively young gullies emanating from canyon walls suggest that water existed very near the surface in geological time, at least ephemerally. Water ice is found exposed at the poles and buried under shallow soil deposits at high latitudes. Further, selected equatorial regions have enhanced water signatures associated with residual ice deposits or hydrated minerals. Finally, Martian meteorites provide a view of an early wet planet, with production of aqueous minerals, and tantalizing, but very controversial evidence for ancient life.

To answer the question of whether or not there is or was life on Mars requires a deep intellectual understanding of how the planet's interior, surface, and atmosphere have evolved and interacted over time, and the extent to which conditions were conducive to formation, evolution, and preservation of evidence for life. We need to understand if Mars ever possessed the essential chemical species (including water), the environmental conditions (e.g. temperature, radiation levels) and energy sources available in concert at the right time and place to support development, evolution, and sustenance of life. The scientific community has come to consensus that by understanding the history of water on Mars we can derive the greatest insight into the processes that have affected Mars' evolution and potential habitability; thus the Mars science strategy has come to be known as "Follow the Water". This strategy was established years before announcement of the Vision for Space Exploration, but it remains highly consistent with the goals articulated in the Vision and provides an excellent linkage between the goals of scientific understanding and preparation for human exploration.



In this section of the Roadmap Report we summarize what is currently known about Mars and its potential habitability, past and present. We provide a preview of robotic exploration and discovery missions through the next two decades that focus on developing the intellectual basis to understand the planet and whether or not life developed and evolved. We then consider how to further deepen this understanding as we transition from robotic to human expeditions to the red planet.

From Initial Reconnaissance to 2005
Water and the Evolution of Mars

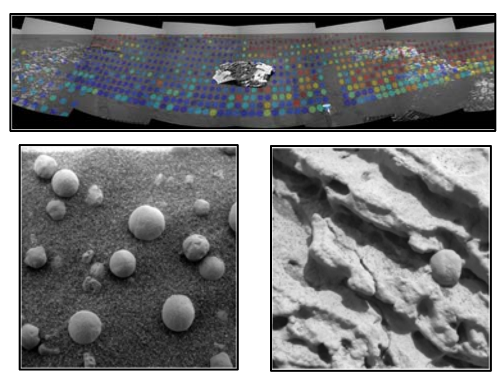
Key Discoveries and Achievements:

- Planetary spacecraft data and Mars meteorite studies have led to our emerging view of Mars as a water-rich planet
- Liquid water existed at and beneath the surface over most of geologic time
- Mars appears to have had the ingredients needed to develop and sustain life

The period from the first flyby reconnaissance of Mars, by Mariners 4, 6, and 7, to today, when the two Mars Exploration Rovers explore the surface in great detail as three active orbiters circle overhead, has revolutionized our understanding of the Red Planet and the role of water in its evolution. This understanding has been complemented and extended by study of approximately three dozen meteorites that have isotopic signatures indicative of a martian origin.

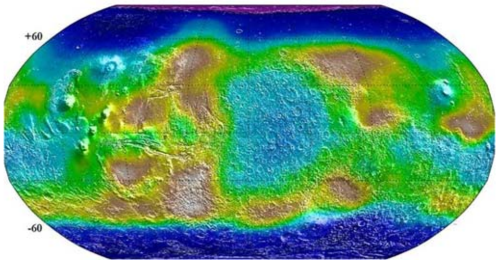
The emerging view of Mars is one of a planet with very active tectonic and volcanic evolution, particularly early in geologic time. An internal dynamo in a liquid core generated a magnetic field for approximately the first billion years of geologic time. The great Tharsis Plateau, a long-term locus of volcanic activity, formed early in time and massive volcanic emissions (water, carbon dioxide, and many other gases) from this and other volcanic systems caused greenhouse warming that raised surface temperatures. Fluvial channel systems formed during this period and open or ice-covered lakes and shallow seas may have existed at least on an ephemeral basis. As the rate of volcanism associated with the Tharsis Plateau and other magmatic centers declined, conditions grew colder because of the lack of supply of greenhouse gases, and surface water became less likely. In addition, analyses of Mars meteorites show that these materials are igneous rocks with an age range from 100 million to 4.5 billion years, supporting the idea that volcanism extended over most or all of geologic time. This indicates that, at least locally, conditions may have been warm enough, due to transient greenhouse warming and the presence of active hydrothermal systems, to allow liquid water to exist. This interpretation is bolstered by tantalizing evidence for on-going and occasional release of ground water from canyon walls. This evidence is in the form of morphologically fresh gully systems that extend downward from tops of cliffs and, in some cases, produce fan deposits that cover relatively recent wind blown dunes.

Recent results from the two Mars Exploration Rovers are also consistent with an extended presence of water and demonstrate its interaction with surface and near-surface materials. The first Mars Exploration Rover, Spirit, reached the Columbia Hills after traversing 157 sols across volcanic plains to find older rocks that have been altered by salty ground water. The second rover, Opportunity, traversing across the plains of Meridiani, found evidence for cross-bedded, hydrated sulfate evaporite deposits that formed in shallow, open water, with subsequent modification by corrosive ground waters. The deposits are at the top of a 300 m layer of sedimentary rock that covers the dissected, channeled cratered terrain. *This means that a water-rich environment existed at or near the surface* even after deposition of the 300 m section – that is, after burial of the channel systems within the cratered terrains.



Direct detection of aqueous processes by Opportunity

Mars Express OMEGA data show that hydrated sulfate deposits are found in abundance exclusively in association with layered deposits, including those in Meridiani Planum, and extensive deposits found within Valles Marineris. This result suggests that Mars, when wet, was dominated by acid-sulfate aqueous systems. The acidic conditions would have precluded formation of carbonate deposits. OMEGA data also show that clay minerals occur, but only in the older cratered terrains, consistent with a warm, wet early Mars. Finally, martian meteorites show evidence for magmatic fluids in their formation, as well as overprinting in the martian crust by circulating water-rich fluids. These materials also contain secondary minerals such as carbonates and sulfates formed in aqueous environments. The evidence in total from analyses of spaceborne and meteorite data shows that *Mars had and probably still has, to some extent, an active hydrological cycle and likely had environments in the near surface that were habitable by terrestrial standards.*



Concentrations of subsurface water detected by Mars Odyssey

Today, water on or near the surface is largely in the form of ice deposits in the permanent polar caps, shallowly buried ice deposits in the high latitudes, and hydrated minerals and perhaps residual ice deposits in the low latitudes. Mars undergoes orbital changes (akin to Earth's Milankovitch cycles) with major variations in obliquity, eccentricity, and the positions of the equinoxes over timescales ranging from ~100,000 to millions of years. These cycles have modulated the characteristics of the climate, including the atmospheric pressure and the ability of the atmosphere to transport water vapor and ice, carbon dioxide, and dust. The record of these cycles is within the hundreds of meters of layered polar deposits of dust and ice and the shallow water ice deposits beneath a thin cover of soil at high latitudes. Interestingly, these deposits may have supported the development of lenses or pockets of water during chaotic excursions of obliquity to values as high as 45 degrees that occur over approximately ten million year timescales.

The motivation for the current era of intensive Mars exploration arises from the mounting evidence for the presence of water, both as liquid and ice, on and beneath the surface throughout geologic time. In addition, martian meteorite ALH84001, a piece of the ancient cratered terrain, contains substantial evidence for modification by aqueous fluids, and morphologic evidence suggesting microfossils. The fossil evidence is highly controversial, but it has helped to energize both the science community and the public in exploring Mars to search for life. We note that the recent announcement of the presence of small amounts of methane in the martian atmosphere provides an additional piece of evidence that the planet is still active and/or may have extant life. Methane can be produced by cometary impact, by on-going volcanic emissions, and as a by-product of microbial metabolism. Methane is quickly destroyed by ultraviolet radiation in the martian atmosphere and thus demands an on-going source from the surface or subsurface. The methane evidence is also controversial and is being subjected to intense scrutiny by the science community.

Roadmap Phase 1: 2005-2016
Toward an Understanding of the Potential for Current and Past Life on Mars

Key Discoveries and Achievements

- Thousands of sites will be mapped from orbit and evaluated for habitability
- The modern climate and ancient hydrological processes will be characterized
- High-latitude soils and ices will be analyzed to determine current and past climatic conditions and to search for evidence of reduced carbon compounds
- High-priority sites will be studied in detail for evidence of accessible subsurface water and habitable environments
- A comprehensive understanding of Mars' environmental characteristics will enhance both our scientific foundation and our ability to plan future exploration

On ancient Mars, climate and surface conditions may have been favorable to the origin and evolution of life. The next step, beyond the missions already flown or still operating at Mars, is to search for past and present habitable environments. The MER Opportunity results suggest that such an environment may have existed long ago in Meridiani Planum. Perhaps Spirit will find that Gusev Crater was also once habitable. Future planet-wide searches will be conducted from orbit and on the surface in order to identify other habitable sites for in-depth study. Aqueously deposited sediments and surface alteration by water will be the primary subjects of this search, since it is in these sites on Earth where evidence of past life is found. *By finding these sites we will have identified locations on Mars where the potential is highest for finding evidence of past life.* Landed mobile missions will then examine these sites for evidence of biosignatures. Missions will be targeted not only will sites to temperate latitudes, but also to high latitude sites where surface or near-surface water ice may now be present.

In the coming decade, the investigations to be conducted at potentially habitable sites will include measurements of carbon chemistry in near-surface rocks and soil. Definitive mineralogy will also be critical, including identification of any evidence of formation or alteration by water. The tools for these investigations will be analytical instruments, under development for the past decade in universities and NASA centers, which begin to approximate the capabilities available in ground-based laboratories but which have size, mass, and power requirements consistent with robotic missions. These *in situ* studies will lay the scientific and technical groundwork for the return to Earth of martian samples taken from the highest priority sites, long considered a key to complete understanding of Mars and its potential as an abode for life.

Robotic Science Missions for the Coming Decade

Mars exploration begins a transition from reconnaissance from orbit and on the surface to studies that focus in great detail on martian phenomena and processes. Increasingly sophisticated and complex missions are required enabling measurements similar to those employed to better understand the Earth. Future measurements will be more like those used in Earth field geology and in laboratory analyses of samples collected in the field. Measurements from orbit will match the physical scale and precision of those currently being made by Earth satellites.

Using orbiters, landers, and rovers to carry sophisticated instruments, missions in the period from 2005-2015 will gather data to define in detail ancient habitats that might have supported the emergence and maintenance of life, search for the best locations to test for the presence of past and extant life, and conduct detailed analyses both *in situ* on Mars and with returned samples to understand if environmental conditions and chemistry were conducive to the emergence of life and to search for evidence of past and present life itself.

Mars Reconnaissance Orbiter. In the summer of 2005, the Mars Reconnaissance Orbiter will launch with a payload designed to characterize the atmospheric structure, map in detail numerous candidate sites that might preserve detailed evidence for aqueous processes (i.e., sites with high habitability potential), use of ground penetrating radar to map ground water and ice deposits, and continue investigation of the deep interior of Mars (i.e., through mapping the gravitational field). A primary objective is to provide detailed topographic maps, images, and mineralogical maps for up to 10,000 targets on the planet. These data will be of high enough spatial fidelity (30 cm/pixel imaging data and 18 m/pixel mineral maps from reflectance spectra) to “virtually” explore the geologic setting of these targets. Besides conducting scientific investigations with these data, numerous landing site analyses will be done to select the optimum sites for the subsequent Mars Science Laboratory Mission. The Mars Reconnaissance Orbiter will also provide four dimensional (location, altitude, time) maps of the atmosphere (temperature, pressure, water vapor, dust profiles) over a full martian year, observations that are crucial for understanding the current state of the atmosphere and resultant climatic conditions. The current atmosphere is a boundary condition for understanding earlier atmospheres and climate changes on the red planet.

Phoenix Lander/ Mars Scout. The Phoenix Lander will, during the summer of 2008, descend to the high northern latitudes, where water ice may be within 10 cm of the surface. A robotic arm and scoop will be used to excavate a trench and deliver soil and ice samples for detailed analyses of aqueous chemistry, mineralogy (including ices), and isotopic composition of evolved gases (including search for reduced carbon compounds). An imaging system will be used to map the landing site and investigate the evidence for periglacial (i.e., ice-related) processes. The imaging system will also track the opacity and color of the atmosphere while a LIDAR system maps aerosols and a meteorology package measures atmospheric pressure and temperature. Relative humidity will be determined, along with the isotopic composition of the atmosphere. The payload will also be used to search for trace amounts of methane in the atmosphere. Phoenix, the first

Scout Mission, is an example of discovery-driven science in that it was conceived, proposed, and selected after Odyssey observations demonstrated that water ice exists at high northern latitudes, covered by perhaps 10 to 20 cm of soil deposits. Phoenix will characterize the current atmospheric conditions at high northern latitudes, the nature of the ice deposits, and search for the presence of organic compounds.

Mars Science Laboratory. The cornerstone surface mission of the decade will launch in 2009 and/or 2011. The Mars Science Laboratory rover(s) will focus on traverses over its Mars year mission to explore a number of sites of interest and conduct initial measurements to define the extent to which Mars was or is habitable. Using an ensemble of remote sensing, arm-based contact sensors, and an analytical laboratory with elemental, mineralogical, and isotopic and molecular analysis capabilities, the mission will provide data to determine the aqueous history of the landing site and surrounding areas and search for and characterize reduced carbon compounds and other biochemically important compounds. In fact, this mission will begin the detailed search for biosignatures on Mars. Biosignatures are defined as characteristic "fingerprints" indicating that life exists or existed, including direct evidence in the form of recognizable life forms and an array of indirect evidence. For example, analyses of reduced carbon compounds will allow testing of biotic or prebiotic origins for these materials, since these two types of processes are likely to produce distinctly different compositional and isotopic signatures. Biotically produced methane may show isotopic signatures of metabolic processing, while the complex organic species produced by life may show distinct patterns in molecular weight or structure due to enzyme processing and other mechanisms. Fragile organic molecules from past biological activity on Mars are likely to have been substantially altered by chemically processes such as oxidation, but chemical patterns should still be retained. The Mars Science Laboratory payload is designed to find the rocks that maximize the probability of preserving biosignatures, acquire and prepare samples, and make initial measurements to search for the key elemental, mineralogical, and isotopic signatures indicative of life and its effect on the environment.

Future Mars Scouts. A hallmark of the Mars Exploration Program is the ability to respond to discoveries and make new measurements designed to better understand the evolution of Mars, its current and past habitability, and whether or not life developed and evolved. For example, the Phoenix Scout Mission was proposed in response to the discovery of shallow and accessible water ice deposits beneath a thin soil cover in the high northern latitudes. We fully expect to maintain program flexibility through continued Scout missions or their equivalents. The very nature of these missions precludes listing their foci and objectives in detail; nevertheless we expect that Scout missions will make important contributions to both fundamental Mars science as well as to preparation for human exploration.

Mars Environment Mission. Mitigation of engineering risks and science come together in the Mars Environment Mission. This will be a mission focused on scientific study of key environmental characteristics that will help to define the future human exploration architecture; thus it is an important precursor to human exploration. One option under consideration is an orbiter to enable thorough understanding and characterization of the martian atmosphere. Experience -- most recently demonstrated in the entry, descent and landing of the MER rovers -- has shown that knowledge of the Mars atmosphere is inadequate to confidently assure successful landing in all cases. Surface operations are also influenced by unpredictable weather; dust storms are one example. Measurements from orbit will monitor winds at low altitudes where landers are most vulnerable, characterize the variability of atmospheric density due to weather and season effects from the surface to 125 km, and monitor dust storms from local to global scales.

Other options for the first Mars Environmental Mission are a stationary lander to drill down to 10 meters or so in search of usable subsurface water, or a mobile lander to prospect for water/ice deposits over a broader region with shallow (~2-m) drilling. Either of these missions would be key to understanding the potential of water-based *in situ* resource utilization, which can have a dramatic effect on architecture selection and other capability investments. A decision should be made in about 2008 on which MEM mission to fly, so that launch can occur in 2013.

Mars Sample Return. The end of phase will see the launch of one of the most important robotic missions from the perspectives of both science and preparation for human exploration. For decades, the goal of returning samples from Mars has been considered one of the key missions in all of planetary science. Analyses of returned samples from a site selected using information obtained by preceding missions will allow the entire complement of sophisticated analytical tools available on Earth (and impossible to send in bulk to Mars) to be used to search for biosignatures and thus test for the presence life. Literally dozens of laboratory instruments, weighing thousands of tons, producing terabytes of data, will be used to unlock the history recorded in the returned martian materials. Further, as the first round-trip mission to Mars, and the first to launch from the martian surface, the sample return mission will directly connect robotic exploration to future human missions. The samples to be delivered to Earth will also be critical enablers for human exploration. Analyses of rocks and soils will allow the hazards (biological, chemical and mechanical) and utility of martian surface materials to be assessed. Mars sample return is a key to understanding critical

astronaut health issues that are likely to remain open until detailed analyses are performed on martian dust, soil, and rocks in laboratories on Earth.

Mission Summary

The table below depicts the recommended mission sequence for the coming decade, with options that can be selected based on budget and programmatic factors.

Opportunity	***Mission***
2005	Mars Reconnaissance Orbiter
2007	Phoenix lander (Mars Scout)
2009	Option 1: Mars Science Lab #1 Option 2: Mars Telecom Orbiter #1 plus Mars Scout
2011	Option 1: MSL #2, plus Mars Scout and/or MTO #1 Option 2: MSL #1 plus MSL #2
2013	Option 1: Mars Environment Mission #1 plus Mars Scout
2016	Mars Sample Return

Roadmap Phase 2: 2016-2025
Developing a Detailed Understanding of Habitability and Life

Key Discoveries and Achievements:
- Investigations will seek to confirm evidence of past life at ancient or modern habitable sites
- Martian samples will be studied in Earth laboratories to provide a definitive understanding of surface chemistry, climate history, and potential habitability
- Major water and ice deposits may be found, and key elements of *in situ* resource utilization systems will be tested.
- Detailed study of Mars' environmental characteristics will provide a window into the planet's past and to the possibilities for future human exploration

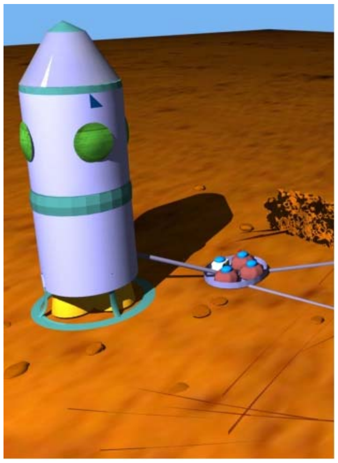
Having identified and investigated with analytical instruments one or more sites, tests will be performed for evidence of extinct organisms and present life, where appropriate. Detection and confirmation of even fossil life would be a discovery of profound importance that would alter our understanding of life on Earth and elsewhere in the cosmos. In the search for extant life, the demands of protecting martian organisms becomes paramount. In addition, this phase of exploration requires care to avoid false-positive detections of life. Consequently, technologies must be found to ensure that spacecraft and instruments are clean and sterile. The blunt tool of heat sterilization used by the Viking spacecraft is expensive and potential disabling for delicate electronics and mechanisms.

Astrobiologists are not of one mind on what measurements could provide definitive confirmation of life, past or present, Disagreement focuses on the matter that remains unresolved in the ongoing study of the martian meteorite ALH84001, namely the putative detection of microfossils in the meteorite that has not yet been proved beyond doubt. The interpretation of microfossils and associated biosignatures is a subject of intense debate, unresolved even with all the instruments and researchers available in laboratories world-wide. There are astrobiologists who argue that unambiguous *in situ* measurements can be made sufficient to prove the presence of fossil life. Others disagree, asserting that only through analyses in laboratories by experienced researchers can proof or refutation be obtained. At present, the Mars Program takes the matter as unresolved and plans for both investigations -- *in situ* to establish a preliminary detection and sample return for definitive answers.

By subjecting carefully selected samples to sophisticated analyses, the information embedded in a rock can extracted to trace the origins and history of the environment that it has experienced. The planetary science community thus ranks the return of samples from Mars as the highest priority for investigations in the next decade. Scientists seek to determine from returned samples their mineralogy, petrology, geochemistry, reduced carbon content and weathering histories, among many other characteristics commonly ascertained from Earth rocks and soil. Many of the most critical measurements required to unravel the evolution, history and current state of the martian surface ultimately depend upon complex instruments that occupy large laboratories; furthermore, many important measurements also require that samples undergo considerable preparation before being introduced into these laboratory instruments.

Robotic Missions: Intensive Science and Preparation for Human Exploration

Missions that follow sample return will employ advanced measurement technologies together with long lateral traverses and drilling to intermediate depth (3 to 10 m). The sites might be an "oases", localities where liquid water is or has been recently close to the surface. Drilling might be to depths of 10 meters or more, with down-hole measurements made to complement analyses of drill core samples. Such an Astrobiology Field Lab will provide perhaps our best opportunities to search a variety of environments for evidence of life.



A second major emphasis will be to search for and find accessible water deposits, perhaps as shallow ice or as liquid aquifers perched as "oases" above the deep water table. These water bodies may be sustained, for example, by continued magmatic activity at depth. These ices and aquifers will be examined for biosignatures. In addition water will be extracted from the deposits and perhaps utilized in prototypical ISRU experiments. A follow-on to the earlier Mars Environmental Mission may be a more sophisticated water extraction and processing experiment, which may even provide fuel to be used to launch another Mars sample back to Earth. This would amount to a full "dress rehearsal" of the key architectural elements required for a human landing and return, and would be an important factor in confirmation of the selected architecture and providing the required confidence to go forward with the human mission.

Roadmap Phases 3 and 4: 2025-2035 and Beyond
Preparing for and Implementing Human Expeditions

Key Discoveries and Achievements

- Robotic outposts will be established for extended scientific and environmental studies and preparation for human missions
- Human exploration of Mars will begin, representing one of the major scientific and engineering achievements in human history
- Humans and robots will form unified systems that will maximize detailed study and understanding of the evolution of Mars and life

In the coming decades, Mars orbital, *in situ*, and sample return studies are planned to achieve a comprehensive understanding of martian environmental characteristics and potential life. A likely evolution of the robotic program and a direct step toward human exploration is the establishment of a "robotic outpost". This is a localized collection of landed robotic assets that performs science and/or engineering tasks cooperatively, and may be an effective means of preparing for the arrival of human explorers. Cooperation may be directed by Earth-based controllers or autonomously. Tasks suitable for outposts will most often be those for which single independent robots cannot accomplish a task. We are confident that the scientific exploration of Mars will grow increasing challenging (in complexity or intricacy) such that some objectives will require cooperative engagement of robotic systems. An example is drilling to depths of 100 m and greater – a task that may be valuable for science and for access to resources needed to support human missions. In obviously challenging task, not only is the drilling itself mechanically sufficiently complex to require multiple robots but the analysis of samples for drill-operations and scientific purposes requires that numerous additional robotic skills be brought to bear.

Robotic outposts will be a powerful tool in the more advanced stages of the robotic exploration of Mars. Outposts are naturally a tool for the future because we must first locate and explore preliminarily sites that warrant devoting the significant amount resources required by outpost deployment. The discovery of an active hydrothermal vent on Mars would easily qualify as a site for follow-up and, potentially, the emplacement of an outpost. Deployment of infrastructure at the first human landing site is another likely role for robotic outposts. In fact, robotic outposts will be excellent candidate sites for landing humans because of the scientific opportunities there and the accumulated understanding of the site and its environment. Preparing a site for human explorers would involve erection and assurance of the habitat, deployment and test of an in situ resource utilization (ISRU) system, and deployment of a surface power system.

Robotic Outposts Supporting Human Exploration. The period from 2025 onward will focus on continued detailed scientific study of one or more key sites. Small outposts will be deployed for continued monitoring of the planet and its external and internal environments. Further, a primary outpost will be designated for a human landing, with robotic systems deployed to prepare the site. Deployment and assurance of infrastructure for humans (habitats, ISRU, power, power distribution) will likely be an enabling role for robotics.

Finally, we see the humans and robotic systems working together on Mars to continue to understand habitability and life on the red planet. In particular by this time period we should be able to characterize in detail how any martian life sustains or sustained itself, i.e., the ecological system. If the ingredients for life were or are present and life did not form and evolve, an equally challenging and important question is why not, with definite implications for formation and evolution of life on Earth.

Preparing for Human Exploration: Goals and Recommendations

Human exploration of Mars will be the culmination of a multi-decade program of discoveries and developments. But human exploration is decades away; our near-term goal must be to understand Mars and to enable sound strategic decisions that will create an affordable and sustainable architecture. Among the required elements that will lead to these decisions are:

- Architecture development and systems studies to identify and address the architectural swingers
- A flexible design reference mission to guide investments and decisions and provide the context for architecture assessment
- Articulation of an objective function by which candidate architectures will be compared and selected
- Knowledge of Mars resources and environment, and the effects on humans of Mars surface presence and interplanetary travel
- Understanding of human exploration in a planetary environment through extended human lunar missions
- A comprehensive capability development program using a variety of venues for validation

Overview of Key Goals and Challenges

Human exploration missions to Mars will require systems engineering and operational planning on a very large and perhaps unprecedented scale. The first step in the process is the selection of an overarching architecture that properly connects all the phases of the mission, beginning with launch from Earth and continuing through not only descent and landing on Mars and a surface mission of significant duration, but also ascent from the Mars surface and a safe return to the Earth. Over the past two decades, in various studies conducted by NASA and independent space groups, dozens of candidate architectures for human missions to Mars have been examined. But there exists no single architecture that represents a best baseline, or reference, mission for human exploration of Mars.

All candidate architectures require an enormous amount of mass to be placed in Earth orbit, at least 500 metric tons. All the architectures call for at least one precursor robotic cargo mission to land major infrastructure elements on the surface of Mars, and for this cargo mission to be followed by a pinpoint human landing in the immediate neighborhood of the landing site of the cargo mission. This is a huge delivery requirement, up by almost two orders of magnitude from the delivery capability of today's robotic Mars missions, and represents one of the major technological challenges of a human Mars mission.

Another feature common to all the Mars human mission architectures is the requirement for substantial power availability on the surface, both to support the deployment and maintenance of the infrastructure elements delivered by the cargo missions, and to sustain the human presence for any significant period of time.

All the architectures also assume that a long-term investigation program will eventually conclude that it is indeed safe to send human beings to Mars. At present human safety for such a mission has not yet been firmly established. To certify that the Mars environment itself is not harmful to humans, both in situ measurements by robotic spacecraft at Mars and the careful examination of samples brought back to the Earth from Mars are necessary.

Assumptions about in situ resource utilization (ISRU) are another major factor differentiating among the existing architectures. ISRU technology could be used to manufacture propellant for the Mars ascent vehicle, to produce water to sustain the crew, and to conduct other even more sophisticated tasks. However, ISRU technology is not yet mature. Before a human mission to Mars could include ISRU as a critical link in its architecture, the reliability of the ISRU processes would have to be demonstrated.

Strategy for Defining, Downselecting, and Confirming Mars Human Exploration Architecture

To determine the “best” architecture for a human mission to Mars requires the establishment of quantitative metrics, or at least evaluation criteria, relating such diverse attributes as human safety, mission risk/resiliency, system performance and robustness, technological readiness including development cost, schedule, and risk, science quality/quantity, and program policy. The single most important recommendation of the Mars roadmapping committee is the immediate establishment of a blue ribbon, multiyear, multidisciplinary, One NASA systems engineering team, whose primary function will be the development of these metrics and criteria to permit the comparative evaluation of the overall merit of the different possible architectures for a human mission to Mars. This recommendation, along with the other findings and recommendations resulting from the committee study, is presented in more detail in the subsequent paragraphs of this section of the report.

<u>Proposed program of NASA/industry studies</u>

An integrated “Super Systems Engineering” team should be formed immediately to guide decisions and investments for the integrated robotic-human Mars exploration program. This team should be multi-organizational in nature, including personnel within and external to NASA. Industry should also be heavily involved in the overall activity, both through broadbased systems engineering contracts and through more focused contracts emphasizing the key enabling systems This team should develop and assess candidate architectures and evaluation criteria for an integrated robotic and human Mars exploration program. The team should guide a series of joint NASA/industry studies which focus on architecture development and on study and downselection of key technology options. These studies should be initiated immediately so that there results can be available for the initial architecture downselection in 2008.

Reference human mission framework for capability needs assessment

A 2–4 year time period is required to perform thorough *preliminary design* level mission and flight system designs that are technically feasible. With these preliminary design efforts as a guide, prioritization will be possible among the many specific technologies that could be applicable to human Mars exploration. This effort will also allow requirements development for a Mars human exploration program to proceed and develop a technology development plan.

The initial focus of this team should be on the appropriate evaluation criteria against which to assess potential Mars exploration architectures. A multi-parameter evaluation scheme should be developed, with quantitative metrics if possible, that includes, but is not limited to, factors like human safety, mission resiliency, system performance and robustness, technology readiness, program policy, cost, schedule, and science quality/quantity must be developed. In addition, specific technology assessments should be undertaken in parallel.

Decision Strategy

The roadmap committee recommends the following timeline for key architectural decisions leading to human Mars exploration. This will take advantage of the scientific results of robotic missions, as well as capability development and validation of human operations on the Moon, and should be an affordable process that allows sufficient time for analysis and debate.

- Refine architectural and system studies and prepare a small set of *candidate architectures by 2008*
- Based on data from Mars robotic science and environmental measurements, select *preferred architecture(s) by 2015*
- Develop and test key capabilities, conduct further Mars science and precursor missions, and validate human exploration systems and concepts on the Moon to support *architecture confirmation by 2025*
- Begin emplacing long-lead infrastructure in a robotic outpost, continue capability development and sustained lunar exploration, verify readiness, and prepare to *launch the first crew to Mars by 2035-2040*

A number of technical factors will contribute to the design and final verification of the architecture. Among these key architectural decisions are:

- Select a new human Mars Design Reference Mission to guide capability investments and future mission planning
- Select lift capability of new heavy-lift launch system and determine timeframe of availability
- Identify and validate feasible means of safely landing large (~40 MT) mass elements on the surface of Mars

- Confirm the presence of usable subsurface water on Mars
- Identify the Mars mission elements for which validation on the Moon is critical
- Decide whether to proceed with fission reactor system for Mars surface power
- Determine the nature and degree of human health hazards likely to be encountered on Mars
- Determine need for high-efficiency in-space propulsion based on fission power
- Confirm the ability of humans to live and work safely in deep space long enough for transit to Mars, exploration of the planet, and return to Earth

An Integrated Robotic-Human Program: Role of Robotic Missions

Just as the robotic lunar missions of the 1960's were critical precursors to Apollo, robotic missions to Mars will lay the groundwork for sending humans to explore the Red Planet. Any national commitment to sending humans to Mars will depend critically on a robust program of robotic precursor missions that will enable good architectural decisions and maintain an acceptable level of risk to human explorers.

Robotic missions have already yielded a wealth of scientific data for reconnaissance, site selection, environmental characterization, surface operations planning, and resource mapping. They have laid the scientific foundation that will ultimately determine how and when, and perhaps whether, humans will travel to Mars, and what tasks they will accomplish when they get there. Mars Sample Return can be viewed as a clear tie point between the robotic science and human exploration program elements, since it will exercise all required elements of a round-trip mission and will help provide scientific and operational confidence in our exploration decisions.

The robotic exploration program's current mission plans focus on expanding our scientific knowledge of Mars in areas that are closely aligned with the needs of preparing for human exploration. The science priorities, such as the understanding the role of water in Mars' past and its current form and abundance, characterization of the regolith, and determining the biological potential of past or present Mars, are directly applicable. The science missions now planned will address many of the critical measurements needed for human exploration, including: toxicity and trafficability of the Martian surface; dust characteristics; potential biohazards from possible Martian life; atmospheric characterization for electrical properties; Martian meteorology and characterization of dust storms; and the existence, extent and location of water. MSL, AFL, and MSR will provide critical measurements in the characterization of possible organics; biohazard potential from extinct and/or extant life; radiation environments at the surface over time; meteorological data; lateral distribution of near surface water, dust mineralogy, adhesive properties, and toxicity; and surface soil variations by location. MRO, through high resolution imagery and moderate resolution sounding will globally extend previous measurements, identify and evaluate possible landing sites, identify location of resources and shallow subsurface features, and improve the understanding of the atmosphere.

Common threads link our scientific study of Mars with preparation for human exploration

	Scientific Imperative	*Human Preparation Imperative*	*Key Missions*
Search for Water	• Habitability • Geology/climate history	• ISRU method • Dramatic mass reduction	• Odyssey, Phoenix, Mars Science Lab, Mars Sample Return, Scouts • Mars Environ. Mission
Characterization of the Environment	• Planet evolution and processes	• Safety and productivity • Design of systems and habitats	• Mars Recon Orbiter, Mars Science Lab, Mars Sample Return, Scouts • Mars Environ. Mission
Search for Life	• Evolution of habitats • Origin, nature, prevalence of life	• Where and how to explore • Planetary protection	• Mars Sample Return, Astrobiology Field Lab, Mars Scouts

<u>Mars Water and Human Exploration</u>

The search for Mars water represents a key unifying theme that links robotic science and human preparation goals. Confirmation of accessible /usable water in the near sub-surface will open new architectural domains for future human Mars exploration. It can provide a source for both propellant production and human consumables, and can result in significant mass reduction and potential crew safety enhancements. While these benefits are clear, a negative result (absence of usable Martian water) will not invalidate human missions to Mars. Alternative pathways of resource utilization should be preserved until an informed decision can be made. Recommendations for near-term studies and missions are:

- Highest priority is Mars Science Lab to confirm and localize water in the near sub-surface
- Use search for accessible water as one of the architectural elements integrating the near-term science and human precursor missions
- Form a Science Study Group to suggest investigations and measurements (to be incorporated in science missions and dedicated Mars Environment Missions)

Key Capability Requirements

A large number of new capabilities and technologies will be required to enable advanced robotic exploration and eventually human exploration of Mars. The roadmap team has not attempted to specify each and every such development; clearly, that can only be done as a part of the detailed architecture and mission development and assessment that will continue throughout the decades. However, there are several capabilities that can be considered “architectural swingers”. These developments are considered so important that they will define the architecture and many other decisions will flow from them, and thus represent the top priorities for immediate study and development. Capabilities that are judged to be required include:

- A heavy-lift launch vehicle with lift capability to LEO of approximately 100 metric tons
- Advanced entry/descent/landing (EDL) technologies that will enable safe and precise landing of large robotic missions such as Mars sample return. This technology may also be suitable for landing elements of human infrastructure in a robotic outpost.
- Human-scalable EDL techniques capable of delivering about 40 metric tons safely and precisely to the surface.
- Systems for human life support, health, and safety during interplanetary travel and exploration of the surface of Mars. Development decisions will depend on research on the International Space Station as well as results from Mars robotic missions and human lunar missions.
- Power systems that will supply 60-100 kW on the Mars surface. This power level may be supplied by several units capable of 20-40 kW each to allow deployment flexibility. The roadmap team believes that fission power systems will be the most viable means of power generation for human exploration and thus advocates continued research and development of space nuclear power systems. Advanced radioisotope power will continue to be required for robotic missions.
- Advanced telecommunications and data networks on Earth, including an next-generation Deep Space Network

Several capabilities are judged to be possibly required, depending on the results of architecture studies and Mars robotic missions. These include:

- In situ resource utilization for production of propellant and human consumables, as well as for materials that may be used for construction or shielding on the surface. A key determinant of the value of ISRU is the availability of accessible subsurface water on Mars. In the view of the committee, water-based ISRU opens architectural pathways that may be of substantial benefit, and so the search for water is an important aspect of preparation for human exploration. Even if water is not available, however, ISRU may still be an important architectural element. Research into multiple types of ISRU should continue until enough is known to make a well-informed selection.
- High-efficiency interplanetary propulsion using nuclear power. The mass benefits of nuclear propulsion can be substantial, but its value must be assessed in the view of other parameters such as heavy-lift capability, ISRU, acceptable duration of human space travel and total mission, and other factors. Architectural studies should carefully consider the entire trade space before a judgment can be made on the need for nuclear propulsion.

Robotic Technology Leading to Human Missions

Technology on robotic science missions will lead the way to human-required technologies. Large-mass landing systems will be required to place humans on the surface. Entry, Descent and Landing technology investments will begin with precision entry and navigation with the Phoenix mission, and evolve through MSL and MSR where mass-to-the-surface will continue to increase, and pin-point landing will be achieved to access high-priority locations. Surface mobility technologies will evolve through increasingly autonomous robotic exploration of the Martian surface. Surface accessibility through mobility has rapidly advanced from the several-meter roving capability of Mars Pathfinder, to the several kilometer capability of Sprit and Opportunity, to the tens-of-kilometers planned for the MSL. MSR will be the first demonstration of a round-trip mission capability to Mars. While not directly scalable to human mission needs, MSR will serve as a “model” for patterning the following decade’s sub-scale/scalable missions in advance of the first human mission. These missions will provide test-beds that will achieve critical technological hurdles before human landing.

NASA performed a study in 2004 to initially define precursor measurement and technology needs and priorities for human exploration of Mars. These initial studies yielded a series of measurement and technology gaps between human precursor requirements and the existing Mars Program portfolio. They provide a framework from which a more extensive series of study tasks should be undertaken. These new studies should define new potential human architectures, and the resulting measurement and technology pathways necessary to accomplish a human landing in the fourth decade.

Integration of robotic science mission plans and objectives, and human precursor requirements will lead to cross-program efficiencies and mutual benefit. NASA should focus the program through a coordinated management structure, such as a Mars “Super Systems Engineering” Group. Engineering-level determination of technology development and precursor mission requirements, acquisition, and partnering strategies, and near- and long-term architectures should feed into this steering group. NASA should initiate industry/government study tasks to help define the technology and mission compositions for human precursor missions and provide pathways for human architecture options.

Mars Environment Missions and Human Precursors

Initial studies mentioned above culminated in a strawman set of possible Mars Environment Missions (MEM) that also serve as precursors to human exploration. The extended studies are crucial to the definition of the first dedicated MEM mission. The Committee defined the following principles:

- Leverage the science mission portfolio to meet as many precursor measurement requirements as possible, without compromising the scientific integrity.
- Mission priorities must be set through community-wide studies, and should lead to human architecture supporting the first human landing in the century’s fourth decade.

- The first testbed mission should be launched by 2013, and must concentrate on the "gap" requirements, by priority.
- Target a major subscale, but human-scalable, landing in the latter part of the next decade or early in the 3rd decade (an excellent opportunity for a second sample return from a high-probability human landing site).
- The overall Mars program, with the core science, Scout and precursor elements, must support a human mission architecture validation by 2025. Prior to this decision point, selection of a human mission architecture should be made in the middle of the 2nd decade to ensure that a sub-scale/scalable demonstration mission is conducted in the early in the 3rd decade.
- Joint industry/government studies must be conducted so that NASA can determine the construct of the first MEM mission. This decision must be made by 2008 to ensure a 2013 launch.

Initial infrastructure establishment with Mars Telecommunications Orbiter (MTO) is an important step toward future missions. Additional MTO missions, with advances through essential technology infusion, should be included in the program.

Test Venues: Verification and Validation

Technology advancement should be accomplished using cost-effective strategies across multiple test venues. Technology development activities should include: System studies and analyses, Earth-based testing and test-facility improvements, flight testing in the Earth's atmosphere, flight testing in Earth orbit or at the Moon, and human precursor investigations on flights to Mars. Earth test venues should lead the way and offer high data quantity and quality, a high-degree of test setup control, resilient data acquisition and return strategy, and reasonable test cost.

Unique Contributions of Lunar Missions

The Vision for Space Exploration clearly articulates the linkage of the Moon and Mars. Human exploration of the Moon is a step toward human exploration of Mars; likewise, human missions to Mars will only be undertaken after sustained lunar missions have provided validation of exploration systems and concepts. Exploration of the Moon will motivate advances in technology, operations concepts, program development and management, and engineering of large complex "systems of systems", all of which are key to human Mars missions. A number of specific technical contributions have been identified for which validation on the Moon may be important, including:

- Habitat design, construction, and operation
- Autonomy and human-robot interaction
- *In situ* resource utilization and launch from planetary surface
- Utilization of heavy-lift launch system for human missions
- Ascent from planetary surface and high-speed Earth entry of high-mass systems

Human Mars mission requirements should be derived and levied on lunar missions to ensure a unified exploration program in which the Moon is a platform to demonstrate "Mars-like" exploration systems and procedures. Architecture/system study results and initial human precursors will provide and validate requirements. NASA should strive to implement the lunar and Mars programs as an integrated endeavor to assure continuity and maximize value of common investments. Lunar exploration activities should be phased to provide maximum benefit to Mars architecture confirmation in ~2025

Required Infrastructure and Core Competencies

- The NASA workforce, infrastructure, and facilities must be energized and defined to meet the challenges of Mars exploration. A first step is to survey engineering talent and facilities to establish baseline and identify gaps. Strategic partnerships among government, industry, and academia will enable the nation to accomplish the required tasks most efficiently. In the view of the committee, key areas of emphasis for workforce include:
  - Systems engineering and mission planning
  - Robotics, mobility, instrument/system integration
  - Physiological research
  - Nuclear systems
  - Atmospheric entry and dynamics
  - Planetary science

Key areas of emphasis for facilities include:
- Atmospheric entry simulation and test
- Nuclear systems testing
- Mars simulation with realistic surface material/environmental properties
- Testing, simulation, and modeling of large-scale complex systems
- End-to-end ISRU system operations in a simulated Mars environment

NASA should begin immediately to ensure that these core competencies for Mars exploration are addressed.

What We Need to Know About Mars and the Interplanetary Medium

To make well-informed decisions about the feasibility, risks, timeline, and required developments that will lead to human exploration of Mars, we must acquire critical knowledge about the interplanetary medium and the Martian environment. The key measurements are those which cannot be made using any other test bed, but require robotic precursor missions. It cannot be stated categorically that all these measurements must be successfully accomplished prior to human arrival on Mars, as the acceptable risk for human Mars missions has not been addressed. However, it is important to understand how to mitigate as much risk as possible.

This committee reviewed the work of prior committees who have addressed the needs for robotic measurements on Mars prior to human arrival. Primarily two reports were reviewed. The first was the NRC Safe on Mars Report (NRC, 2002) which addressed hazards arising from exposure to the environment, including chemical and biological agents. The second and primary source of information was the report of the Measurements Subteam of the Mars Exploration Program Analysis Group (MEPAG) Mars Human Precursor Science Steering Group, Beaty et al. (2005) to analyze the kinds of measurements that robotic precursor missions could make that would have a significant effect on the cost and risk of the first human missions to Mars (MEPAG Goal IV). They considered Mars-related risks to the flight or surface systems in addition to environmental hazards to human and focused on design risk with recommendations for specific measurements to be made on robotic precursor missions. We highly recommend the reading of these reports as they address many interesting issues and contain much more detail than we have included here. Our discussions and recommendations borrow (and quote) heavily from the MEPAG report.

Interplanetary medium

The major risk during in-space transit is radiation. The interplanetary flux is fairly well characterized, although specific vehicle designs need to be developed to protect the crew against galactic cosmic radiation and infrequent but very intense solar particle events associated with solar storms. The roadmap team makes no recommendations for any additional robotic missions to characterize the radiation in the interplanetary medium.

Martian environment

Of interest here are environmental, physical, chemical, and biological issues that need to be well characterized prior to the first human mission to Mars. We are also concerned about what contamination may be transported to Mars and what may return with the vehicle and crew. Of high importance is confidence in the ability to land successfully on the Martian surface and lift off at the end of the mission. The following list of recommended measurements is roughly in order of priority.

- Perform sample measurements to characterize shape and size distribution, electrical and chemical properties of Martian dust. Perform *in situ* measurements of polarity and magnitude of charge of suspended particle both during quiescent periods and during dust storms. Include subsurface samples.

- Collect samples of air-borne dust to determine if life is present in the Martian near-surface soil and if it is a biohazard. Collect biological assays at the landing site reflecting all geological materials with which humans may come in contact as part of an MSR mission.

- Make basic measurements of atmospheric electricity. Also collect measurements of dust density from storms as a function of time at the surface for at least a Martian year. Use an orbiting weather station to monitor dust storm frequency, size and occurrence over a year, at varying altitudes if possible. Temperature measures should also be made as a function of time.

- Perform sample measurements to characterize toxicity of Martian dust. Assay for chemicals with known toxic effects on humans and assess possible impact on human tissue. Include subsurface samples at the landing site.

- Design *in situ* measurements, which, without contaminating the Martian environment, determine the fate of terrestrial organisms on Mars. Include measurements to determine such things as the rate of oxidation, the mechanisms and rate of dispersion, transport properties from into the Martian subsurface, and perhaps most importantly, if the terrestrial microbial life can survive and reproduce in the Martian environment. This almost certain terrestrial contamination, particularly if the effects cannot be well-characterized, makes finding indigenous life prior to human arrival a high priority to avoid the chance of a false positive.

- Measure mechanical and physical properties of the soil and ice/soil mixtures including variation with depth: (i) the cohesion, (ii) the soil density before and after volatiles are expelled thermally, (iii) an index test of shear strength, and (iv) the specific energy of boring.

- Make *in situ* measurements to determine the absorbed dose in a tissue-equivalent material on Mars at the expected or representative landing site and working area.

- Use orbiting satellites and in situ measurements to acquire accurate knowledge of the roughness, vertical terrain information including steepness, traction and cohesion in the Martian soil for the human mission landing site and expected area of operations during EVA.

It bears repeating that the reports mentioned earlier, particularly the full version of the MEPAG Goal IV recommendations (substantially quoted here) should be referenced for more detail and information.

Summary of Decadal Steps Toward Human Exploration

The following are a series of key achievements by decade for an integrated robotic-human Mars exploration program:

<u>2005-2016:</u>

- Follow the water: study geology, climate, habitability
- Characterize surface, dust, atmosphere
- Understand biological potential
- Identify accessible water
- Conduct physiological studies of human space flight and hazard mitigation
- Develop candidate architectures
- Emplace telecom network elements

- Develop key technologies such as EDL, ISRU, laser com
- Extensive field testing

2016-2025:
- Lab study of Mars samples
- Intensive search for life
- Subsurface exploration
- Understand potential Mars hazards - toxicity, biohazards,
- Scaleable demos of key capabilities (ISRU, EDL) and dress rehearsal
- Develop other major capabilities
- Expand Mars telecom infrastructure
- Human habitation and ops validation on Moon
- Select and validate human Mars architecture
- Select site for robotic outpost
- Commit to timetable for human Mars exploration

2025-2035:
- Understand and predict Mars weather and atmospheric variability
- Robotic outpost/landing site detailed surface characterization and resource surveys
- Discovery-driven opportunistic science
- Develop tools for human scientists and explorers and build flight elements
- Emplace infrastructure at Mars and verify performance of key elements, including ISRU capabilities
- Demonstrate sustained human exploration on the Moon
- Prepare to launch the first human crew to Mars

2035-beyond:
- Unified human-robotic exploration and science
- Human surface expeditions and outpost development
- Deep drilling for resources and samples
- Human teleoperation of robotic explorers in harsh Martian locales
- Return to Earth of first Mars crew
- Continuation of sustained robotic-human Mars exploration

Growing the Community of Mars Explorers

Overview: Analysis of Needs and Priorities

A 30-year roadmap for robotic and human exploration would not be complete without considering the next generation of explorers, who will carry forth the Vision and roadmap outlined today. Out there in classrooms across America are the talented and curious students who will play vital roles in leading future scientific discoveries or in creating technologies that will eventually land humans safely on Mars, sustain them on the surface, and enable them to conduct ambitious first-hand scientific studies on another world. Among these young students are those who will set foot themselves on the surface of Mars, representing humankind as a whole in a quest for knowledge about the habitability of worlds beyond our own. Reaching and inspiring these students is a paramount goal.

The NASA workforce is aging, and many critical skills are at risk of being lost. National Science Foundation and other studies show undergraduate and graduate enrollment in science and engineering has steadily decreased over the past decade, while job opportunities in these fields have grown. Because diversity in science and engineering fields remains low, much more must be done first to attract diverse talent, and then to retain it. As cited in NASA's Education Enterprise Strategy, national education statistics also show that roughly one-third or more of K-12 students score below average in science and mathematics. It is from this currently weakened pool that NASA and the overall US economy are fed.

Of concern is a decline in the NASA budget for higher education programs as detailed in NASA's FY06 Budget Estimate (from $77.4M in FY04 to $39.4M in FY06 and roughly stable thereafter). While many effective efforts are made at the K-16 level, a break in the pipeline seems to occur at the pre-professional (graduate) and early career level, exactly where traditional NASA education and outreach (E/PO) programs end. That gap should be corrected.

Next-generation Explorer: Graduate student working with mentor on mission data.

For a robust program, strong links must also be maintained between NASA education programs and the science and engineering communities. The mission teams hold the content, are the current practitioners in relevant career fields, actively serve as role models for future generations, make strong contributions to NASA educational programs and materials, and are mentors for career paths in space science and engineering. E/PO programs should be rigorously evaluated for educational effectiveness, but not decoupled from the heart of research and exploration taking place in the mission directorates, at universities, and with industry partners.

Cultivating a future NASA workforce with strong science, technology, engineering, and math (STEM) skills is critical, but not sufficient, to achieving the Vision over three or more decades. Sustained public support is essential to a robust, long-term program. As recent internet records for public interest suggest, Mars exploration has the chance to become a true "people's program" if investments are made to increase opportunities for direct experiences. A strong commitment to public participation would recognize that NASA ventures into space on behalf of citizens who support its scientific discovery and technological innovation through hard-earned tax dollars. Along with enhancing public awareness of the goals, challenges, and potential rewards of Mars exploration, opportunities for direct public involvement should be prioritized as part of an effort to build a greater return on the public's investment than ever before.

Strategy for Growing the Community of Next-Generation Mars Explorers

Attracting and retaining a diverse workforce to support the Mars Robotic and Human Exploration Roadmap depends on a strong strategy to strengthen and expand needed talent across the nation at universities, research centers, and industry. Such a strategy would actively support NASA's goal of inspiring and motivating students to pursue careers in science, technology, engineering, and mathematics and help meet NASA's Office of Education "pipeline" goals.

Increasing Diversity: Attracting women and other underrepresented graduate students is a key strategy for Growing the Mars Community.

In designing a strategy, the first step is to understand what success would look like in terms of workforce size and disciplinary mix. That understanding is important so that NASA can assess which specific areas may need targeted efforts to ensure an adequate workforce and which will likely have a ready supply based on trends in graduates and career choices. From the student and recent-graduate perspective, it is also important not to oversell the availability of possible NASA jobs—transparency in prospective job availability in various disciplines, at given timeframes, is important.

On the science side, an initial assessment of impediments for graduate students in choosing to enter Mars (or planetary science) careers was conducted by the Mars Exploration Program Analysis Group (MEPAG), which has a membership of 100+ Mars scientific researchers. Student input was found to be essential in assessing barriers and solutions, as many of the impediments cited by the students were not anticipated by those already established in the field.

Factors limiting a future Mars Science Community addressed in this report include: financial uncertainties in Mars research; inaccessibility of data and slow publication of research results; few student opportunities for involvement in flight missions; lack of awareness of planetary science as a career option; and, too few inter- and cross-disciplinary researchers.

Recommendations: Grow the Community
1. Define and characterize the current Mars science and engineering communities (size, disciplines, age distribution, diversity etc.)
2. Characterize and quantify future needs in the Mars science and engineering communities, both in terms of numbers and disciplines, to support both robotic and human exploration. Specifically, determine how many will be needed, and in what careers, in 2010, 2015, 2020, and 2025 (i.e., in 5-year increments or by program milestone) to support Mars (and lunar) exploration.
3. Determine gaps, barriers and solutions on the basis of findings. Incorporate results from prior studies, such as MEPAG's *Grow the Community* report, and commission similar studies for engineering fields.
4. Adequately fund solutions, ensuring that mission (and not R&A) funding for attracting and retaining early-career professionals from diverse backgrounds is a high priority

Potential solutions offered include: enhanced research and data- analysis funding; improvements related to data accessibility and online student publishing; competitive intern programs in all Mars missions; changes in proposal selection criteria to encourage graduate-student participation; the creation of a Young Postdoc/Mentor program; Mars visiting lecturers for student and faculty training at and beyond universities producing most of the current planetary science candidates; training for graduate students and faculty to access Mars data; websites laying out "stepping stones" to Mars science careers; and, interdisciplinary technical workshops and NRAs.

Among these recommendations, adequate funding for early career professionals is of highest priority. Most research grants are not large enough to cover a competitive salary, so mission funding is recommended. Increasing funding to "livable" levels is important so that the best and brightest are not forced to go elsewhere career-wise. Early-career funding is also important to attracting and retaining diverse talent in the NASA workforce, as more attractive possibilities for new graduates are currently found elsewhere. For example, there were 68 participating scientists in the past four Mars missions. Only 15% were within 5 years of their Ph.D., and only 7% were women.

Beyond graduate-student and early-career science professionals, funding is also inadequate for retaining many outstanding researchers interested in studying Mars. Nor does funding exist to address many of the most compelling questions in Mars research. Therefore, it is also necessary to increase average grant size and duration of Mars investigations, and provide new opportunities for trans-disciplinary teams to attack large problems in Mars research.

Mars science will flourish only with increasingly interdisciplinary teams of researchers, and there is insufficient connection between the Mars community and other relevant areas of science. Increasing inter- and cross-disciplinary opportunities for collaboration is key. For example, the health of the community would benefit from convening technical workshops that bring Mars researchers together with Earth researchers and encouraging collaborations by adding interdisciplinary research to the funded post-doc portfolio.

In terms of instruments, there are two significant areas that need attention. First, the community of instrument scientists at universities is insufficient to sustain Mars exploration, as evidenced by the complete lack of university PIs in the recent Mars Science Laboratory investigations. For that reason, it is imperative to ensure that instrument development programs like MDIP are well-funded and focused on university PIs. Second, capability for in-situ instrument development is very low, and has dropped considerably since Viking. To meet the Mars roadmap goals, support is recommended for enabling scientists to continue to push the state-of-the-art in laboratory studies of meteorites, samples returned from flight missions, and Earth rocks. Funding scientists to adapt and apply cutting-edge techniques to flight instruments on the basis of laboratory studies will also be important.

Recommendations: Handling Large Data Sets
9. Allocate funding to ensure an accessible data system by establishing uniform standards, reconciling dataset discrepancies, and developing user-friendly software tools for data access, analysis, and visualization.
10. Fund MO&DA at a healthy level. [ADD]
11. Form a cross-institutional education and training program to teach graduate students and faculty how to process and analyze data.

On the engineering side, reports from the Capability Roadmap teams provide initial information for characterizing future jobs that are essential to the robotic and human exploration of Mars. A formal MEPAG-style study addressing barriers to engineering students and recommended actions should be formally conducted as well, with solutions adequately funded.

Handling Large Data Sets

The Mars science community is grappling with the need to handle exponential increases in the return of scientific data. Mars Reconnaissance Orbiter alone, for example, plans to return 34 terabits of data, 3 times as much as five other missions put together (DS1, Odyssey, MGS, Cassini, and Magellan).

Having a large enough scientific community to analyze the results of successful missions is a goal that will enable NASA and the nation to fully capitalize on their investment in Mars exploration. Currently, the community struggles with access to Mars data and research results. Access to data is crucial to the health of the existing community and to attracting talented researchers from other related disciplines.

Developing uniform standards and reconciling data discrepancies is a baseline need. The software currently in place is cumbersome and discouraging to users who are unfamiliar with the tools. Creating user-friendly software tools for data access, analysis and visualization is key. Robust and sustained funding for Mission Operations and Data Analysis (MO&DA) is also critical.

Instituting an education and training program at universities, perhaps employing postdocs and early-career professionals as mentors and trainers, would assure that more of the data returned would be accessed. The purpose would be to teach graduate students and faculty how to process and analyze data, thus making career and research opportunities more accessible and attainable to the next generation of researchers.

Mars Public Engagement

The 2015 – 2030 workforce is in school now, so continued and expanded reach to the K-16 level is necessary. Currently, the Mars Exploration Program's efforts in Mars Public Engagement have begun to build a strong infrastructure for reaching students and teachers in key areas of interest to growing a future generation of Mars explorers.

Next-generation Explorers: Considering the best place for humans to land on Mars.

The current Mars Public Engagement Program is a model for comprehensive and coordinated efforts to reach teachers, students, and the general public. Organized programmatically rather than mission-by-mission, the effort has several advantages. When the plan was first adopted, it was considered a model for the Agency, and with adaptations for roadmap priorities, it can be again.

The longevity of the program (tied to current and next-decade missions) enables the development of lasting relationships with partner networks that increase in depth, sophistication and reach over time. Missions do not "reinvent the E/PO wheel" every 26 months, resulting in considerable cost-savings, leverage, and continuity. Missions are highlighted within the overall thematic context, allowing key messages to be conveyed about Mars Exploration, while bringing in current science to enliven content and to enable an experience of discovery as it happens.

Recommendations: Mars Public Engagement
12. For K-16 and informal learning, build on the current 20-year Mars Public Engagement Plan and related infrastructures for a 30-year timeframe, seeking expanded opportunities in areas that promote Grow the Community goals: student imaging and analysis (science, data analysis), robotics education (engineering), and other areas promoting Mars-related career skills and general STEM literacy. 13. Create greater opportunities for direct public participation in Mars exploration, including a citizen's advisory group, public engagement payloads, and other interactive ways for citizens to participate in discovery. Assess areas where NASA is willing to take input and ensure opportunities are authentic.

Mars Public Engagement has consistently received excellent reviews from NASA HQ, and has established a number of baseline programs that can be expanded and built upon. The current 20-year plan can be easily modified to incorporate Mars roadmap goals over a 30-year period and to accommodate cross-Program, cross-Roadmap (especially moon-Mars) priorities.

Among current Mars Public Engagement activities, several relate directly to the goals of growing the community by developing Mars-related career skills and science, technology, engineering, and mathematics (STEM) literacy.

Student imaging and analysis is a key focus in the Mars Public Engagement Plan. Several pilots are in place, with the goal of increasing the number and quality of students working with real Mars data. For example, students in the Mars Student Imaging Project target a camera on the Odyssey orbiter and analyze the resulting data. This program is being expanded to include Mars Reconnaissance Orbiter, Phoenix, and other future mission data sets. To date, 700 high-school students in the Mars Exploration Student Data Teams created data products during the Mars Exploration Rover mission, and 26 student interns worked for more than a year with mentoring science team members before participating in science operations during MER's primary mission.

In these programs, students have proven they can produce data products that aren't critical to mission success, but still of high interest to the science teams (e.g., rock abundances, weather animations etc.)

The Mars Public Engagement Program's focus on robotics education is designed to reach the next generation of engineers. As with student imaging, opportunities beyond the existing baseline can be built, and is an appropriate area for cross-Program coordination.

Next-generation Engineers: Tribal college students learning robotics principles.

Another existing sample program that aligns with the roadmap, and relates directly to human exploration, is Imagine Mars. This program asks students to design an ideal community on Mars. The program has resonance with elementary schools and with teachers who do not have strong science backgrounds themselves. In essence, it is It is a "gateway" activity for introducing Mars topics given its multidisciplinary approach (a blend of science, technology, civics, and the arts). An interagency partnership with the National Endowment for the Arts and HUD, it is beginning to attain national reach, particularly with after-school groups.

Because it is one of the few NASA education and outreach programs that is thematically and programmatically organized, Mars Public Engagement is already in a good position to carry forward Roadmap priorities, building on current partnerships and a strong baseline of student, teacher, and public participation.

The Mars Public Engagement Program's focus on public participation is highly encouraged. Mars exploration is undertaken on behalf of the American public and reaches the world.

A new initiative to be considered is a citizens' advisory group. Notionally, two individuals from each state could be randomly drawn from entries collected at museums and other venues. Participants would serve a two-year-term, learn about NASA programs, and have the opportunity to offer input on given topics. A caution is that opportunities for input should be authentic – NASA should be careful in selecting in what areas it is willing to take input.

The plan's concept of public engagement payloads has begun to be incorporated at the margin by missions. For instance, the upcoming "People's Camera" on Mars Reconnaissance Orbiter and video capabilities on Mars Science Lander recognize the importance of public participation and direct, immersive experiences of Mars and exploration on the red planet. Commitment to public engagement payloads, however, could be formally built into mission planning.

The Mars Robotic and Human Exploration Roadmap is ambitious and visionary, with many technical challenges and risks associated with its fulfillment. Following the Mars Exploration Program's Risk Communication Plan, continuing to be transparent and open about the challenges of Mars exploration with the general public and specific stakeholders is vital, and a cross-Roadmap issue. Engaging stakeholders such as environmental groups, the launch-area community, sample-handling-facility communities, and Native American groups among others is recommended, with a focus on fulfilling NASA's public-information responsibilities.

Other innovative ways of engaging the public should also be considered, especially those that provide virtual experiences of Mars exploration. Some ideas include a video game analogous to that funded recently by the Army in which the game is augmented every few months to keep interest high. NASA could also celebrate exploration each year with an event with prizes for the best exploration of the year. It would keep the public aware of the value of exploration, and would resonate with the concept of a nation of explorers.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
ROBOTIC AND HUMAN EXPLORATION OF MARS
STRATEGIC ROADMAPPING COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Robotic and Human Exploration of Mars Strategic Roadmapping Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on Mars exploration, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. The purview of the Committee also includes advice and recommendations on human expeditions to Mars after acquiring adequate knowledge about the planet using these robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

SRM 3 – The Solar System Exploration Strategic Roadmap

TABLE OF CONTENTS

I. Introduction

The solar system—our Sun's system of planets, moons, and smaller debris—is humankind's cosmic backyard. Small by factors of millions compared to interstellar distances, the spaces between the planets are daunting but surmountable stepping stones toward the human dream of interstellar flight. And it is within this cosmic backyard that the immediate clues to our own origin—that of life, and of the Earth as a persistently habitable world—are to be found. We wonder, as we look up at our neighboring planets on a dark, moonless night, whether life is to be found on these worlds, either viable communities of simple organisms or remains that have been dead for geologically-long periods of time. If so, then perhaps the universe beyond our backyard is teeming with life, from the simple to the complex. If, instead, we find our planetary neighbors to be sterile testaments to a delicate fine-tuning of conditions necessary for initiating and sustaining life, then we must ask ourselves whether we are alone in a vast, impersonal cosmos.

It is for these reasons that we explore the solar system with robotic emissaries: to flex our technological muscle by crossing vast distances and operating in exotic and extreme environments; to understand how the planets came to be and what triggered different evolutionary paths among worlds; to trace the early history of our own planet Earth and how it came to be habitable; to search for evidence of extinct or extant life and life's precursory chemistry on and within neighboring planetary bodies. Mars is an important target of these endeavors but not the only one; were the red deserts and canyons of that world to be our only goal, humanity's explorations beyond Earth would be greatly impoverished. Likewise the Moon, despite its importance as a signpost of the first billion years of Earth's history, is no more than a stepping-stone to a surprising array of vastly different and more complex planetary worlds that lie beyond. We must explore the solar system in its vastness and variety; we must commit as the Earth's most advanced spacefaring nation to extending humankind's reach across an almost daunting array of different worlds. We must *explore!*

The United States has committed itself to the continued exploration of the solar system through the President's "Moon, Mars and Beyond" initiative. As a result of this initiative, it is an agency goal to

> "Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore the moons of Jupiter, asteroids, and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources."

But how do we construct an economically rational and technologically achievable ordering of planetary targets and exploration? The approach suggested in this roadmap begins with a set of five "scientific objectives":

1. Learn how the sun's family of planets and minor bodies originated

2. Determine how the solar system evolved to its current diverse state including the origin and evolution of the Earth's biosphere
3. Explore the space environment to discover potential hazards and search for resources that would enable permanent human presence
4. Understand the processes that determine the fate of the solar system and life within it
5. Determine if there is or ever has been life elsewhere in the solar system

The five objectives can be understood as addressing, in different ways, the fundamental goal of understanding *how our solar system became, and planetary systems in general become, habitable—and how they maintain that ability to nurture life.* How do planets that can support life arise, and what is the probability that any given system will have a habitable planet? Scientific objective 1 addresses the goal through a deeper understanding of the mechanisms by which our solar system formed, and whether our own system is a typical or unusual outcome of the general process of planetary system formation. Scientific objective 2 seeks to quantify how the planets and the space environment surrounding them evolved to the state we see today, and how this evolution affected the capability of particular planetary environments to nurture life. Scientific objective 3 addresses habitability through the present day space environment, the hazards that it presents in the near-future to Earthly life, and the potential opportunities it provides through resources to support the spread of humankind throughout the solar system. Scientific objective 4 stimulates exploration of planetary neighbors whose current environments are uninhabitable, and whose evolutionary history in arriving there might presage aspects of the future evolution of our own, currently habitable, home world. Finally, the search for life or evidence of past life elsewhere in the solar system is embodied in scientific objective 5—a mandate to understand whether Earth is and has always been the only habitable planet in our solar system.

Habitability, then, is the key word that drives the strategy in the program of exploration laid out here. But the question of habitability must be parsed, from a practical standpoint, into two threads that lead more directly to a prioritization of targets and exploration objectives. The first thread is that of habitability in planetary environments: how have specific planetary environments evolved with time, when and in what way were they habitable, and does life exist there now? The second thread is habitability associated with planetary system architecture: what determines the arrangements of planetary systems, what roles do the positions and masses of giant planets play in the formation of habitable planets and moons and the delivery to them of the chemical ingredients of life, and how have our own giant planets shaped the evolution of the impact hazard population in our own system? Both threads speak to the fundamental issue of how planetary systems become habitable by exploring our own solar system from two complimentary perspectives—comparative exploration of worlds, and exploration of planetary architecture. Both threads connect to other strategic roadmaps through the exploration of Mars as a once habitable world, and the exploration of the Moon as a preserved record of the earliest evolution of the Earth and its impact environment. And both connect to the compelling question, encapsulated in a third roadmap, of the potential variety and habitability of planetary systems around other stars.

Both threads require a mixture of small-, medium-, and large-class missions. The small ($300-500M) missions, carried out through the Discovery Program, are PI-led missions that allow fast response to address a specific set of high value scientific questions at targets that may be less technically challenging. For this reason, Discovery will pay a crucial role, as described below, in the exploration of small bodies—asteroids, comets—that provide key clues to the chemistry of solar system formation, impact hazards through time, and the shaping of the architecture of our own planetary system.

Medium-class ($500-800M) missions in solar system exploration, New Frontiers, are PI-led but respond to strategic targets specified in the Roadmap and other planning documents. New Frontiers missions will enable aspects of the exploration of a range of objects, from Venus to giant planets, but will be limited in scope in terms of the complexity of operational capabilities at these bodies. Hence, they too will play key roles in solar system exploration but cannot achieve all of the measurement and exploration objectives necessary to answer the basic questions that motivate robotic exploration of the planets.

"Flagship-class" ($800 to 1400M or $1400 to $2800M) missions will be needed in order to reach and explore difficult but high priority targets. These critically important targets could help establish the limits of habitability, not just for our solar system, but for planetary systems in general. In particular, they potentially provide an opportunity to identify prebiotic organic molecules or even extant life beyond Earth, should it exist, in our own solar system. The targets of flagship missions include the surface of Venus, the lower atmosphere and surface of Titan, the surface and subsurface of Europa, the deep atmosphere of Neptune and the surface of its moon Triton, and the surface of a comet nucleus in the form of cryogenically preserved samples.

The next section discusses the program of missions and supporting research and technology development that will be necessary to answer the scientific questions posed above.

II. Science Implementation

Contributions of Flagship-class Missions

Venus, so similar in size to Earth and our closest planetary neighbor, is a nightmarish world of vast basaltic volcanic flows lying under a carbon dioxide atmosphere whose pressure is 90 times the pressure at sea level on Earth. The surface temperature of Venus, over 460 Celsius, is above the melting point of lead and well above the temperature beyond which water cannot exist as a liquid, no matter what the pressure. Such extreme conditions are surprising even though Venus is 30% closer to the Sun than is the Earth; its globe circling sulfuric cloud layer reflects so much sunlight that the Venusian lower atmosphere actually receives less sunlight than does the Earth's surface. But the massive carbon dioxide atmosphere creates enormous greenhouse warming, and the resulting complete lack of water in the crust and on the surface not only rules out life but also profoundly affects the geology of this otherwise near-twin of Earth. How long Venus has been in this state is unclear—its basaltic veneer might have formed within the second half of the age of the solar system, and the isotopic enrichment of heavy hydrogen in the atmosphere's trace amount of water points to potentially large amounts of water earlier in Venusian history. The disorganized pattern of rolling highlands and lowlands are a stark contrast to the Earth's granitic continents and balsaltic ocean basins, suggesting that plate tectonics failed on Venus eons ago, or never began.

But the ancient Sun of 4 billion years ago was 30% fainter than it is today, and early Venus might not have experienced much more solar heating than does the Earth today. Did Venus lose its water and form a massive carbon dioxide atmosphere late in its history, or right at the start? To know the answer to this question is to understand whether the 0.7-AU region around a Sun-like star (Earth sits at 1 AU, or 150 million kilometers, from the Sun) forms part of the long-term habitable zone or is just too close. Together with a fuller understanding of the evolution of the Martian climate, we can then address whether the habitable zone around a solar-type star is narrow, perhaps extending only 0.1 AU inward and outward of 1 AU, or might extend inward and outward a significantly larger distance, with obvious implications for Terrestrial Planet Finder's search for extra-solar habitable worlds. And to know the answer is also the key to better understanding how far in the future our own planet will yield up its life-giving oceans to a relentlessly-brightening Sun and become a Dante-esque hell like Venus.

Venus' atmosphere will not tell us this story by itself. We must send mobile vehicles to the highlands of Venus, possibly with drills, to find ancient crust that has a granitic or andesitic signature—the signs of persistent plate tectonics and the action of liquid water on crustal formation. Should we find such crust—an indication that Venus was at one time more like the Earth—we might then plan a later and more ambitious effort to bring samples back to Earth to perform more detailed and delicate chemical and petrologic studies possible only in terrestrial laboratories. The surface exploration of Venus, and ultimately possible sample returns, are flagship-class missions.

The exploration of Venus is a dual attack on the question of habitability from the point of view of planetary architecture (how wide is the long-term habitable zone?) and habitable worlds (by what processes did Venus lose its early habitability, and to what extent was this purely a question of proximity to the Sun versus small differences in intrinsic properties relative to Earth. In conjunction with the study of Mars, the triad of atmosphere-endowed terrestrial planets will then be fully explored.

But a triad of a different kind awaits our robotic explorers in the outer solar system: three moons with varying atmosphere and ocean environments that parallel in an odd way the differences among Venus, Earth and Mars. Europa, Titan and Triton orbit Jupiter, Saturn and Neptune at distances of 5, 10 and 30 AU, respectively, from the Sun. Europa, tidally heated by Jupiter, is a warm rocky body possessed of an icy shell that is melted to some extent. That is, a global ocean of liquid water exists under an ice crust of indeterminate thickness. Yet the extent to which this subsurface ocean is endowed with organic molecules, the stuff of life, is unknown; the icy surface of Europa shows little evidence for carbon-bearing compounds, but few would survive for long exposed in vacuum to the high-radiation Jovian environment.

Titan has a Europa-sized rock core wrapped in a massive mantle of water ice, making it larger than its Jovian cousin. Resident in the colder environment of the Saturn system, Titan has a massive nitrogen-methane atmosphere with a thermal structure much like Earth's but with much lower temperatures (-180 Celsius at the surface), and abundant organics in the atmosphere and apparently (from early Cassini-Huygens results) on the surface. Neptune's moon Triton is less massive than Titan in the same proportion as Mars is to the Earth. It too has a nitrogen-methane atmosphere, but being so far from the Sun the atmosphere is mostly frozen out on the surface and moves seasonally from pole-to-pole, as does that of Mars. The Earth-Mars analogy carries through nicely with Titan and Triton; the former has methane rain and rivers of methane and perhaps ethane, while the latter is in deep freeze but shows evidence of a much warmer (perhaps tidally-driven) earlier history. Yet the origin of Triton almost certainly lies in the Kuiper Belt, like that of Pluto, and so the nitrogen-methane atmospheres of Titan and Triton could have very different origins.

To explore these three worlds is to address primarily habitability in planetary environments, but also (through the origins of the methane and nitrogen atmospheres of Titan versus Triton) planetary architecture. We seek to discover life in the subsurface oceans of Europa, but we must first know how deep we must drill and where to do so; are there places where tidal stresses open fissures and expose the water oceans to space? To address these issues requires sending a spacecraft to orbit Europa and map its crustal thickness and surface geology for as long as the intense Jovian radiation can be withstood, but at least a month. With or without a surface lander or penetrator on the same carrier, this requires a Flagship-class mission.

Cassini-Huygens has revealed Titan to be a world with processes much like those on Earth, but operating under different (colder) conditions and hence on different materials. Volcanism does not involve melting rock into lava on Titan; here water mixed with antifreeze (perhaps ammonia) produces buoyant "cryolavas" of viscous water that flow across the surface. Atmospheric jetstreams transition to variable and gentler surface winds that blow dark material across the surface and appear to form dunes of organic powders. Impact craters are few. Rainfall-driven streams seem to intermingle with intricate springs in the hills of the Huygens landing site; liquid methane and ethane evaporated into the warm Huygens probe to reveal their subsurface presence, and may have carved the springs and streams, as well as rounding the pebbles of uncertain composition at the landing site. Hints of benzene and cyanogen in the surface materials bespeak the presence of the products of methane and nitrogen chemistry.

Recent work hints at a prebiotic Earth atmosphere containing not just nitrogen and carbon dioxide, but significant amounts of methane and hydrogen as well. The present Titan environment may be compositionally much more akin to that of the pre-biotic Earth than was thought at the time Cassini-Huygens was launched. And the absence of stable liquid water may be a blessing for pre-biotic studies rather than a curse; without life gaining dominance on Titan, the surface may preserve the products of occasional encounters between organics and volcanically- or impact-generated liquid water. What happens when organic deposits on Titan encounter flows of water and ammonia? Are amino acids and other pre-biotic molecules created? How far toward life has organic chemistry proceeded on Titan's surface over eons of time, protected from destructive UV radiation? Could exotic life forms that utilize liquid hydrocarbons as primary solvents exist on Titan today? Is the chillingly familiar yet alien scene revealed by Huygens only a sampling of Stygian panoramas that await us on Titan? To address these questions we must return to this complex world with a mobile platform, perhaps taking advantage of the benignly dense atmosphere, to course over the surface and sample where interesting geology has occurred or large deposits of organics are present. To do so requires a flagship-class mission.

Exploration of Triton completes the study of the triad. Just as Cassini will reveal whether Titan has a significant amount of liquid water in its interior, a future mission to Triton will do the same. Such an experiment, as well as closer analysis of the weirdly melted crust of this frigid moon first imaged by Voyager 2 in 1989, will be part of a mission to explore the Neptune system. Neptune itself is a smaller "giant planet," often called an ice giant, with much less hydrogen and helium than Jupiter or Saturn It poses a number of important questions regarding how giant planets form and just what truncates the formation of multiple giant planets in a planetary system. Residing on the edge of our planetary system, Neptune may hold deep in its interior chemical clues to the nature of the rocky and icy debris that formed the giant planets. Because the proportion of rock and ice relative to hydrogen is much larger for Neptune than for Jupiter, the "signal" associated with the abundances of oxygen, carbon, nitrogen and noble gases more strongly reflects the origin of the solid material. Were the planetesimals primitive, hardly altered from the parent molecular cloud, or were they heavily processed in the outer disk? To what extent are ice giants like Uranus and Neptune the norm in other planetary systems, versus gas giants like Jupiter and Saturn or terrestrial planets like Earth? Neptune may provide a connection to a class of worlds around other stars just barely detectable with current technology, and whose commonality we do not yet understand. A flagship mission to Neptune would deploy deep probes in its atmosphere for comparison to elemental abundances in Jupiter, revealed in part by Galileo, but completed with New Frontier-class probes. It would make multiple flybys of, or orbit, Triton, exploring that world while it establishes the role our outermost giant planet played in shaping the leftover debris of planet formation we call the Kuiper Belt.

Comets are samples of rocky and icy bodies from the outer solar system that survived perturbations by the giant planets, being neither thrown in to the Sun nor ejected from the solar system. They supplied some fraction of the Earth's water and organic inventory, but their importance in making the Earth habitable in this regard remains uncertain. They are part of a population of impactors, along with debris in the asteroid belt and elsewhere that first frustrated the formation of life on Earth, but then perhaps stimulated the formation of new organisms over time through ecosystem-emptying catastrophic impacts (such as the Chicxulub impact that may have extinguished the dinosaurs 65 million years ago). Placing comets as primitive bodies in the framework of the planetesimals that formed the planets themselves requires understanding their relationship to asteroids and meteorites, a process to be completed by a New Frontiers class sample return from a comet nucleus. But to understand how comets relate to material in the cold, dark molecular clouds out of which planetary systems like our own may have formed, requires preserving and analyzing the most delicate ices and organics present in cometary nuclei. Such preserved samples could contain the most primitive precursors to life that we could obtain—organic molecules resident in ices that have been preserved far from the Sun for much of the age of the solar system. To return such a sample would require a Flagship mission.

The exploration of the solar system to understand why we exist as living, conscious beings, the extent to which we share the cosmos with others, and the long term fate of life on Earth, is a risky and challenging endeavor. Having laid out the science rationale for the program and the principal targets of the most ambitious, Flagship, missions, we next map out a Roadmap strategy that—in its combination of small, medium and large missions, together with decision points that determine the direction of exploration from one decade to the next—will bring humankind to a much deeper understanding of its place in the cosmos.

Contributions of New Frontiers (medium-class) Missions

As noted above, the New Frontiers Program comprises Principal Investigator-led medium-class missions addressing specific strategic scientific investigations that do not require flagship-class missions. The recent National Research Council (NRC) Report, "New Frontiers in the Solar System—An Integrated Exploration Strategy," identified several high priority targets for this mission class. The goals of one of these, a Kuiper Belt-Pluto Explorer, are addressed in part by the first New Frontiers mission called New Horizons. New Horizons would make the first reconnaissance of Pluto and Charon - a "double planet" and the last planet in our solar system to be visited by spacecraft. Then, as part of an extended mission, New Horizons would visit one or more objects in the Kuiper Belt region beyond Neptune. Study of Kuiper Belt Objects (KBOs) including Pluto will provide important insights into the physical nature of these planetary building blocks and allow us to survey the organic matter and volatiles that they contain. Objects such as these, diverted into the inner solar system by the gravitational influence of giant planets, may have provided the volatiles and organics needed to create habitable environments on the terrestrial planets.

The second New Frontiers mission will address the goals of one of two other high priority investigations identified by the NRC. The Lunar South Pole-Aitken Basin Sample Return mission was given priority by the NRC in part because of the importance of tying down the Moon's early impact chronology. Radioactive age dating of returned samples from this ancient impact basin could change our understanding of the timing and intensity of the late heavy bombardment suffered by both the early Earth the Moon. The emergence of life of Earth may have been stymied by the late heavy bombardment, so a better understanding of its chronology could provide important constraints on the timescales for the development of Earth's first life. The Jupiter Polar orbiter with Probes was identified by the NRC as a high priority investigation to determine if Jupiter has a core, to measure its water abundance (and hence its O/H ratio, which is uncertain by an order of magnitude), to measure the deep winds down to the 100-bar level, and to explore the magnetosphere, particularly to understand how Jupiter's magnetic field is generated. Such a mission would contribute greatly to our understanding of how Jupiter formed, and hence to advancing knowledge about the second habitability thread, i.e., how planetary system architectures affect habitability.

The other two highest priority investigations identified by the NRC for the New Frontiers Program were the Venus In Situ Explorer (VISE) and a Comet Surface Sample Return. VISE is envisaged as a balloon mission that would study Venus' atmospheric composition in detail and descend briefly to the surface to acquire samples that could be analyzed at altitude where the temperature is less extreme. The VISE scientific measurements would help to constrain models of the Venus greenhouse history and stability as well as the geologic history of the planet including its extensive resurfacing. VISE would also pave the way for the flagship-class mission to the Venus surface and for a possible subsequent sample return from Earth's hellish neighbor.

A Comet Surface Sample Return mission, particularly if targeted to an active area, would provide the first direct evidence on how cometary activity is driven, e.g., whether water is very close to the surface. Such a mission would also provide the first real data on how small bodies form and what they are made of at the molecular level. It would provide information on how the particles in a cometary nucleus are bound together. For example, is there an organic glue? Finally, it would provide direct information on physical and compositional heterogeneity at both microscopic and macroscopic scales.

These are the missions identified by the NRC as the highest priority in the medium New Frontiers class. Missions similar to these are anticipated to be solicited in upcoming New Frontiers Program competitions. It is likely that other high priority medium-class missions beyond these will be identified in future studies and may be the subject of competitions in the more distant future.

Contributions of Discovery (small-class) Missions

The Discovery Program of small ($300-500M) PI-led missions was begun in the early 1990s. It provides opportunities for relatively rapid flight missions to respond to new discoveries. Ten full missions and three Missions of Opportunity (investigations flown on a non-NASA spacecraft) have been selected in the past decade. The Discovery Program has not been constrained to address specific strategic objectives, but is open to proposals for scientific investigations that address any area embraced by NASA's solar system exploration program and the search for planetary systems around other stars. It thereby provides an excellent means for tapping the creativity of the planetary science community.

The Discovery Program has thus far included missions to planets (Mars Pathfinder and the Messenger mission to Mercury), the Moon (Lunar Prospector), comets and asteroids (the Near-Earth Asteroid Rendezvous mission, the Comet Nucleus Tour mission which was lost, Deep Impact, Stardust, and Dawn), the Genesis mission to return samples of the solar wind, and the Kepler mission to detect Earth-size planets in the habitable zones around distant stars. Details on these past and current missions can be found on the Discovery Program web site at http://discovery.nasa.gov/index.html

In the future, the Discovery Program will continue to provide competitive opportunities for focused investigations that address the scientific objectives described in this roadmap. Although the specific contributions of future Discovery missions cannot be predicted, the many past and current accomplishments show that Discovery missions will continue to be an extremely important part of solar system exploration for the foreseeable future.

Contributions of the Research and Analysis Program

The Research and Analysis (R&A) programs comprise competitive grant awards to researchers in a wide range of disciplines and inter-disciplinary fields germane to solar system exploration including cosmochemistry, planetary geology and geophysics, planetary astronomy, planetary atmospheres, and astrobiology. In combination with mission-specific Data Analysis (DA) programs, the R&A Program provides to the science community the resources necessary to convert information returned by space missions into knowledge and understanding. It also supports laboratory, theoretical, telescopic, and field investigations that contribute to understanding the results of missions or other aspects of exploring the solar system. Further, the R&A Program makes possible new and better instruments to fly on future missions and helps complete the cycle by which the knowledge derived from flight missions is used to formulate new questions about the solar system and new mission concepts to address those questions.

The following two tables summarize the scientific achievements that are anticipated over the 3 decades encompassed by this roadmap from the combination of all flight missions and the R&A program.

The role of the R&A program is well laid out in the decadal survey of the NRC-NAS on solar system exploration, to which the reader is referred for specific examples.

Table 1

Roadmap Achievements

Agency Strategic Goal: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.			
	Phase 1: 2005-2015	Phase 2: 2015-2025	Phase 3: 2025 - Beyond
Roadmap Objective 1: Learn how the sun's family of planets and minor bodies originated.	a) Probe the interior of a comet (Deep Impact) b) Return samples of dust from a comet's coma (Stardust) c) Conduct detailed studies near a differentiated and a primitive asteroid (Dawn) d) Conduct detailed studies of a cometary nucleus (Rosetta)	a) Complete the reconnaissance of the solar system with a flyby of Pluto b) Explore the diversity of small bodies with missions such as multiple comet flybys and Trojan/Centaur asteroid flybys c) Study individual small bodies intensively by means of sample return missions	a) Return cryogenically preserved samples from a comet b) Characterize the diversity of KBOs
Roadmap Objective 2: Determine how the solar system evolved to its current diverse state including origin and evolution of the Earth's biosphere.	a) Conduct an intensive orbital study of Mercury to understand how and where it formed (Messenger) b) In conjunction with the expected achievements for Roadmap Objective 1, investigate the origin of Earth's water, organics and other volatiles c) Investigate the earliest life on Earth through studies of Earth's oldest rocks as well as modern analogue microbial communities	a) Land on Venusian highland to search for granitic or andestitic rocks consistent with an early earth-like tectonic evolution b) Search for evidence of past massive oceans of water on Venus c) Characterize the past and present population of asteroidal impactors to understand the impact history of the terrestrial planets	a) Drill into various places on Venus to determine the mechanisms by which Venusian highlands were formed b) Return selected geologic samples from Venus
Roadmap Objective 3: Explore the space environment to discover potential hazards and search for resources that would enable permanent human presence *NEO=Near Earth Objects*	a) Complete (>90%) the inventory of NEOs larger than 1-km diameter b) Characterize potentially hazardous objects via telescopic remote scensing c) Study remotely the resource potential of a sample of accessible small bodies	a) Precisely track and characterize any NEO with an earth impact probability of concern b) Explore near-Earth asteroid minerology in situ to determine resource potential	a) Develop technologies to alter trajectories of potential large Earth-impacting bodies b) Study an L2 and NEO human-visit capability to understand need for robotic and piloted extraction of asteroidal resources for use in space and on Earth

Table 2

Roadmap Achievements (cont.)

Agency Strategic Goal: Conduct robotic exploration across the solar system for scientific purposes and to support human exploration.			
	Phase 1: 2005-2015	Phase 2: 2015-2025	Phase 3: 2025 - Beyond
Roadmap Objective 4: Understand the processes that determine the fate of the solar system and life within it.	a) Determine the nature of interactions and balance of processes on/in Titan's surface, interior and atmosphere b) Quantify the nature of changes in Saturn's atmosphere c) Understand the evolution of satellite surfaces and ring structure	a) Study the nature of Pluto's surface and its evolution over time b) Look for clues to the origin of the Pluto-Charon system c) Determine the composition of the surface of a typical Kuiper Belt object and hence constrain the origin of the Belt	a) Determine the range of detailed properties of Kuiper Belt objects b) Quantify the composition and conditions within the deep envelopes of the giant planets, particularly Jupiter and Neptune c) Determine the origin of Triton's volatiles and the origin of this body's apparent early episode of melting/resurfacing
Roadmap Objective 5: Determine if there is or ever has been life elsewhere in the solar system	a) Through the astrobiology program, determine plausible pathways for the origin of life on the Earth b) Determine if there are organics on Titan distinct from those made by photochemistry, and accessible for study	a) Determine if material from Europa's subsurface ocean is accessible to surface or near-surface-drilling study b) Deploy a mobile platform to study the detailed structure and composition of biogenically-relevant organics on Titan	a) Determine if there is evidence of biological activity in selected materials samples directly on Europa b) Drill into cryovolcanic flows on Titan for Organic material evolved in the presence of liquid water c) Explore for life throughout the outer solar system

2

Contributions of the Technology Development Program

As we ask more challenging questions about the solar system, we require greater technological capability to develop missions capable of addressing those questions. This is particularly true for flagship-class missions, the most difficult missions discussed in this roadmap.

Two areas of technology development have been identified as of the highest priority to enable the flagship mission concepts discussed here. These are radioisotope power sources and technologies for "extreme environments" including those characterized by high radiation, high and low temperature, extreme pressure, and the high heating rates encountered by atmospheric entry probes. In addition, technologies for ultra-high bandwidth and ultra-high pressure (for deep atmospheric entry probes) communications warrant careful assessment, as do technologies for autonomous systems, in situ science instruments, nanotechnology, and advanced modeling. These and other areas of technology development, including advanced propulsion to shorten trip time to distant destinations in the outer solar system, are discussed in more detail below.

Contributions of the Education and Public Outreach Program

"For more than half a century, the United States has led the world in scientific discovery and innovation... However, in today's rapidly evolving competitive world, the United States can no longer take its supremacy for granted. Nations from Europe to Eastern Asia are on a fast track to pass the United States in scientific excellence and technological innovation."

— Task Force on the Future of American Innovation

In the United States of America in 2005, the need for a technologically-literate—or at least a technologically-appreciative—public has grown as new technologies have entered virtually all aspects of public life, to grocery shopping to pumping gas. Recent studies* show the US lagging behind our counterparts in science, technology, engineering, and math (STEM) education, along with other benchmarks of technical innovation. Outsourcing of US jobs at all levels, including high-level science and technology fields, has become a topic of increasing debate. The implications for the future of the nation are profound.

NASA's exploration of space, and of the Solar System in particular, has motivated and inspired young people of all backgrounds to pursue STEM fields. Much as the Apollo moon landings spurred a generation to become science and technology enthusiasts, so too have recent discoveries in our Solar System, and of planets around other stars, captured the imagination of a new generation. By emphasizing STEM aspects of space exploration, NASA engages young minds and entices them to continue along educational pathways, providing a wealth of opportunities later in life, to both their benefit and to the benefit of the nation.

NASA has long had active programs of education and public outreach (EPO) in Solar System Exploration (SSE). An EPO program is more than classroom visits by astronauts and astronomers, press releases and photo ops, key chains and coffee mugs. It incorporates all elements across the EPO spectrum, reaching into classrooms, homes, and public institutions across our nation. Ongoing Space Science EPO programs demonstrate that many activities are significantly strengthened when embedded within the Science Mission Directorate. Direct engagement of NASA science programs (missions, R&A programs), scientists, and engineers yields more exciting and richer education experiences. Successful SSE activities have created collaborative programs that include both active scientists and EPO professionals, ensuring effective integration of science results in the educational realm. NASA shares its "hot" research results through press conferences, available to all through its web site. Mandating a fraction of mission funds for EPO has ensured its visibility and created a culture of EPO appreciation, especially among younger scientists and engineers.

NASA should continue to engage the public with Solar System exploration. Strategic focus for future NASA SSE-EPO efforts should nurture and expand successful programs, and re-align or re-energize programs that have not achieved full potential. The resulting strong SSE EPO program will: create and cultivate a technologically-literate 21st century workforce; create and cultivate an EPO-literate NASA workforce; stimulate scientists in their research endeavors; motivate students from diverse backgrounds to pursue STEM careers; provide teachers with materials and programs to inspire and educate their students; explain what NASA does; and return to the taxpayers—who fund NASA's work—the fruits of their investment.

* "*The Knowledge Economy: Is the United States Losing Its Competitive Edge? Benchmarks of our Innovation Future*," released February 2005 by the *Task Force on the Future of American Innovation* (available at http://www.futureofinnovation.org/).

III. "The Roadmap"

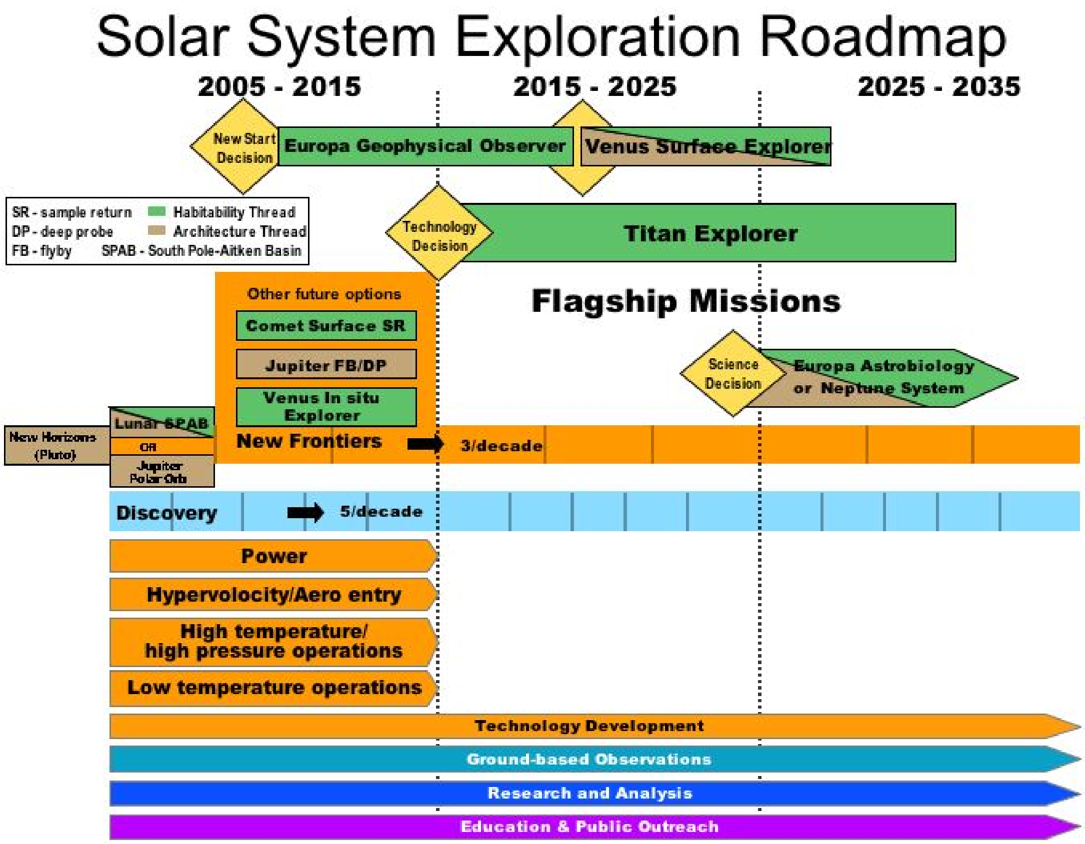


Figure 1

The SSE Strategic Roadmap is shown in Figure 1. The format shows the various program elements across three decades. The various flight programs are color coded to reflect which of the overarching science threads, i.e., Habitability and/or Planetary System Architecture, they principally address. The flight programs include the Discovery Program, New Frontiers Program, and larger flagship missions as discussed in Section II. Underlying these flight programs are the essential supporting programs: Technology Development and Research & Analysis. Ground-based Observations, a component of R&A, is illustrated to emphasize its importance in certain research areas such as studies of Kuiper Belt and Near-Earth Objects. As discussed above and in more detail below, the Technology Development Program is crucial for providing the technical capability to enable key decisions based on scientific discoveries. Education & Public Outreach is illustrated to emphasize its importance as a principal channel through which solar system exploration provides returns to the nation.

There are four key decision points (shown as yellow diamonds) in the Solar System Roadmap as illustrated in Figure 1. These decision points all involve the start of flagship missions. The Discovery and New Frontiers Programs will face critical decision points at every selection. However, the openly competed nature of these programs prevent us from assuming their outcomes beyond the missions already selected. It is clear however, that as a significant part of the portfolio of missions, they will influence decisions beyond the span of their investigations.

Decisions at any point, and particularly at the key decision points, will be influenced by the confluence of 3 major factors: scientific priorities and knowledge, technological and capability readiness, and programmatic considerations. What we learn from earlier missions will undoubtedly influence not only the destinations, but the architecture of the investigations, the approaches, and what we do once we arrive at later target destinations.

Examples of considerations that can enter into the decision making process are provided in Table 3:

Table 3: Examples of Scientific, Technology and Programmatic Considerations in the Decision Making Process

Scientific	**Impact**
Do comets have complex layered structures?	Emphasis on sample return strategy
Are cometary and meteoric particles the same?	Emphasis on sample return strategy
Strong differences between comets?	Multiple comet flyby mission(s)
NEO's with significant probability of Earth impact?	Hazard mitigation and emphasis
Strong differences among asteroid surfaces?	Multiple asteroid flyby mission(s)
Evidence of non-basaltic geochemistry on Venus?	Driller/mobile platform lander
Continents, plate tectonics on Venus?	Sample return strategy
Subsurface ocean at accessible depths on Europa?	Lander/drill strategy
Diverse organic deposits on Titan?	Mobile platform/organics explorer
Atmospheric and surface evolution on Triton?	Return missions with landers(?)
Strong diversity among Kuiper Belt objects?	Multiple KBO strategy
Organics found in Europan ocean?	Life search strategy for Europa
Life processes found on Europa or Titan?	Large scale bio laboratory
Technological	**Impact**
Cryogenic sampling and storage	Cryo Sample Return
Nuclear electric propulsion	KBO/Asteroid belt survey, Icy Moon tour, Triton
Aerocapture	Titan exploration, Triton orbiter
Extreme environment technology (cold)	Titan long duration mission
Extreme environment technology (hot, high pressure)	Venus long duration surface exploration

Aerial vehicle technology	Titan regional exploration
Surface mobility	Europa, Titan, Venus
High radiation environment	Europa long duration
Ultrahigh pressure communication/survival technology	Deep giant planets probes
High thrust/payload rockets	Venus, Titan sample return, NEO mitigation
Nuclear fission or other high power technology	Deep outer solar system exploration
High bandwidth communication	Outer solar system exploration, high data rate throughout
Programmatic	**Impact**
Human presence beyond cislunar space	Asteroid resource exploration, hazard mitigation
Emphasis on life and its origins	Europa, Mars Titan, comets
Emphasis on Earth evolution	Venus, Moon, Mars, asteroids

The first key decision point occurs in the 2006/2007 timeframe for the start of the Europa Geophysical Orbiter. The stunning discovery of a young icy surface, perhaps covering an ocean with a potentially habitable environment in Europa, made this mission one of the highest priorities for a new start flagship mission in the NRC decadal survey. The technology and capabilities are ripe for a new start. The Vision for Space Exploration, supported by the objectives of the Solar System Exploration roadmap and its emphasis on habitability, clearly reinforce this recommendation. This mission offers an opportunity for significant international collaboration.

The second decision point will occur in the 2012/13 timeframe to decide upon the phasing and start of one of the two flagship missions envisioned for the second decade. The Cassini/Huygens findings, and a preliminary assessment of technology readiness leads to a Titan Explorer ahead of a Venus Surface Explorer at this time, but other discoveries and advances in technology may require that the phasing be revisited. Both missions offer an opportunity for significant international collaboration.

The third decision point will occur in the 2018/19 timeframe for the start of the flagship mission not chosen at the second decision point. As presently envisioned, it will be a new start for a Venus Surface Explorer.

The fourth decision point, between a number of compelling scientific investigation options, will occur in the 2023/24 timeframe for the start of a large (~$3B) flagship mission. The decision will be heavily dependent upon technology and capability investments, and the scientific knowledge and priorities at the time. The principal options are discussed below in the “Third Decade” section.

A basic assumption in developing this Roadmap was that the total program content must fit within the present projected budget for solar system exploration, or approximately $900 million per year by 2010, adjusted for inflation thereafter. The flight mission model of 5 small or Discovery class, 3 medium or New Frontiers class, and 1 or 2 (depending on scope) Flagship class missions per decade, in addition to research and analysis and the technology investment base is (as a first order approximation) consistent with this assumption. Many elements of the budget plan however are preliminary and will require further study with the help of the science and engineering communities to develop viable and affordable mission concepts.

A more detailed decade-by-decade discussion of the roadmap follows.

First Decade: 2005-2015 For the first decade of the SSE Strategic Roadmap we expect to start approximately five new Discovery missions. This rate of a new start every 24 months will sustain the present level of Discovery program activity that includes five projects in various phases of implementation: Genesis, Stardust, Deep Impact, Kepler, and Dawn. In the New Frontiers Program we expect to start approximately three new missions by 2015. This rate of a new start approximately every 36 months will sustain the present level of program activity including the New Horizons mission to Pluto/Charon,. One Flagship mission is identified for this decade with a new start in the 2006/07 timeframe, a Europa Geophysical Observer.

The primary objectives of the **Europa Geophysical Observer** (EGPO) mission will be to determine the existence of a subsurface water ocean and to characterize the composition and physical properties of the overlying ice. These mission objectives flow down from the fifth Roadmap Objective: Determine if there is or ever has been life elsewhere in the solar system. This is a 6-year mission launched late in the first decade and completed around 2020. It is envisioned as a single Europa Orbiter spacecraft that may include a two-year tour within the Jupiter system using several gravity-assist maneuvers at the Galilean satellites to reduce the orbit capture requirements at Europa. The planned EGPO payload consists of a sounding radar and other remote sensing instruments. The primary mission science phase in Europa orbit is currently constrained to 30 days due to the harsh radiation environment expected to yield an integrated ionizing dose of 50 Mrad in this short orbital time span. To enable this lifetime, further development of radiation hard electronic components is needed especially for power electronics and non-volatile memory. If sufficient mission mass margin exists, however, this additional technology development can be traded against shielding mass. Sterilization of the spacecraft will also be a requirement to comply with expected planetary protection requirements for Europa.

The SSE Technology Program for the first decade emphasizes four strategic investments:

- Power
- Hypervelocity Aerodynamic Entry
- High Temperature/High Pressure Operations
- Low Temperature Operations

On-going power technology development is required to enable most new outer solar system missions that must rely on nuclear-base power systems; extended primary battery capabilities are also needed for atmospheric probes. Hypervelocity Aerodynamic Entry technologies are needed to reestablish giant planet entry capability, especially for Jupiter probes. High temperature/high pressure technologies are needed for Venus missions and for giant planet deep entry probes (typically >100 bar penetration). Low temperature capabilities are needed for future outer planet satellite atmosphere/surface missions, the first of which is expected to be to Titan. While these technologies are clearly enabling to the proposed SSE Roadmap strategy in the second decade, other are also needed, e.g., planetary protection, deep space communication, and in-space transportation. These needs are discussed in detail below. Technology investment needs should be reviewed at least every 2-3 years to ensure that needed technology readiness levels are met in a timely manner to support the on-going roadmap mission developments.

Second Decade: 2015-2025 Discovery and New Frontiers missions are planned to continue at the same flight rates during this decade. The New Frontiers AO mission set, however, will be updated with new priority missions, as the original set recommended by the National Research Council (NRC) Decadal Survey is completed. Examples of possible additions, as suggested by the 2003 NRC Decadal Survey include: Geophysical Network Science, Asteroid Rover/Sample Return, Galilean Moon Observers, and Trojan/Centaur Reconnaisance Flybys. Two smaller flagship missions are proposed as new starts for this second decade, a Titan Explorer and a Venus Surface Explorer.

A **Titan Explorer** is proposed for a new start at the beginning of the decade. Scientifically, this mission would build upon the observations of Cassini and Huygens. In addition to aerial imagery below the haze of a much larger amount of terrain than was possible with the Huygens Probe, and exploration of lower atmosphere winds, clouds and precipitation, in situ measurements of ices and organic materials at the surface to assess pre-biotic/proto-biotic chemistry will be conducted. The goal is to characterize those materials but also to contribute definitive observations concerning the origin of the diverse landforms identified in Huygens visual images and Cassini radar data. A single aerial platform with repeated access to the surface for in situ sampling is envisioned. Because of cost limitations, communications will either be direct to earth or through Cassini if it is still operating; a companion orbiter is not affordable. The mission concept is an 8-year mission, including an indirect Earth gravity-assist and direct entry into Titan’s atmosphere with at least several months lifetime at Titan. Results from Titan are expected by 2030. Certain aspects of the extreme environment make in situ exploration much more challenging than the in situ exploration of Mars. The very cold temperatures (less than 100K) at Titan present challenges for materials mechanisms and electronics. However, other aspects of the environment – specifically the high atmospheric density at the surface (4.5 times terrestrial) and the very low surface winds - enable the use of a mobile buoyant platform that can move with much less energy use and with much less risk of becoming immobilized than a surface vehicle; sampling is done in a fashion analogous to the acquisition of a sea floor sample by a submersible. Visual imaging and on board machine vision implemented from a range of altitudes will play a key role in scientific exploration and navigation. The precision of targeting and the degree of mobility control are both subjects for a trade study.

A **Venus Surface Explorer** (VSE) is proposed for a new start in the second half of the decade. This mission is sequenced after the Titan Explorer for several reasons. The later start date permits an opportunity for the selection of a New Frontiers Venus *In Situ* Explorer as a precursor mission (currently in the NF AO mission set), and also provides additional time anticipated to develop high-temperature electronics/power technologies needed at the surface of Venus. VSE would take the next step in exploration of the Venus surface beyond the epic radar reconnaissance of the Magellan spacecraft and the presumed *In situ* Explorer. This mission would perform extensive measurements at the Venus surface including a search for granitic and sedimentary rocks and other vestiges of a period in the history of Venus when Venus may have been water-rich. Equipped with visual imaging and a targeted set of geochemical sensors, the VSE will use the methods of mobile scientific exploration that were so effectively validated by the Mars Exploration rover. Hence, it would include a surface rover with limited capability (100s meters). The entire project, from new start to end-of-mission, could be accomplished in 6-7 years, including a surface stay time of days or weeks. The extreme temperatures (almost 500C) at the Venus surface present challenges for materials mechanisms and electronics. The surface conditions may also be potentially hazardous due to extremely rough terrain limiting sample accessibility. The technology challenges drive previous decade technology investments and predicate this mission's new start with a strategic technology decision point early in the decade.

The Technology Program for the second decade is expected to include continuation of some elements of the first decade investments.

<u>Third Decade: 2025-2035</u> Science opportunities are expected to continue both for the Discovery and New Frontiers program lines through the third decade approximately at their planned flight rates. For flagship missions however, two strategic conditions become apparent: 1) the science objectives become more challenging requiring more costly missions (<$3B), and 2) mission choices become less clear, being driven by the results of previous missions which are not yet known. Hence, there is a strategic science decision point at the beginning of this decade to address the next step in Flagship missions. Many options exist embracing both smaller and larger Flagship missions, but with the anticipation that implementation of a single larger Flagship mission in this decade may be compelling. Foremost among these candidates are a Europa Astrobiology Lander, a Neptune System Mission, Comet Cryo-nucleus sample return, or a Venus Sample Return.

The **Europa Astrobiology Lander** would focus on the investigation of chemical and biological properties of surface/subsurface materials associated with life. Selection of this Flagship mission would be driven by the results of the Europa Geophysical Observer undertaken in the first decade. It would have a large payload of scientific instruments and would be equipped to make a precision landing on the surface of Europa to avoid hazardous terrains. It would also have the ability to acquire samples from well beneath the contaminated surface layer. Long life in the high radiation environment, and planetary protection will therefore be major issues that need to be addressed with appropriate investments in relevant technologies.

The **Neptune System Mission** would be an "all-in-one" exploration package. It would include orbital remote sensing, deep atmosphere Neptune probes, and a Triton Lander. The spacecraft could be launched on a fast trajectory toward Neptune using aerocapture technology to enter Neptune orbit, or perform the transit with nuclear electric propulsion benefiting from ample power once at Neptune. Subsequently, a two-year tour of the

Neptune system involving multiple gravity assists at Triton has been shown to provide comprehensive high resolution imaging coverage of Triton. A limited lifetime lander on Triton could be targeted to site based on real-time Triton imaging to sample the composition and physical properties of frozen volatiles on the satellite's surface. Overall mission time from launch would be 10-12 years. If aerocapture at Nepture is employed, a second generation aerocapture technology employing high L/D aeroshells would be needed with the necessary control authority to account for uncertainties in the entry corridor and the properties of the Neptune atmosphere. This advanced technology can be used for aerocapture at any planet. However, it is only Neptune for which it is enabling. Conversely, if low-thrust propulsion is chosen, Prometheus class capabilities would be needed. Hypervelocity entry technology is needed for the Neptune probes but well within the capabilities enveloped by Jupiter probes.

The **Comet Cryogenic Nucleus Sample Return** would involve landing on and collecting a sample of the delicates ices and organics that exist on a cold and relatively fresh comet. The intent is to preserve this material in its average ambient state on the comet nucleus so that isotopic and nuclear spin ratios can be preserved along with the physical-chemical state of the sample. This requires rendezvous with a relatively fresh comet, which could require very large delta-VZ, and preserving the sample cryogenically through its return to the Earth. The propulsion and power requirements these levy on the mission make it a Flagship class endeavor. Advanced propulsion, sample collection, refrigeration (hence power) technologies are required for this mission.

A **Venus Sample Return** is a very difficult mission that would certainly follow a successful Mars Sample Return and an effective Venus Surface Explorer mission. The implementation challenge lies not so much with Venus environmental issues (although they are not trivial) as it does with the mission energetics. There would need to be a buoyant ascent stage to collect the sample either from the surface or from another vehicle (deployed to the surface and back into the atmosphere) and then carried to an altitude from which atmospheric density is low enough for launch to be feasible. At this point the propulsion needed is equivalent to a inner planet mission starting at the earth's surface. Needless to say, even with a very small sample return payload the buoyant stage would only be capable of reaching Venus orbit, where another Earth Return Vehicle would have to be waiting to rendezvous with the ascent stage, to transfer the sample for a return flight to earth. Sample recovery at Earth would be similar to Mars sample return with a direct entry to a suitable recovery site (e.g., UTTR) expected. Advanced airborne systems and high-energy rocket propulsion are key capabilities needed for this mission.

Finally, even though this is the last decade of the Roadmap, a continuing technology program aggressively developing new enabling capabilities is advocated. Not only are there many strategic SSE missions to be performed, but synergistic technology needs with a active human exploration program in this period are to be anticipated.

IV. Critical Inter-Roadmap Dependencies

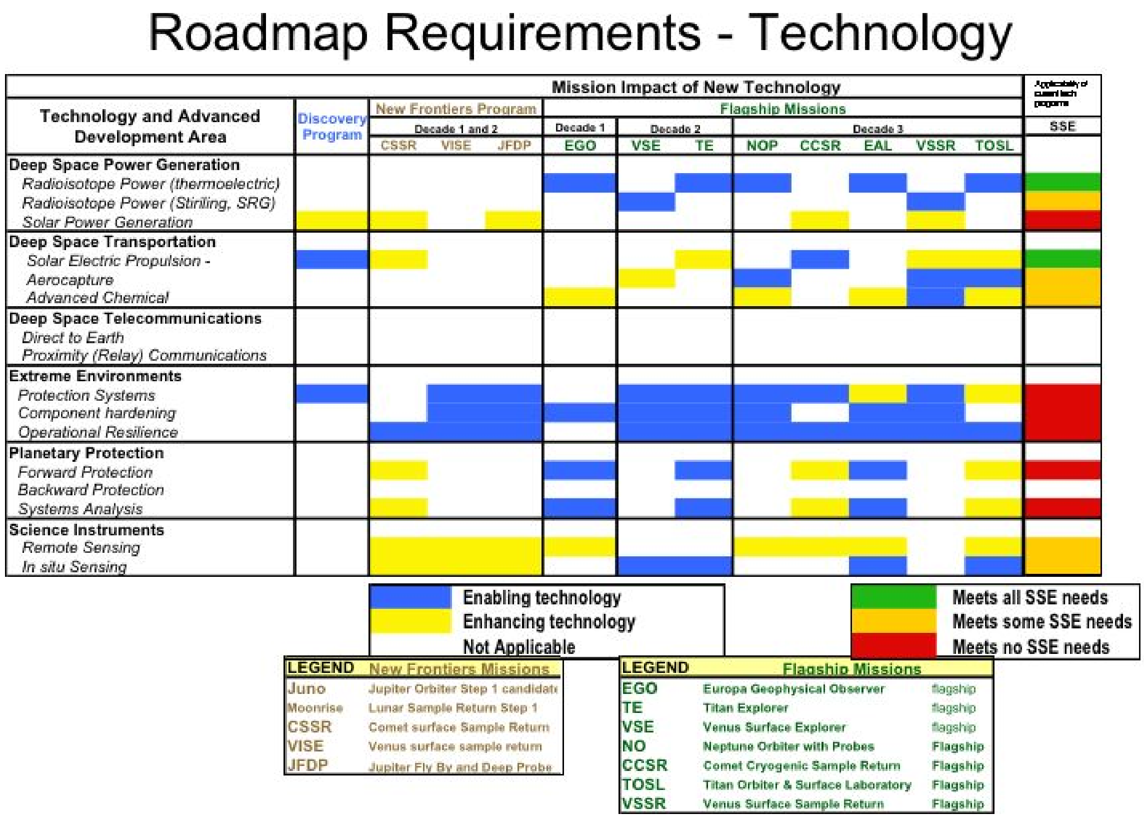


Figure 2

This section outlines the technologies to enable the Flagship missions in the Solar System Exploration Road Map. Where appropriate, the relevance of technology needs to potential New Frontiers and Discovery missions are also covered. Figure 2 summarizes the most important areas of technology development for solar system exploration. The right-most column indicates the adequacy of current technology investment levels for the solar system exploration program. The following sections are ordered as shown in Figure 2.

<u>Deep Space Power</u>

Solar System Exploration depends on existing programs in Radioisotope Power Systems included here are some of the ingredients of what we need.

Radioisotope Power – Thermoelectric conversion:

Radioisotope power generation is needed for those missions where solar photovoltaic power is not feasible and stored energy from batteries is inadequate. NASA is currently investing in the *Multi Mission Radioisotope Thermoelectric Generator (MMRTG)* that is capable of operating in space or in an atmospheric environment. This dual-purpose system, driven largely by the needs of the Mars Exploration Program, has involved performance compromises. The MMRTG will support the requirements of the *Europa Geophysical Orbiter (EGO),* if available in time, and particularly the *Titan Explorer* mission. Advanced versions of the MMRTG, incorporating improved thermoelectric converters, can provide more power from within the same physical package and could benefit EGO with a focused effort. A modular RTG, that is also envisaged, will provide a much greater range of power levels with comparable specific power and efficiency and represents the road forward. It is important for NASA to continue development in this technology,

Radioisotope Power – Stirling Radioisotopic Generator

NASAis also currently investing in a *Stirling Radioisotopic Generator (SRG),* which has comparable specific power but much greater thermal efficiency than the MMRTG. The SRG technology is needed for the *Venus Surface Explorer (VSE)* mission to provide sustained power at the high temperatures of the Venus surface. The mechanical conversion device used in the SRG enables a highly efficient heat pump that can be used to enable the use of conventional electronics on the Venus surface. The current SRG development work does not include a requirement to operate in the 500C Venus environment. The SRG program should be refocused to address the Venus high temperature need.

Solar photovoltaic Power

Solar generation will continue to play an important role in deep space missions not only for powering avionics, sensors and communications but also as an integral part of solar electric propulsion systems (see next section). Solar power can, in some circumstances, be a cost effective alternative for orbital and flyby missions to the Jupiter system and beyond. The *Juno* mission – a Jupiter Polar Orbiter currently under consideration as the second New Frontiers mission – plans to use solar power and a *Jupiter Flyby Probe (JFP)* mission – identified in this road map as a New Frontier mission opportunity could also use this technology. Fly by, rendezvous and sample return missions to small bodies in the outer solar system would be major beneficiaries of this technology. NASA is currently planning a New Millennium space validation that would validate arrays with 175W/kg – double the current state-of-practice. The potential exists for doubling the performance again over the next decade in arrays that are tolerant of operation under Low Intensity Low Temperature (LILT) conditions and high radiation environments. However, this technology is not currently being addressed within NASA.

Deep Space Transportation

The existing NASA program in In Space Propulsion technologies already contains many of the key technologies for the road map. However, the program will need to be refocused to reflect the Flagship mission priorities in this road map and to enable a more rapid insertion of technologies that can enable or enhance future Discovery missions.

Solar Electric Propulsion:

Solar Electric Propulsion enables missions requiring large in space velocity changes approaching and exceeding 10km/sec and has applications to rendezvous and sample return missions to small bodies and fast trajectories towards the outer planets. The path of development of this technology is now largely evolutionary with significant performance gains, moderate development risk and significant impact on the capabilities of new missions. Current plans include near term enhancements to the NSTAR 30cm engine used on the Dawn mission, completion of the NEXT 40cm engine which is targeted at New Frontier and Small Flagship missions, and Hall technology which is a lower cost technology benefiting Discovery missions.

Aerocapture:

Aerocapture enables rapid access to orbital missions at the outer planets. As trip times to the outer planets are reduced the mass penalty of insertion with chemical propulsion becomes prohibitive. From a purely technical point of view, Titan is the natural choice for first use of this technology because of its deep atmosphere and large scale height and modest approach velocities and can use an aerocapture system which is a derivative of a conventional symmetric Mars aeroshell. For an orbital mission at Neptune with trip times of less than ten years, aerocapture technology is enabling but will require the high lift to drag, highly asymmetric *Ellipsled* design which will require a flight validation experiment before use. Aerocapture introduces constraints and challenges to RPS-powered spacecraft packaging and design associated with the impact of being completely enclosed during long duration flight, which may require additional advances in systems such as thermal management and communications. Aerocapture for Venus missions has also shown significant mass savings in comparison to propulsive orbital insertion. Currently, the Mars Program is evaluating the benefits of aerocapture for insertion of larger orbiters and sample return rendezvous vehicles.

Advanced Chemical Propulsion:

Chemical propulsion is a comparatively mature technology but one where advances in components and propellants can still have a significant impact on NASA missions. The development of lightweight components and gel propellants can improve payload fraction in orbital missions and landed missions at airless bodies. However, the primary investments in this technology will be needed late in the second decade to enable the ascent vehicles needed for Venus Surface Sample Return.

Deep Space Communications

The NASA investments in the Deep Space Mission Systems (DSMS) include work on the trunk line from Earth to deep space and proximity communications between orbiters and landed assets. The Mars Exploration Program has been taking the lead in the proximity communications. There is an ongoing technology program to look at this, but there is also a need for infrastructure investments to either maintain or upgrade the Deep Space Network.

Extreme Environments

This topic embraces a range of technologies needed for surviving and operating in the severe environments of the inner and outer planets. These environments include the intense radiation environment near Europa, the extreme radiant and convective heating of planetary entry, the high temperatures and pressures of the Venus surface and the deep Jupiter atmosphere and the frigid temperatures of the Titan atmosphere. The technologies for surviving and operating in these environments are organized into three categories: technologies for protecting or shielding vulnerable components from the environment, components specificly designed to tolerate the environment and operational strategies that are resilient to the environment.

Protection from the Environment

Protection systems are the preferred approach for coping with the induced environment of planetary entry and for many components and systems that are needed in missions to the surface of Venus and deep in the atmospheres of outer planets.

Hypervelocity Entry

Entry into planetary environments exposes the entry capsule to severe thermal environments. The use of atmospheric drag to reduce from the hyperbolic interplanetary speed to perform scientific measurements at low speeds or to deliver payload results in the extreme aerothermal environment around the entry probe. In addition to the entry speed, entry probe shape and the atmospheric properties such as gas composition, density, temperature and pressure determine the extreme environmental conditions. Thermal Protection System (TPS) design required to protect the entry probe from this extreme condition requires tools and facilities,

Entry into Mars is benign compared to conditions that will be encountered by probes to the Outer Planets as well as Venus. When the Galileo probe entered Jupiter it experienced total heating in excess of 30,000 W/cm^2 as compared to 120 W/cm^2 of convective heating encountered by the Mars Pathfinder. The Galileo entry environment produced both radiative heating in excess of 20,000 W/cm^2 and convective heating approaching 10,000 W/cm^2 a combination that is unmatched by any other environment.

NASA has not retained the capability for hypervelocity entry into the atmospheres of the outer planets – gas and ice giants. This includes the capability to design entry probes including the Thermal Protection Systems for the outer planets and Venus. The technology investment envisaged here is intended to not only recapture this capability but will represent a significant advance enabling higher velocity entry with smaller entry vehicles with larger payload fractions than used for the Galileo probe. A substantial investment in a hydrogen-helium arc jet test facilities is needed for both development and qualification of Thermal Protection Systems (TBS). The investment to revive and develop advanced TPS will enable probe missions not only to Outer Planets but also Venus missions, aerocapture missions to Neptune as well as Sample Return missions,

Extreme Pressures and Temperatures

This probe must also descend much deeper on Jupiter /Neptune/Saturn than Galileo and communicate from those depths. Investments in the analysis tools for predicting the behavior of probes during descent and for extended operation on the surface of Venus are needed. New structural and thermal control materials will improve the fraction of these vehicles available for payloads. The benefits of new technologies will increase with the depth and duration of vehicles operation.

Thermal Control

Protection systems for tolerating both very hot and very cold environments are needed. For short duration missions, passive approaches may be adequate. For longer duration missions an active approach for adding or removing heat is needed. For long duration protection of payloads on the surface of Venus, a heat engine is needed to “refrigerate” the thermal controlled avionics and sensor module. Only small heat loads can be handled so heat leaks and dissipation must be minimized. Very little work has been done on this technology. An aggressive early program of systems analysis will be needed to define the best approach and determine realistic performance goals for this technology.

Components tolerant of the Environment

For certain components, it may be impractical to provide protection for the environment. In these cases, it is necessary to develop components that can tolerate the environment.

Radiation Hard Electronics

Operations in the near-Europa space environment, exposes hardware to the severe Jovian radiation environment. Shielding can mitigate these effects but at the expense of useful payload. Both the cumulative dose and the prompt effects of the radiation are of concern to the performance of spacecraft systems and science instruments. For the *Europa Geophysical Orbiter*, with a design lifetime of one month, there is a compelling need for advanced development of power electronics and non volatile memory (NVM) systems. This can leverage prior work performed in the Europa Orbiter and Jupiter Icy Moon Orbiter (JIMO) projects and continuity with the early work is highly desirable. For the *Europa Astrobiology Laboratory,* which is a mission in the third decade, the required lifetime is many months or even years and an investment in basic technology and innovative approaches to radiation protection will be needed.

Electronics – high temperatures

Passive thermal control can only permit operation on the surface of Venus for time periods measured in hours to tens of hours. For extended lifetime missions, active thermal control and high temperature electrons are complementary approaches.
Not all electronic components can or should be implemented in high temperature component. Communications and power electronics have the most payoff. Digital electronics, which have low power dissipation, are best implemented in conventional electronics by using active thermal control.

Both semiconductor and vacuum tube approaches have been developed to the 300C range but operation at 500C represents a unique NASA need. There is currently no NASA program in this technology and an early start in this area is needed to ensure availability for Venus Surface Explorer and Venus Surface Sample Return as well as the potential for experiments and validation on earlier missions.

Sample Acquisition Mechanisms

Actuators that can operate at very high temperature and very low temperatures are the thrust here. Also there must be understanding of the mechanical properties of natural materials such as ice and rock over a comparably broad range of temperatures. Permanent magnetic materials and soft magnetic materials are required that retain their magnetic properties at high temperatures.

Systems technologies resilient in severe environments

In order not only to survive but successfully operate in severe environments, a number of systems technologies are needed.

Descent and Landing

Future solar system exploration missions must land on airless objects of widely divergent gravitational fields, contend with extreme relief and to descend land and in some cases ascend under conditions of active plumes from the surface posing major technological challenges. In contrast, landing on the planets with dense atmospheres (Venus and Titan) represent comparatively straightforward engineering: for both objects, descent vehicles designed primarily as atmospheric probes Pioneer (Venus) and Huygens (Titan) have survived landings on these objects.

The *Comet Surface Sample Return (CSSR)* mission requires the capability to rendezvous, descend and ascend from these low gravity objects using terrain relative navigation to ensure the recovery of samples from the required targets. The *Comet Nuclear Cryogenic Sample Return (CNCSR)* mission will require still greater precision and the ability to anchor to the object to facilitate deep sampling. The *Europa Astrobiology Laboratory* mission will required similar precision but because it has a substantial gravitational acceleration, terrain relative navigation must be performed at high rates and must be tolerant to spurious radiation effects.

Mobility – aerial and surface

Mobility is required to provide close up imaging and chemical and mineralogical sampling at many different sites for both the Venus Surface Explorer (VSE) and Titan Explorer (TE) missions. These vehicles must tolerate highly irregular terrains, deposits of low bearing strengths and on Titan potentially sticky or liquid surfaces. Wheeled vehicles derived from the Mars Exploration Rover and Mars Science Laboratory represent one approach to mobility. However, the dense atmospheres of Titan and Venus also enable buoyant vehicles that are much less susceptible to being immobilized by surface obstacles or surfaces with low bearing strengths. They can also travel over much greater distances with less energy consumption.

A proof of principle has been achieved for thin metal bellows balloons that can operate at Venus temperature and polymer-based films and fabrics that can retain their flexibility and resilience at Titan surface temperatures. High temperature actuators for these extreme conditions are also under development. However, NASA does not currently invest in mobility for extreme environments and a sustained effort in both basic technology and advanced development is needed to get ready for these missions. Test facilities will be required for validating the performance of mobile vehicles in both extremely hot and extremely cold environments.

Autonomous Operations

Operation in these environments will not only require tolerance of the extreme environments but the ability to autonomously respond to hazards. These vehicles may be out of contact with a ground operator during some mission phases for days or even weeks. Some autonomous operations can draw on the experience in operating the Mars rovers where commands are typically issued on a daily cycle. There are also unique challenges for future solar system exploration missions. The autonomous operations needed for proximity operations of sample return missions from small bodies and those of aerial platforms monitoring and acquiring samples from the surfaces of Titan and Venus have no counterpart in the Mars Exploration Program.

Planetary Protection and Contamination Control

For the exploration of Europa and Titan, both objects of biological interest, it will be necessary to undertake a planetary protection program to ensure that they are not contaminated with earth derived biological materials. In addition, measures must be taken to ensure that samples collected by on board instruments on landed spacecraft do not experience contamination by the spacecraft itself or other materials brought from Earth.

While the experience in the Mars Exploration Program is pertinent, Europa presents particular challenges including handling forward biological contamination by an orbiting spacecraft or lander and chemical contamination associated with Titan systems. Significant investments will be needed to handle the challenges of the icy environment of Europa in forward contaminations control, dry heat sterilization and systems analysis.

Science Instruments

Investigating the priority targets that have been identified in the Solar System Exploration roadmap will require both remote sensing and in situ sensing instruments. For outer planet missions payload mass is at a premium. When these are also in situ missions, each kilogram of payload is precious. In this context, miniaturization of instruments will be extremely important.

There are on going technology and instrument development programs for instruments. The Planetary Instrument Definition and Development Program (PIDDP) focuses on the demonstration of new instrument concepts for solar system exploration missions. NASA should continue investment in these instrument development programs.

Capability Interdependencies with other Roadmaps and Organizations

Mars Robotic and Human Exploration Program

The Mars Focused and Base programs invest in technologies that are complementary to the existing solar systems exploration technology program. There is a strong focus on Entry Descent and Landing, Surface Mobility and instruments for in situ science.

Proximity Telecommunications developed for Mars has some applications to Solar System Exploration although may in situ missions will lack an orbital relay and will have to rely on a direct communications link to the Earth.

Planetary Protection and Contamination control technology developed for Mars exploration are relevant to the needs for Europa and Titan exploration. However, Europa and Titan exploration have unique needs.

Lunar Exploration Program

Investments are more narrowly focused on the needs of lunar exploration. Primary benefits are likely to come from investments in power and propulsion.

Other Agencies and Organizations

Notable areas where non NASA efforts are important are in Solar Power generation where DARPA is funding work on advanced solar arrays and in extreme environments where what relevant work exists in high temperature electronics for example is generally implemented outside NASA.

Technology Gaps

The most significant gap is in Technologies for Severe Environments. Another gap area where there are virtually no effective programs is systems technologies for planetary protection.

Strategic Interdependencies with other Roadmaps

Lunar Robotics and Human Exploration

The Solar System Exploration research is closely linked with the Lunar program. To understand the record of solar system processes preserved in the lunar surface materials it is important to analyze Lunar Samples and perform Lunar field studies. The moon is critical in understanding the process under which the solar system developed.

Mars Robotic and Human Exploration

Understanding Mars from both a historical and current perspective will be part of understanding the full story of the development of the entire Solar System. This includes understanding the current state and evolution of the atmosphere, the surface and interior of Mars as part of understanding the development of the Solar System. Determining the nature of any habitable environments on Mars and if life exists or has ever existed on Mars, is key to the study of solar system evolution.

Earth-Like Planets and Habitable Environments

Studying the Giant Planets in our Solar System and understanding how they effect Habitability is key for understanding how life evolved and what role the giant planets may have played. Also, studying extrasolar planetary systems and understanding how they become habitable is a parallel model to help understand the evolution of life.

Exploration Transportation

Exploration of the outer Solar System will necessarily require longer transit times and as more sophisticated science data is gathered, instruments will be required which have larger launch mass and volume. Therefore the solar system exploration research will ultimately need Heavy lift launch for high mass robotic mission; Precision entry/decent and landing; In space propulsion; In space automated rendezvous and docking (depending on design of launch and transfer vehicles); Pre-deployed surface/orbit assets (fuel, power, instruments, etc); Surface ascent/sample return to earth.

Sun-Solar System Connection

Solar System Exploration is closely linked with Sun-Solar System Connection to specify and predict space weather at solar system destinations and along interplanetary routes. This would include measuring and understanding planetary atmospheric state for ascent, aerobraking, aerocapture, descent and landing. This also includes understanding the ionospheric state for communications and navigation and energetic radiation morphology and, spectral content for reliability of electronics and materials. This strategic link also includes Solar and Galactic Radiation environment prediction, detection, warning, upper atmospheric characteristics (e.g. Titan, Neptune) for aerocapture and Magnetoshperic science.

Aeronautical Technologies

It is envisioned that in the future Atmospheric vehicles will be needed as part of the capability for planetary surface or near surface mobility.

Nuclear Systems

Radioisotope Power Sources are critical for missions at extreme distances or extreme environments. It is important for providing propulsion to/from the outer solar system and in communications and in providing power for planetary surface investigations.

V. Conclusion

The President's Vision for U.S. Space Exploration observes that "Today, humanity has the potential to seek answers to the most fundamental questions posed about the existence of life beyond Earth." This Roadmap illustrates that habitability, by definition a precursor to the existence of life, is an overarching concept that unites the endeavor to explore our solar system and understand its mysteries. Pursuing the objectives discussed in this Roadmap will not only inform us about the potential for life or prebiological activity in this solar system, it will provide "ground truth" for interpreting the growing body of information concerning planetary systems around other stars. Our journey into the solar system will also be a journey to our roots as living creatures. In reaching toward the base of the tree of life, we express our highest aspirations.

Appendix: Goals of Solar System Science: The Solar System Exploration Subcommittee White Paper

The Solar System Exploration Subcommittee prepared a white paper as its contribution to the Solar System roadmap process. The purpose of the white paper is to provide a narrative exposition, in detail, of the science goals and objectives of solar system exploration consistent with the Academy Decadal Survey, but updated to the end of 2004.

The white paper was organized around four goals. The Solar System Exploration Strategic Roadmap Committee rearranged the material in the white paper to conform to the "Five Roadmap Objectives" structure of the Roadmap. The content was otherwise unchanged or modified only editorially. This modified version of the white paper is included here to provide the reader more detail on the science rationale and detailed goals/objectives of the exploration of the solar system. The text is fully consistent with, and expands upon, the goals described in the introduction to the roadmap.

Note regarding hierarchy: The Roadmap recognizes five Objectives. In this Appendix those Objectives are called Goals. Following each Goal in the Appendix hierarchically are Objectives and Investigations. We regret the potential confusion incurred by using the term "Objective" for different hierarchical levels in the Roadmap and in the Appendix, but other solutions to this conundrum would have introduced confusion of their own.

Goal 1: Learn how the sun's family of planets and minor bodies originated

We are in a time of major changes to our understanding of how solar systems form and evolve. Detections of very different planetary systems orbiting other stars, and of young protoplanetary disks, are giving us new insights into the processes that operated in the earliest history of our own solar system. Our solar system was born about 4.6 billion years ago when a cloud of gas and dust collapsed to form a nascent Sun surrounded by an accretion disk. Subsequently, material in this disk condensed and coalesced to form solid aggregates that became the building blocks of the planets and their moons, the asteroids and comets. Many of the characteristics of our solar system, and the bodies within it, were established during the first billion years of its history. This is also the period when life emerged on Earth and possibly elsewhere in the solar system. A record of these early events is still preserved in the physical and chemical makeup of primordial solar system materials, such as the oldest rocks on the Earth, Moon and Mars, in primitive asteroidal meteorites, comets, and in the Sun itself. New determinations of the elemental composition of the Sun's photosphere are changing the paradigm for its interior structure and composition, and may have profound implications for the composition of the Sun's protoplanetary nebula. Similarly, high-precision measurements of abundances of key elements and compounds in the atmospheres of our giant planets and extrasolar giant planets will lead to further revolutionary changes in our understanding of planetary formation and evolution.

Objective 1.1: Understand conditions in the solar accretion disk and processes marking the initial stages of planet formation.

Investigation 1.1a: Chemical and isotopic compositions of primitive meteorites and their components.

Primitive meteorites are time capsules that preserve information about the chemical and physical processes that operated at microscopic to planetary scales in the early solar system. Reading this information requires understanding the origin of chemical and isotopic signatures in these meteorites and their components. Although it is now clear that the solar nebula was not homogeneous, the details of the processes responsible for the known heterogeneities, including their spatial and temporal dependencies, are still poorly understood. Elemental heterogeneities among different classes of primitive meteorites may point to large-scale chemical gradients within the solar nebula and to different conditions in the inner and outer solar system (Benz, Kallenbach and Lugmair 2000). Isotopic heterogeneities in different primitive meteorites and their components, such as refractory inclusions and other less refractory components such as chondrules, may stem from processes such as incomplete homogenization of pre-existing presolar components or the decay of short-lived radioactive isotopes that were present when the solar system formed (Zinner 2003). Therefore, understanding the origin of elemental and isotopic heterogeneities is important for elucidating the earliest processes and their time scales in the early solar system.

Primitive meteorites also harbor genuine stardust, which was present in the molecular cloud from which the solar system formed (Bernatowicz and Zinner 1997). These "presolar grains" formed in the winds and ejecta of dying stars such as red giants and supernovae, and survived a number of potentially destructive processes before being incorporated into the parent asteroids of primitive meteorites. What was the mineralogy of the dust grains originally present in the molecular cloud? What was the chemical and isotopic make-up of these grains? What processes altered or destroyed presolar grains within the solar nebula and on parent bodies? Answers to such questions will help us to gain an understanding of the initial conditions in the solar nebula and the raw materials that contributed to all matter in our solar system. It is also desirable to know if any organic compounds were inherited from the interstellar medium, and the extent to which any of such compounds were chemically processed within the solar nebula (Fegley 1999, Irvine et al. 2000). This is likely to have a bearing on the important issues related to the origin and inventory of prebiotic organic materials in the solar system.

Investigation 1.1b: Physical, chemical and isotopic characteristics of Kuiper Belt objects and comets.

In the outermost reaches of our solar system, icy bodies probably grew very slowly. The largest bodies found in the Kuiper Belt at 40 AU today are Pluto and its moon Charon, although a number of other bodies have been discovered recently that are nearly as large. One of the new objects – Sedna – is the first known example of a body orbiting between the Kuiper Belt and the Oort cloud of comets. Kuiper Belt objects (KBOs) are of particular interest because their dynamical properties, physical state and chemical composition reflect the conditions prevailing at the beginning of the solar system. The sizes and reflectivities of the major KBOs will soon be determined by a combination of optical and infrared imaging. At present, ground-based telescopes can probe the chemical composition of only the very largest KBOs through spectroscopy. In the near future, however, the New Horizons mission will produce high-resolution chemical maps of the surfaces of Pluto and Charon and at least one other KBO, which will help to determine their interior structures. This research will be complemented by observations of debris disks orbiting other stars using the Spitzer telescope. These observations will allow us to study the dust generated by collisions between objects in the outer regions of extrasolar planetary systems, providing new insights into the composition and evolution of KBOs in our own solar system.

On the other hand, a host of smaller bodies, the short period comets, has been scattered from the Kuiper Belt, and on occasion these objects enter the inner solar system. As these comets travel closer to the Sun they begin to vaporize, generating beautiful comae, which can be examined to determine the chemical composition of the cometary nuclei themselves. Comets are sufficiently small and cold that they should provide a window not only to the formation of the solar system but also to the earlier stages of cosmic evolution in the interstellar medium before the Sun was born. The data gleaned from telescopic observations can be greatly expanded for a few comets by robotic missions, and especially by sample return. The first such sample return mission, Stardust, will soon provide us with examples of cometary dust, and the Deep Impact mission will yield the first glimpse of the deeper structure and inner volatile content of a comet. Ultimately, however, in order to answer the critical questions surrounding the origin and evolution of icy bodies in the solar system – What are comets and KBOs made of? Does their physical state and chemical composition tell us about how and where they were formed? Are comets a significant source of the Earth's oceans and its early organic inventory? – it will be necessary to return an intact sample from the surface of a comet.

Investigation 1.1c: Theoretical modeling and experimental investigations of the processes in the initial stages of planet formation.

The formation of planets involves a number of steps with different physical and chemical processes occurring at each stage. For the rocky planets, early stages involved interactions between dust grains and diffuse, turbulent gas in a microgravity environment (Cuzzi and Hogan 2003, Youdin and Chiang 2004). Later stages involved high-speed collisions between large solid bodies and gravitational interactions during near misses (Chambers and Cassen 2002). Giant planets such as Jupiter are mostly composed of gas, but a large solid core may have been necessary to trigger their formation (Wüchterl et al., 2000; Inaba et al. 2003). Such cores would have formed in the same way as the rocky planets. The ice-rich planets Uranus and Neptune may be similar to the cores of the hydrogen-rich planets Jupiter and Saturn, suggesting that the Sun’s primordial gas nebula had largely dispersed when Uranus and Neptune formed. The discovery of extrasolar planets is providing a wealth of opportunities and challenges for our understanding of planet formation. More than a hundred Jupiter-mass planets have now been detected in orbit around other stars (http://cfa-www.harvard.edu/planets/), and the Kepler Discovery mission promises to greatly expand this number. It is already clear from the new discoveries that there is a correlation between the likelihood of finding a planet orbiting a star and the star’s chemical composition (Fischer and Valenti 2003). One interpretation of a paucity of Jupiters orbiting low-metallicity stars is that cores of the necessary size cannot form around such stars (Hubbard, 2004). It has also been suggested that nebular metallicity determines the extent to which giant planets migrate within their system, and this affects how easily these planets can be detected (Sigurdsson et al. 2003).

Gravitational interactions between growing planets and the Sun's protoplanetary nebula played a big role in determining the current configuration of the planetary system (Tanaka et al. 2002). Theoretical simulations of these processes and of planetary migration caused by interactions with the nebula will help us to understand the present and past architecture of our solar system and extrasolar planetary systems. However, theoretical models need to be based on observations and experimental data.

Appropriate interpretation of observations of emissions from dust grains as well as modeling of the protoplanetary disk processes is based on radiative transfer models that require input from experimental measurements of the optical properties of dust grains. Moreover, the dust grains in the disk are generally charged, and the grain charge influences the grain dynamics, grain-grain and grain-gas interactions, grain coagulation and evolution. Experimental investigations of grain charging processes by photoemission, collisions with gas phase electrons, and by triboelectric and contact charging processes are needed to provide more realistic information to understand and model the processes involved. In addition, experimental investigations of the growth and sticking efficiencies of dust grains by studying condensation processes of volatile gases on dust grains will provide valuable information for studies of the growth of dust grains in the early stages (Supulver et al. 1997). Thus, studying dust grain sticking and collisions in a turbulent, low pressure gas and in microgravity will provide an important foundation for our understanding of the early stages of planetary growth and essential ground truth for computational models of planet formation.

Objective 1.2: Learn about the earliest processes occurring on the surfaces and interiors of planets and minor bodies.

Investigation 1.2a: Studies of ancient rocks on the Earth, Moon, Mars and asteroids.

Events that occurred early in the solar system have left their imprint on the terrestrial planets and asteroids. Unfortunately, most rocks older than 3.5 billion years on the Earth have been eradicated by impacts, weathering, tectonics, biological activity and other processes. Nevertheless, there are a few localities where rocks and minerals preserve a record of the first billion years of Earth's history. Petrologic, chemical and isotopic investigations of these rare materials can help us to understand the environment on the early Earth and the processes that shaped it.

Unlike the Earth, the Moon retains a substantial record of its early history. Recent computational models have shown that the Moon could have formed by an energetic impact of a Mars-sized body into the early Earth (Canup and Asphaug 2001). Confirmation and refinement of this theory will require detailed examination of samples from the Moon. Rocks returned by the Apollo and Luna missions and lunar meteorites are helping to shed light on the Moon's early history, but these rocks sample only a small fraction of the lunar surface, and more will be needed in future Additional samples will help constrain the impact rate in the Earth-Moon system during the first billion years of solar system history. This has important implications for the environment on the early Earth and the emergence of life. The South Pole-Aitken basin on the Moon is one of the largest impact structures in solar system. The impact was sufficiently energetic to expose materials from the deep crust and possibly the upper mantle. The discovery of this basin provides an opportunity to sample materials unlike those that are currently available and obtain a precise age for the basin-forming event.

The ancient highlands of Mars also preserve a record of the earliest processes occurring on that planet. Remote analyses by spacecraft and detailed studies in state-of-the-art laboratories on Earth of returned samples of ancient Mars rocks will be invaluable towards a better understanding the earliest conditions and processes occurring on the terrestrial planets.

Some meteorites from asteroidal bodies are among the oldest known materials found in the inner solar system. These rocks contain a record of processes such as aqueous alteration, differentiation and core formation that occurred at a very early stage on their parent bodies. As such, investigations of their physical characteristics, chemical composition and mineralogy through spacecraft and returned samples will be important in understanding the earliest processes occurring on such bodies and in clarifying such long-standing questions as the relationship between asteroids and meteorites.

Investigation 1.2b: Interior structure and chemical-isotopic compositions of the deep atmospheres of the giant planets and comparison with characteristics of exoplanets.

In our solar system, most of the planetary mass is contained in the four giant planets, Jupiter, Saturn, Uranus, and Neptune. However, we still know little about the composition and structure of these bodies. How much water do they contain? What is the cloud-layer structure in the gas-giant planets? How massive are their deep cores and if such cores indeed exist, how and when did they form? Information on the isotopic compositions of key elements such as carbon, nitrogen, oxygen, and the noble gases is an essential diagnostic tool for understanding giant-planet formation and evolution in our solar system and in other planetary systems. A comprehensive understanding of the formation and evolution of giant planets around other stars requires better observational data for chemical and physical properties that only can be provided by spacecraft.

The highly successful Galileo probe mission gave us our first look at Jupiter's atmospheric chemistry, but the results left us with some mysteries (Atreya et al. 2003). For example, the probe did not provide measurements of the water content - a key tracer of Jupiter's formation - of the deep atmosphere and measured less water in the upper atmosphere than models had predicted. The Cassini Saturn orbiter and Huygens Titan probe will provide remote-sensing (for Saturn's atmosphere and rings) and *in situ* compositional data (for Titan), which will strongly constrain theories for the origin and evolution of these bodies. An extended orbiter mission will be critical for more complete coverage of Titan's surface and atmosphere, as well as for better constraints on Saturn's interior structure. Definitive measurement of the abundances of noble gases in Saturn's atmosphere still requires an entry probe mission.

We now have our first measurements of atmospheric compositions in giant exoplanets. Interpretation of these measurements is difficult given their dependence on many poorly understood processes such as cloud formation, deep convection and local "weather", and effects of irradiation from the parent star. The same processes are at work in the atmospheres of our own giant planets. Some hot giant exoplanets may even have observable silicate clouds analogous to those thought to be buried deep in the atmospheres of our own giant planets, together with more easily observable water vapor (Lodders, 2004). Definitive measurement of Jupiter's deep water abundance is needed to understand the formation processes for giant planets, and will be needed for comparison with planned exoplanet measurements (Hubbard et al., 2002).

Therefore, reliable *in-situ* measurements of the abundances of key elements and compounds are required for *all* of the outer planets to build a solid base for understanding giant planet formation in our solar system and in planetary systems of other stars. We need to probe Jupiter's atmosphere again, preferably at locations that have varying meteorology, as well as to deeper levels, preferably to about 100 bars. Similarly, it is essential to make comparable measurements in the atmospheres of our other three giant planets.

Objective 1.3: Learn what the Solar System tells us about the development and evolution of extrasolar planetary systems and vice versa.

Understanding how the Solar System evolved to its current state provides the context and ground-truth for understanding planet formation and evolution processes, and therefore for understanding the diversity of possible extrasolar planetary systems. Theoretical models for the origin of the planets and satellites in our solar system provide important constraints on the possibility of similar systems elsewhere, including those with potentially with habitable planets.

Jovian planets, including the more than 100 extrasolar planets detected to date, are believed to form through either a protracted accumulation of ice-rock cores followed by gas accretion, or through an extremely rapid gravitationally induced collapse. Determining the internal structure, composition, and thermal state of Jupiter and Saturn provides key constraints on these processes and on the overall nature of giant planet structure and evolution.   Such models provide a crucial foundation for understanding extrasolar planets. In addition, interactions between the planet's magnetic field and surrounding plasma, particularly at Jupiter, may shed light on processes important for angular momentum and mass loss from protostars.

The close proximity of many extrasolar planets to their parent stars seems to necessitate that they migrated inward significantly, and a possible cause of such migration is the gravitational interaction between planets and their precursor nebular disks. The concept that angular momentum exchange occurs as orbiting objects interact with a disk of material was first understood in the context of planetary rings, where signatures of such processes are directly observable. Studying the interaction of satellites and rings thus shapes our understanding of planet migration processes, which in turn may affect the degree to which extrasolar systems could harbor terrestrial-like planets. The large regular satellites of the outer gaseous planets provide additional and accessible test cases for models of both planet accretion and migration because, like planets, these satellites are believed to have formed within disks of gas and solids. Other dynamical processes whose effects are observable in the Solar System, including resonant and tidal interactions and gravitational scattering, are also believed to be important potential shapers of extrasolar systems.

Models of the formation of rocky planets provide the basis to assess theoretically the potential for extrasolar terrestrial planet systems. Formation models may rely on the properties and temporal evolution of a circumstellar gas of nebula and the formation accompanying jovian planets. Likewise, studies of the factors that influence habitability in our solar system help to constrain the general astronomical conditions related to the formation of Earth-like planets elsewhere.

Understanding the formation and ongoing dynamical and collisional evolution of the asteroid and Kuiper belts is relevant to understanding dust and debris disks around other stars, and what their structure may imply for the possible presence of embedded planets.

Investigation 1.3a: Observations and modeling of the architecture of and gravitational interactions among Solar System bodies at scales from planets to dust.

Investigation 1.3b: Comparative studies of the internal states, orbital histories, and magnetospheric interactions of the outer gaseous planets and their satellites to constrain their origin and evolution.

Investigation 1.3c: Studies of planet and satellite formation (including accretion, volatile delivery, and dynamics), especially as pertinent to planetary habitability.

Decadal Survey mapping:
12. What Does the Solar System Tell Us About the Development and Evolution of Extrasolar Planetary Systems and Vice Versa?

Goal 2: Determine how the solar system evolved to its current diverse state including the origin and evolution of the Earth's biosphere

Objective 2.1: Understand why the terrestrial planets differ so dramatically in their evolution.

The terrestrial planetary bodies share many similarities, but solar system exploration has revealed that they are also fundamentally different in many other ways. The Moon, Mercury, and Mars stabilized their crusts and lithospheres early in planetary evolution and became "one-plate" planets. In contrast, Earth evolved into a dynamic, multi-plate planet that is constantly renewing itself through atmospheric erosion and recycling of the lithosphere into the interior. Venus shows no active plate tectonics and may have been catastrophically resurfaced within the last billion years.

Terrestrial planet atmospheres also show major differences, with Venus and Mars both being CO_2-dominated, but with orders-of-magnitude different surface pressures. On Earth, liquid water provides a substantial thermal buffer to sudden changes in the climate; nevertheless, ample evidence indicates that the climate has varied considerably with time. Climate can be altered by changes in global volcanism, solar output, celestial mechanics, and the effects of pollutants made by humans. Atmospheric constituents have been removed over time by the solar wind. The interactions among these influences are so complex that they are not fully understood, yet they are fundamental to understanding atmospheric evolution and planetary habitability.

Our neighboring planets Venus and Mars provide compelling examples of atmospheric evolution along very different paths from that of Earth. The thin CO_2 atmosphere of Mars represents an extreme in which temperatures are low and a significant fraction of the "atmosphere" lies buried as ice within the regolith and upper crust. It is critical to understand climate change at Mars and its potential causes and effects. The influence of a planet's dynamical history, notably its obliquity and orbital eccentricity, on climate and habitability are important to understanding the differences between Earth and its neighboring terrestrial planets.

The surfaces of the Moon and Mercury are superficially similar but differ in detail, for example with Mercury showing only indirect evidence for volcanism. Moreover, their interiors are quite different, with Mercury having a very large iron core and the Moon a very small one. Fundamental questions remain regarding the current state and the evolution of the lunar surface and interior, and Mercury's level of internal and crustal evolution is uncertain. Both planetary bodies have tenuous exospheres with multifaceted solar wind interactions; however, he role of the magnetic field of each is very different, as Mercury has a significant magnetosphere. Both bodies show evidence for volatiles in polar cold traps.

For the Moon, seismic data would resolve the internal structure, permitting a much-improved estimate of bulk composition. Samples of rocks from major unsampled terrains, primarily the South Pole–Aitken Basin which excavated into the lower crust of the Moon, are needed to determine an accurate crustal composition and stratigraphy. For Mercury, basic information is needed on surface composition, internal structure, and distribution of mass, each of which provides important constraints on bulk major-element composition.

Investigation 2.1a: Comparative studies of climate evolution of Mars, Earth, and Venus to better evaluate the roles of planetary parameters (composition, volatile inventories, dynamical properties, and surface processes) in determining terrestrial planet habitability.

Investigation 2.1b: Comparative studies of the current state and inferred evolution of the interiors and surfaces of Mercury and the Moon.

Decadal Survey mapping:
9. Why Did the Terrestrial Planets Differ So Dramatically in Their Evolution?

Objective 2.2: What environmental factors were required for the emergence and sustenance of life?

The origin of life occurred through a set of chemical and physical processes that are likely to have occurred on numerous other planets circling sun-like stars. These processes must be understood not only in terms of the Earth, but also with regard to possible origins of life elsewhere. A clear starting point is to determine what raw materials of life can be produced by chemical evolution in interplanetary space and on planets. From recent investigations we now know that one possible source is photochemical processing that may have synthesized some of the organic compounds found in comets, interplanetary dust particles (IDPs) and carbonaceous meteorites. Presumably these can be delivered to planetary surfaces during accretion. A second major source of prebiotic organics is geochemical synthesis taking place on planetary surfaces and within their interiors; this may be relevant to meteorite parent bodies as well since alteration by liquid water is seen in some chondritic mineral phases.

Next, we must establish how organic compounds are assembled into more complex molecular systems and the processes by which complex systems evolve those basic properties that are critical to life's origins, persistence and evolution. Primary properties of life include capturing energy and nutrients from the environment, manufacturing copies of key biomolecules, and self-replication of the individual. There remains a vast gap in our understanding of how such properties first appeared in molecular systems on the early Earth, and NASA flight missions and ground-based research will be essential for answering these fundamental questions.

Changes in the physical and chemical environment of Earth have had a profound influence on the history of life on Earth. We must identify the dates of origin of key metabolic pathways and the divergences of the major clades in prokaryotic and early eukaryotic life, of the establishment of complex life, and its relationship to significant events in Earth’s environmental history. Such information provides critical constraints on understanding the processes of biotic innovation necessary for the persistence of life. The longevity of life on this planet also appears intimately connected with biotic responses to catastrophes mediated by both endogenous and exogenous environmental factors. Although advances have been made in documenting such perturbations, less is known of the subsequent biotic responses.

This will require an integrated program of pan-spectral astronomical and orbital observations, sample return missions, laboratory studies of extraterrestrial materials, and realistic laboratory simulations of inaccessible cosmic environments, as well as a deeper understanding of key evolutionary events in the history of terrestrial life and the factors responsible for driving evolutionary change.

The basic requirements for terrestrial life include liquid water, a source of energy, a source of organic compounds, and environments favorable for the assembly of complex organic molecules into systems that can capture energy and undergo catalyzed growth processes. For life to begin there must be active mechanisms for concentrating and maintaining interacting molecular species in a microenvironment favorable for life's emergence. From this perspective, life began as a bounded system of interacting molecules, none of which has the full property of life outside of that system.

We must also continue to study life in extreme environments. Recent studies have demonstrated that life can adapt to temperatures as high as 121°C in subsurface hydrothermal systems, and sub-zero temperatures in the eutectic phases of polar ice. However, despite 3 billion years of evolutionary history no microbial or multicellular organisms are known that involve a life cycle in environments that are permanently frozen solid, totally dry or lacking a source of energy and nutrients. These observations suggest that there are certain fundamental constraints on carbon-based life, and that these provide initial astrobiological constraints for the exploration of other planets. The challenge of defining these constraints will lead to a more refined definition of habitability and the living state, and will clarify the hurdles faced by self-assembled systems of organic molecules as they evolved toward the first life on the Earth.

Investigation 2.2a: What conditions on the early Earth fostered the emergence of life?

A primary objective of research for this investigation is to establish laboratory models of primitive planetary conditions and determine how plausible mixtures of organic compounds can undergo self-assembly processes. These systems will have the capability to capture energy and nutrients from the environment, grow through polymerization, and reproduce some of their polymeric components. We must also to continue to explore the likely nature of the environment of the early Earth and its influence on the origin and early evolution of life.

Investigation 2.2b: Where did Earth's inventory of simple organic molecules and "volatiles" (especially water) come from?

To understand how life can begin on a habitable planet such as the Earth, it is essential to understand the origin of both organic compounds and the water to form the necessary aqueous environment.

For organic compounds we need to know what was likely to have been available. Prebiotic organic synthesis also occurs by photochemical processes in interstellar clouds. Laboratory simulations have recently demonstrated that key molecules can be synthesized in interstellar ices that are incorporated into nascent solar systems, and astronomical observations and analyses of extraterrestrial materials have shown that many compounds relevant to life processes are also present in meteorites, interplanetary dust particles and comets. It is likely that substantial amounts of such organic material were delivered to the Earth during late accretion, thereby providing organic compounds that could be directly incorporated into early forms of life or serve as a feedstock for further chemical evolution. Incoming comets and asteroids are rich in organic molecules. Carbonaceous chondrites, the most volatile-rich meteorites contain several types of amino acids and comets appear to contain up to ten times more organics than carbonaceous chondrites. However large objects are subject to extreme thermodynamic stress during entry and impact and as a result interplanetary dust particles (IDPs) have long been indicated as the main vehicle for carrying organic material to planetary surfaces. However, theoretical and laboratory studies have recently suggested that non-negligible fractions of complex organics can survive the shock events associated with large impacts, and secondary organics have been synthesized in strong shock events in the laboratory (Peterson et al., 1997; Blank et al. 2001). It is becoming clear that asteroid and comet impacts played an important role in the development and evolution of the prebiotic inventory of planetary objects, including the Earth (e.g. Pierazzo & Chyba, 1999) Detailed theoretical and laboratory work is needed to determine the rate of survival and synthesis of complex organics in strong shock events, as well as the role of planetary gravity in retaining impactor material delivered in impact events.
Chemical syntheses that occur within the solid crust, hydrosphere and atmosphere are potentially important sources of organic compounds, and they continue to be an important focus of research.

A major question is the origin of the water in the Earth's crust and oceans that has sustained life and regulated climate over our planet's history. A local source of water would require reduced temperatures in the protoplanetary disk in the 1 AU region, where the Earth formed, and this seems inconsistent with the water content of various chondritic meteorite types. However, this source cannot be ruled out. Comets, at least the long-period ones, seem to have a deuterium-to-hydrogen ratio that is twice that of ocean water, and thus cannot be a primary source. Indeed, dynamical models suggest that no more than 10% of the Earth's water may have come from comets. A promising source, from the dynamical and hydrogen-isotopic point of view, is large bodies formed in the primordial asteroid belt, which is generally thought to have been orders of magnitude more massive than the remnant belt we see today. There remain many unanswered questions about how the Earth acquired its water, whether comets truly are ruled out, and how much material was from the 2-4 AU region was acquired by the Earth. Further, we seek to understand the origin of organic carbon on the Earth, much more poorly constrained. It is essential to have samples of cometary materials, and the current Stardust mission with the planned sample return will be an enormous advance in advancing our understanding of this question. As well, exploration fo the asteroid belt to directly sample the chemical and isotopic nature of possible parent bodies of the chondrites, and other meteorite types, is essential. Finally, a firm understanding of the history of water on Mars will tie together the problem of the origin of water on Earth and Mars, providing much tighter constraints for models than can be afforded by either planet alone.

Investigation 2.2c: Are (or were) these conditions found on other planets or satellites in the solar system?

Building on the foundation from the preceding investigations, we must refine our models of habitable zones around other stars to better understand the “real estate” available for the origin and persistence of life on other planets. For the period of this plan, most of these studies will be based on theoretical models and astronomical investigations covered under other roadmaps, but the will provide a necessary foundation for further research

Objective 2.3: Determine the historical relationship between Earth and its biosphere

The Earth and its biosphere have co-evolved over some 4.5 billion years, with changes in one frequently triggering changes in the other. Examples pertinent to NASA’s mission of understanding the origin and early history of life and the possibility of life elsewhere include: the oxygenation of the ocean and atmosphere, the redox history of the oceans through the Archean (4.2-2.5 billion years ago) and Proterozoic, (2.5 billion to 543 million years ago) the relationship between tectonic activity and the weathering cycle and their impact on the habitability of the planet, the diversification of prokaryotic lineages, and the origin of complex multicellular life. In each of these cases research is needed to connect changes in the Earth’s physical and chemical environment to changes in biotic systems, and vise versa. There is also a clear need for more sophisticated, process-based models of the interaction between changes in the physical environment and biological innovation. In addition, NASA has a clear interest in determining the effect of extra-terrestrial impact’s on the Earth’s biota, and more specifically, on the extent to which major biotic crises in the history of life have been driven by exogenous factors (impacts), versus endogenous factors (climate change, volcanism, etc).

Investigation 2.3a: Search for biosignatures (molecular biomarkers, fossils and chemical signatures) of key microorganisms and metabolic processes in Archean and Proterozoic rocks, and correlate them with environmental changes on the early Earth.

Biosignatures provide critical information on the origin of major clades and their constituent metabolic processes during the Archean and Proterozoic. Establishing the timing of these events and correlating them to changes in the chemistry of the oceans and atmospheres will identify whether environmental triggers are responsible for key biological innovations. Fossil biosignature analysis is still a developing field and much progress is needed for the unambiguous identification their presence in ancient rocks. However, fossils provide our only direct record of the history of life on Earth and the reliable recognition of biosignatures will be crucial establishing the timing and history of key biological innovations. In addition, we need to place key innovations within the geological context of paleoenvironmental change (e.g. in the chemistry of the oceans and atmosphere), to evaluate whether or not major evolutionary events were triggered by intrinsic environmental factors. [See also description of Fossil biomarkers below]

Investigation 2.3b: Study the environmental, ecological and developmental conditions that led to the evolution of complex, multicellular life in the Neoproterozoic and Cambrian.

Complex multicellular life arose between 1.2 billion years ago (the earliest multicellular algae) and 543 million years ago (the Cambrian radiation of animals). The pattern of evolution is increasingly well constrained, with decreasing differences between molecular clock estimates of lineage divergences and times of lineage appearance in the fossil record. Connections between geochemical changes in the oceans and atmosphere during the late Neoproterozoic (Ediacaran Period) and the diversification of multicellular life are becoming clearer. Less clear is the relative significance of environmental, ecological and developmental factors in the timing and extraordinary breadth of this event. This is an area where more theoretical models of ecological niche construction and the interactions between ecology, development and the physical environment may prove quite valuable.

Investigation 2.3c: Examine the response of the Earth's biological and geochemical systems to extraterrestrial events, particularly asteroid and cometary impacts and explore the use of the lunar cratering and geochemical crustal records to provide constraints on the Hadean Earth that have been destroyed on Earth.

At least one and possibly more of the six great mass extinctions in the history of life have been associated with impacts of extra-terrestrial objects; other known impacts had no evident biotic effects in the fossil record. The relative importance of endogenous and exogenous influences on the history of life is an important area of research. In the absence of a geologic record for the Hadean Earth, future missions to investigate the lunar cratering and geochemical records coupled with better modeling of impacts and their environmental effects will provide an opportunity to explore the likely influence of Hadean impact events on the emerging biosphere.

Goal 3: Explore The Space Environment To Discover Potential Hazards and Search for Resources that would enable permanent human presence

Our planet Earth moves through interplanetary space and is bombarded by a continuum of energetic particles, cosmic rays, dust, and occasionally larger objects, all of which are hazards to human life. These hazards become even more severe for future human and robotic explorers that will move beyond the shielding provided by Earth's atmosphere and magnetic field, and into space environments that may be vastly different than on Earth. Here we catalogue these hazards to human and robotic explorers, and discuss vital resources needed to sustain life beyond Earth

Once a source of life-giving organics and water, cosmic impacts have the potential to wreak widespread destruction or even to extinguish much of life on Earth. Although the impact flux has declined greatly since the early days of the solar system, these events still occur regularly on planetary timescales. This sobering conclusion stems from the convergence of many lines of study, from geology to astronomy to paleontology. Evidence continues to mount that the so-called Cretaceous-Tertiary mass extinction event 65 million years ago was caused by the impact of an extraterrestrial body about 10 kilometers in diameter. It has also become apparent that even much smaller objects, which impact Earth much more frequently, are capable of doing serious damage to modern industrialized society. Classified satellites detect approximately 1 impact per month into the Earth's atmosphere (Brown et al. 2002). To understand the impact threat posed by asteroids and comets, as well as the feasibility of potential mitigation strategies, we must assess not only the number of potentially hazardous bodies and the frequency of both small and large impacts, but also the physical characteristics of the objects themselves

Objective 3.1: Determine the inventory and dynamics of bodies that may pose a hazard to Earth.

Investigation 3.1a: Updating the inventory of small bodies

The interplanetary space between the major bodies in our solar system is far from empty. Considerable progress has been made in discovering and cataloguing near-Earth asteroids (NEAs) that could potentially pose a threat to Earth and as a direct result of increased knowledge of the discovered population, estimates of the total population of potentially hazardous near-Earth asteroids have become increasingly accurate. Based on this evolved understanding of the population and the threat that it represents about 52% of the potentially hazardous near-Earth asteroids larger than 1 kilometer have now been catalogued. It is estimated that approximately 10,000 asteroids of diameter greater than 140 meters still exist in orbits that directly represent a collision hazard to Earth. Such objects have orbits that could bring them to within 0.05 AU of the Earth and are termed Potentially Hazardous Asteroids (PHAs). Of those, approximately 220+/-40 have diameters of 1 kilometer or larger, with 115 of these having been discovered to date (Stuart, J. S. and R. P. Binzel 2004). An impactor at the smaller end of this size range could wipe out a city or an entire coastal region; at the upper end of this range it could cause global devastation. NASA has played a key role in the discovery of these objects in response to a stated goal of discovering and cataloging 90% of all Near-Earth Asteroids (NEAs) with diameters larger than 1 km by 2008. However, based on the evolved understanding of the asteroid population and the threat that it represents, it is appropriate to modify this goal to better focus resources on the truly threatening population of objects. These changes are as follows:

1) The discovery and cataloging goal focuses specifically on the objects in orbits that represent a direct collision threat to Earth. These are the PHAs rather than the broad NEA category. Only about 20% of NEAs are actually PHAs.

2) The goal has been modified to directly address resolving the largest risk for the amount of resources invested. As such the goal is stated as "discover and catalog the population of potentially hazardous asteroids sufficient to resolve 90% of the risk from the impact of sub-kilometer asteroids". This will also resolve essentially all of the residual collision risk for the 1 km and larger asteroids. This goal indicates the development of a catalog of

PHAs 90% complete for asteroids larger than 140 meters diameter, which is achievable by the application of currently available technology (ref SDT report).

3) The long-period comets represent less than 1% of the total collision risk and therefore are not an important component of the stated goal. However, any such objects on a collision course likely will be discovered with only a few weeks to months of warning time by systems built to accomplish asteroid search.

This represents a unique contribution to the protection of our home planet that is synergistic with our objectives of understanding key solar system processes.

Investigation 3.1b: Understanding the impact process on different planetary settings

Impact cratering is a common geologic process in the solar system (Melosh, 1989). On Earth, craters in water-saturated sediments are larger than their energy-equivalents in dry soils, which in turn are larger than their energy-equivalents in crystalline rocks. Features of Martian craters have been used to indicate presence of water in the subsurface. Craters on the icy moons of Jupiter have morphologies that are quite different from those on rocky surfaces. To date there have been no direct observations of the formation of planetary impact craters in recorded history. While NASA's Deep Impact mission will provide a unique chance to witness a hypervelocity impact, a comprehensive understanding of the impact cratering process requires the combination of planetary geologic and geophysical observations and experimental and theoretical studies. Terrestrial impact structures are in the unique position of providing ground truth information on the impact cratering process. Their investigation can provide crucial information on the cratering process, in particular the importance of target composition and the amount and nature of deformation outward from the crater (Herrick and Pierazzo, 2003). Because of its arid environment and close proximity to the Earth, the Moon has been a valuable natural laboratory for studying planetary impact processes at 1 AU. New data from the science and exploration programs will add significant new constraints to our understanding of the Earth-Moon environment.

A critical component of the impact process is the response of materials to the wide range of temperatures and pressures associated with impact cratering. Specific material properties govern the response of materials to stress, resulting in different behaviors of different materials for nominally the same impact conditions. Gravity is another poorly explored parameter that can affect impact cratering, especially for very low gravity bodies, such as asteroids and comets. As a result, there are clear differences among craters on different planetary surfaces, especially in the outer solar system. To understand the role of impact cratering on the various planetary surfaces of the solar system the science community is in need of experimental data that can characterize the response of different materials in the impact process. This includes shock data relative to the exotic materials making up the surfaces of outer solar system bodies, such as different ices at very low temperatures, as well as mixed materials with very different characteristics, such as water ice and silicate rocks on the surface of Mars. These data can provide precious information for the development of accurate material models that still represent one of the major problems associated with theoretical modeling of impact cratering. Data on low gravity impacts are needed to understand impact cratering where usual scaling laws may not work. Measuring the surface and interior composition and structural properties of comets and asteroids will enable modeling of the effects of impacts and the development of credible mitigation strategies. It will also be important to understand the impact processes under low-gravity conditions, such as will be possible to study with the Deep Impact mission.

Investigation 3.1c: Impacts and Exogenous Delivery/Production of Organics

Incoming comets and asteroids are rich in organic molecules. Carbonaceous chondrites, the most volatile-rich meteorites, are known to contain several types of amino acids. Comets appear to contain up to ten times more organics than carbonaceous chondrites. Objects larger than few kilometers in diameter are the most important contributors of extraterrestrial material to Earth (Anders, 1989). Their usefulness in delivering complex organic molecules to a planetary surface is weakened by the extreme thermodynamic conditions occurring during an impact event. As a result, interplanetary dust particles (IDPs) have long been indicated as the main vehicle for carrying organic material to planetary surfaces. However, theoretical and laboratory studies have recently suggested that non-negligible fractions of complex organics can survive the shock events associated with large impacts, and secondary organics have been synthesized in strong shock events in the laboratory (Peterson et al., 1997; Blank et al. 2001). It is becoming clear that asteroid and comet impacts played an important role in the development and evolution of the prebiotic inventory of planetary objects, including the Earth (e.g. Pierazzo & Chyba, 1999). However, our knowledge of the potential effects of shock-loading on the modification of organic material is still sparse. Detailed theoretical and laboratory work is needed to determine the rate of survival and synthesis of complex organics in strong shock events, as well as the role of planetary gravity in retaining impactor material delivered in impact events.

Investigation 3.1d: Impacts and Extinctions

Collisions of large asteroids and comets with the Earth's surface are rare events that punctuate the geologic record. While the existence of large impact structures on Earth is undisputed, their effects on the biosphere are still not well understood. Based on statistics, the number of major mass extinctions characterizing the evolution of the Earth's biosphere is close to the number of expected large impact events (e.g., Rampino and Haggerty, 1996). On the other hand, hard evidence points to the well-studied end-Cretaceous (K/T) mass extinction (65 Myr ago) as the only one that clearly coincides with a major impact event, although mechanisms linking the impact event with the mass extinction are still debated (e.g., Toon et al., 1997). Attention has recently focused on the possibility of another mass extinction-impact event coincidence, at the Permian/Triassic boundary (P/T) around 250 million years ago (Becker et al., Science, 2002?). The investigation of the Earth's record for the evidence of an impact at the end of the Permian is still in its infancy, and any conclusion of a temporal coincidence with the mass extinction requires a major interdisciplinary investigation effort from the scientific community (*e.g.*, Becker *et al*., 2004). The examination of the Earth's geologic record coupled to the investigation of the effects of large impacts on the biosphere can provide important insights on the consequences of large impacts on Earth and into the processes by which life adapts and evolves. This in turn can help us learn about the role that impacts may have played in affecting the habitability of other planetary bodies of our solar system and beyond.

Objective 3.2: Characterize the Hazards from Radiation in Space and at Other Planets to Improve Forecasting and Mitigation Capabilities

One of the most serious issues facing the future human and robotic exploration of the Moon, Mars and beyond is the radiation hazard posed by solar energetic particles, galactic cosmic rays, and the radiation environments on other planets that are not now well characterized. On Earth, radiation from space is predominantly shielded by Earth's magnetic fields, but as spacecraft move into high altitude orbits, through the magnetosphere and beyond, they are exposed to a variety of serious radiation hazards. The radiation environment places a fundamental limit on human space flight. Over the past 20 years, on average, one to two satellites per year experience a premature partial or total mission loss due to radiation damage to electrical components. Shielding on spacecraft provides some protection from radiation, but for very high-energy radiation (>100MeV), shielding makes matters worse by producing secondary, penetrating particles, such as neutrons and nuclear fragments, that increase the hazard. Large solar energetic particle events can deliver lethal doses to astronauts over short periods of time. For example, the 1989 September event would have delivered a lifetime dose to astronauts in less than 12 hours. The event lasted for many days.

There are three primary categories of radiation hazard from space that dictate specific strategies for mitigation:

1. Galactic Cosmic Rays (GCRs) are an ever-present background radiation in space that is difficult to shield against. Astronauts would accumulate a career limit due to GCRs in roughly 3 years. We need to understand the current limits imposed by GCRs on mission transit time, shielding levels, or develop new techniques to shield against them.

2. Large solar energetic particle events are extremely dangerous to astronauts. To mitigate the hazard due to solar events, we must develop the ability to predict when and where they will occur.

3. There are unique radiation environments at each planet or satellite. At Earth, we have thoroughly characterized locations of the radiation belts, which allows us to mitigate the hazard they pose by transiting them rapidly. For future human and robotic exploration of other planets and satellites, it is essential to characterize the planetary radiation environments so that appropriate mitigation strategies and adequate shielding are designed.

Development and research of new materials and innovative approaches to shielding will be important to help mitigate the risks posed by all radiation hazards.

Investigation 3.2a: Develop an End-to-End Predictability of Solar Storms to be able to deal with lethal transient phenomena

There were Apollo lunar landings in April and December, 1972. Had the great storm of August 4, 1972 happened 4 months earlier or later, astronauts in the lunar module would have been exposed to a high radiation dose, causing acute radiation sickness and possibly death. Solar energetic particles are accelerated either on the Sun through stochastic processes or reconnection in strong magnetic field regions, and through acceleration at strong shocks set up by the formation of coronal mass ejections (CMEs) that plow through the solar wind. These events have a range of intensities, maximum energies, and frequency of occurance from the almost ubiquitous seed population at 10's of keV, up to very intense infrequent events with energies up to and even beyond GeV. The infrequent but very high-energy events are the most dangerous.

The frequency of occurrence and intensity of solar energetic particle events (SEPs) vary strongly with solar activity. When the Sun is extremely active, energetic particle events are more frequent and intense. Near solar minimum, energetic particle events are less frequent, but still pose a significant hazard. The onset of SEP events is prompt and potential alert systems must take the need for immediate actions into account. The composition of flares is also highly variable with heavy elements (Fe) often being enriched by large factors, which significantly increases the radiation dose. An important activity of solar and heliospheric physics is to develop the capability to predict when, where and how intense solar energetic particle events will be. The spiral shape of the interplanetary magnetic field guides particles away from the radial direction. This poses difficulties for developing alert capabilities from direct solar observations, since the relevant solar activity is most often hidden behind the limb of the Sun. The development of end-to-end predictive capabilities for solar energetic particles requires detailed knowledge of the nature and evolution of solar and heliospheric magnetic fields, the generation and influence of magnetohydrodynamic turbulence, and the formation and evolution of shocks from the Sun throughout the inner heliosphere. For short duration space travel, adequate shielding may mitigate the hazard posed by most of the low to moderate intensity solar particle events, but the largest events will remain a critical risk, even with well-shielded spacecraft.

Investigation 3.2b: Understanding Limits to human space flight imposed by Galactic Cosmic Rays

Highly energetic GCRs (100 MeV-10GeV) are always present in space, continually bombarding Earth's atmosphere, producing secondary particles and radiation through cascading high-energy collisions. The outer heliosphere shields us from the majority of GCRs. A small fraction of GCRs penetrate into the heliosphere and propagate toward the Sun and planets. Coronal mass ejections and other large magnetic disturbances are frequent during solar maximum, which minimizes the flow of GCRs during this period. GCRs pose a common health hazard even at low-Earth orbit, where only the lowest energy GCRs are shielded by the Earth's magnetic field. However, during space travel, GCRs are almost impossible to shield [Wilson et al., 1991] since they produce secondary radiation in shielding and other material that is even more hazardous than the primary GCRs. On long duration missions, such as to Mars, GCR radiation is the primary health hazard to astronauts who would accumulate a lifetime does in less than 1.5 years [NAS, 1973, 1997; Cucinotta et al, 2001]. We need to understand the limits imposed by GCRs on the duration of manned missions, or the levels of shielding that must be applied to mitigate the GCR hazard.

What we know about the dominant shielding of GCRs in the inner heliosheath is very limited and based mostly on models and theory. Large changes in the Local Intersetllar Medium have dramatic effects on the heliosphere and the radiation environment of the solar system. Such large changes have certainly occurred in the past and will occur again in the future. Isotopes produced in Earth's atmosphere through interactions with cosmic ray protons have been recorded in Antarctic ice. The ice records show two prominent peaks 35,000 and 60,000 years ago, when the radioisotope production rate was about twice the current value for about 1500 and 2000 years, respectively [Raisbeck et al., 1987]. We do not currently have the observational knowledge required to understand how the local interstellar medium interacts with the heliosphere; observations of that global interaction are essential for understanding the radiation environment that must be traversed by astronauts for long missions to distant destinations, such as Mars.

Investigation 3.2c: Characterizing the radiation environment at other planets and satellites

There are unique radiation environments and radiation belts at the Earth and in other planetary systems. In Earth's magnetosphere, the radiation environment is fairly well known. The hazards posed by the radiation belts can be mitigated because their locations and altitudes are well known and the transit time through them can be minimized. Radiation environments are remarkably different at each planet. For example, Jupiter is, second to the Sun, the strongest source of highly penetrating electrons in the solar system, which can severely damage electronic spacecraft subsystems if adequate shielding is not designed. On the surface of the Moon and Mars, neutrons produced from solar energetic particles and GCRs are one of the most destructive radiation hazards to astronauts. The radiation environment of other planetary systems must be charted and thoroughly understood before manned missions can be executed.

Large-scale ejections by the Sun form shocks as they propagate through the solar wind. These ejections cause large variations in the radiation environments at Earth and other planets by impacting and disturbing their magnetospheres, ionospheres and atmospheres. The types of disturbances released by the Sun are a strong function of solar activity. Near solar maximum, when the number of sunspots is at its highest level, the Sun's magnetic fields are in a continual state of massive reorganization. This causes the frequent eruption of solar matter and energy, coronal mass ejections (CMEs), that disrupt the global structure of the solar wind, cause major geomagnetic storms, and magnetospheric or ionospheric storms at other planets and satellites. Near solar minimum, when there are fewer sunspots, there are disruptions in the solar wind that recur with each 27-day solar rotation due to the interaction between fast and slow solar wind streams. These interactions lead to large spiral-shaped structures that co-rotate with the Sun, co-rotating interaction regions (CIRs), which cause recurrent geomagnetic activity at Earth. Because CIRs strengthen beyond Earth, they cause stronger ionospheric and magnetospheric disturbances at Mars and Jupiter. Understanding the effects of CMEs and CIRs on planetary atmospheres, magnetospheres and ionospheres will be essential for defining the varaibilities in the radiation environments at planets throughout the solar system.

Objective 3.3: Inventory and characterize planetary resources that can sustain and protect humans as they explore the Solar System

Permanent human habitation of space requires knowledge of the resources available from the Moon, Mars, and asteroids, and access to those resources. Assessing space resources requires missions that (1) determine the global distribution of materials (mineralogy and elemental abundances) with sufficient detail to understand geologic context (origin), (2) land on planetary bodies and characterize the surface and subsurface environments, (3) carry resource extraction test beds and pilot plants to develop engineering capability to use extraterrestrial resources; and (4) gain an understanding of the bulk densities of asteroids to ascertain which are solid bodies and which might be rubble piles (this is important from both the planetary defense point of view and the issue of asteroid resources). The combined data returned will be of immense long-term value to both science and resource exploration. There are four areas of investigation:

Investigation 3.3a: Determine the nature of water resources in lunar polar regions, on Mars, and the locations of water-bearing near-Earth asteroids and the most efficient ways to extract oxygen from non-polar lunar regolith.

Water may be the fuel that allows humans ready access to the Solar System. It is essential for life support, of course, but it is particularly useful as its constituents hydrogen and oxygen for use a rocket fuel. Water is found throughout the Solar System, but we do not have a systematic knowledge of its occurrence on specific bodies.

The Moon. Lunar Prospector data show conclusively that lunar polar regions are enriched in hydrogen. We do not know the precise form of the hydrogen (H, H_2O[ice], H_2O[bound], CH_4, organic compounds, etc.), its distribution in the regolith, or its precise location (permanently shadowed craters or over a broader region). To understand the concentration mechanisms, sources of hydrogen, and composition and total inventory of the deposits, requires dedicated mission(s). Such mission(s) would characterize the locations of the hydrogen deposits from orbit and, equally important, make detailed *in situ* measurements of representative deposits. Sub-surface sampling is expected to be important and should reach a depth of at least a meter (ideally to the base of the regolith, several meters). As an independent approach, it has long been known that oxygen can also be extracted from the lunar regolith, particularly from ilmenite and FeO-rich glass such as pyroclastic glass. Landed experiments are needed to test and refine such extraction techniques on the Moon.

Asteroids and Martian moons. Water is abundant in some asteroids, bound in phyllosilicate minerals. CI carbonaceous chondrites, which are believed to come from asteroids, contain about 10 wt% water. Prospecting for water requires missions that characterize the composition and physical properties of a number of specific asteroids that might be accessible for resources. We must identify water-rich near-earth asteroids and characterize their surface properties in sufficient detail to design and develop extraction systems.

Mars. A unifying theme of the Mars Exploration Program is to understand the distribution and history of water. Water is also essential for permanent settlements on Mars. Mars Odyssey neutron and gamma ray spectrometers have shown conclusively that abundant water exists in polar regions within the upper meter of the surface, and modest amounts are present in equatorial regions, probably bound in hydrous minerals. However, we do not have a detailed understanding of water on Mars, e.g., variations laterally or with depth, depth to liquid water, or purity of the water. Understanding water on Mars, along with hydrous mineralogy of the soil and surface rocks, will involve a continued series of orbital, flying, roving, and drilling measurements.

Investigation 3.3b: Determine the Inventory of rare metals

We will soon experience a shortage of rare metals needed for industrial processes (e.g., platinum. Some asteroids are "known" to be rich in these desirable and valuable metals. A large percentage of an impactor on the Moon would not be vaporized in certain lower velocity collisions, thus it may be possible to prospect for precious metal concentrations on the Moon which representing the remains of metal-rich asteroids. While a meteoritic component has long been recognized in lunar fines, these arguments speculate that large areal concentrations of ores can exist on the Moon and that these ore bodies could be mined for resources.

Investigation 3.3c: Use of local resources for primary shielding

It will be essential to shield astronauts from cosmic and solar radiation, especially during solar flare events. Current understanding indicates that more than two meters [check number] of lunar or asteroidal regolith should provide adequate shielding, although further research will be needed to both establish the radiation environments to which astronauts will be exposed (Objective 2) and explore new and innovative shielding techniques and approaches.

Efficient methods must be developed and tested that move large amounts of regolith to construct shielded habitats. Asteroids and the Moon present very different problems for using regolith, however, because physical properties may be different. Measurements of geotechnical properties of asteroid surface materials and development of excavation techniques at very low gravity are needed.

Investigation 3.3d: Assess potential long-term resources

Permanent settlements will require use of materials from the Moon, Mars, and asteroids (because this is less expensive than bringing materials out of Earth's gravitational potential) to build and maintain the infrastructure and generate products for export. Prospecting for these resources and devising mining and processing techniques are crucial steps in human activities in space. More importantly, some space resources, such as producing solar energy on the Moon, are expected to make the transition to be used for the benefit of people on Earth while opening new economic markets that might drive the human exploration of space.

Initial lunar resource utilization will focus on the most concentrated deposits of materials of immediate interest (e.g., highest titanium, phosphorous, or zirconium concentrations [note: explain why these materials specifically]) and development of efficient techniques to extract those resources and manufacture products from them. Although our understanding of the potential value of specific resources is in its infancy, a thorough inventory of raw materials is the baseline information that is essential for extended planning. This requires a combination of orbital exploration that provides mineral and elemental concentrations in detailed geologic context and coordinated landed (roving) investigations of surface composition and physical properties with tests of extraction technologies. Asteroids are diverse and their surfaces poorly explored (although individual asteroids may be homogeneous; see Objective 1). The distribution of potential useful materials (e.g., iron metal, organic compounds) on asteroids needs to be determined through orbital and landed measurements. Techniques to process materials in low gravity must also be developed and tested.

Goal 4: Understand the processes that determine the fate of the soalr system and life within it.

Objective 4.1: Learn how the processes that shape planetary bodies operate and interact, through multidisciplinary comparative studies.

Improved understanding of planetary formation and evolution, and of how habitable environments arise, can be gained through a detailed knowledge of the individual processes that affect planetary bodies. Distinct processes are at work in the very diverse settings of planetary interiors, surfaces, atmospheres, magnetospheres, and in the ring systems of the jovian planets. The dominant process at any given location can operate in relative isolation, but more commonly a suite of processes is at work on planetary bodies. The history of the interactions that affect planetary bodies may be very dynamic in nature, with diverse intermediate states that depend on the time scales of the processes at work. Physical processes describe the essential mechanisms by which the many components on or around a planetary surface can interact and evolve. Many examples of relevant processes could be cited; here we list some illustrative examples for the broad range of settings associated with understanding planetary bodies.

This complex array of interrelated processes must be better understood if we are to correctly identify both the past history and the potential future evolution of diverse planetary bodies. As more is learned about individual and multiple processes active in various settings, it becomes increasingly important to evaluate how processes work together. For example, the dynamics of planetary interiors translates to observable magnetic fields, which in turn directly influence particle interactions around each body. Multidisciplinary comparative investigations of planetary bodies should eventually lead to an integrated understanding of what planetary processes are required to provide a full accounting of how complex planetary bodies evolve.

Investigation 4.1a: Studies of the interiors of planetary bodies.

Interior phenomena include diverse processes such as chemical differentiation, core formation and segregation, mantle dynamics and convection, and heat sources and heat transfer. In the jovian planets, understanding deep interior structure can constrain planet formation. For both rocky and icy worlds, interior evolution is intimately linked to surface and atmospheric evolution, and to habitability. Interior processes operating in icy worlds determine whether habitable oceans might exist within.

Investigation 4.1b: Studies of the surfaces of planetary bodies.

Surface phenomena are affected by processes such as impact cratering, tectonism, volcanism, hydrology, glaciation, and aeolian (wind-surface) interaction. Any particular planetary surface can involve several of these processes, all acting at varying time scales and intensities. Impact cratering may be particularly important to understanding life processes because large impacts can cause major extinctions, intermediate impacts can pose a serious threat to localized life communities, and even relatively small meteoroids might be carriers of organic materials between planets.

Investigation 4.1c: Studies of the atmospheres of planetary bodies.

Atmospheric phenomena include such diverse processes as volatile evolution and loss rate from the planetary body, chemical interactions between the atmosphere and surface materials, particle interactions between the magnetosphere and the upper atmosphere, meteorology, weather and climate.

Investigation 4.1d: Studies of magnetospheric interactions.

Magnetospheres involve electromagnetic processes between particles and fields at many scales, producing interactions with planetary atmospheres and surfaces. Magnetospheric interactions can affect heating, chemistry and loss of atmospheres, and space weathering of surfaces.

Investigation 4.1e: Studies of planetary rings.

Planetary rings involve both constructional and destructional interactions among particles ranging in size from dust to boulders, complex gravitational interactions with neighboring satellites, and magnetospheric interactions. They may provide present-day examples of mechanisms associated with the original accretion of the Solar System.

Decadal Survey mapping:
11. How Do the Processes That Shape the Contemporary Character of Planetary Bodies Operate and Interact?

<u>Goal 5: Determine if there is or ever has been life elsewhere in the solar system</u>

Objective 5.1: Determine if life exists or ever existed on other planetary bodies

As presently understood, the basic requirements for life include liquid water, environments favorable for the assembly of complex organic molecules and metabolically useful energy sources. Because so little is known about the detailed distribution of these requirements within our solar system, exploration logically begins by determining the nature and distribution of potentially habitable environments (i.e., those meeting the basic requirements for life). Earth-based analog studies and theoretical investigations, all informed by data from solar system missions, are crucial activities for helping refine exploration strategies and scientific priorities for future astrobiological missions in the solar system. Research in such widely divergent areas as solar system and planetary evolution, origin of life studies, extremophile biology and microbial paleontology have been instrumental in helping inform NASA about where and how to begin looking for habitable environments, pre-biotic chemistry and life elsewhere in the solar system.

The Viking landers, Pathfinder and now the Spirit and Opportunity rovers provided our initial steps to answering questions of habitability and life. Viking searched (unsuccessfully) for organic compounds in Martian surface samples, and Spirit and Opportunity have returned positive evidence that Mars once had standing bodies of liquid water on its surface. The latter results are enormously encouraging and will inspire future robotic and ultimately human investigations of Mars.

Important next steps in Mars exploration are to: 1) using high spatial and spectral resolution infrared mapping from orbit discover additional deposits of aqueous minerals and sediments on the surface of Mars to guide future surface missions; 2) undertake surface robotic missions to carry out definitive mineralogical, geochemical (including isotopic) and organic analyses of Martian surface materials at high priority sites; 3) probe Martian polar ice deposits to determine whether any organic or even biochemical molecules have been cryopreserved there; 4) investigate the deep subsurface of Mars from orbit and by surface drilling to search for subsurface groundwater; 5) obtain a more thorough understanding of the potential for forward and back-contamination of Mars; 6) carry out the first in situ life detection experiments on the surface of Mars at locations proven to be potentially habitable environments; 7) undertake sample returns from high priority sites to provide definitive life detection studies in Earth-based labs. Significant missions in development involved in this issue include the Mars Science Laboratory, Phoenix and follow-on programs within the Mars exploration program.

Life can be described as a chemical system that links a common property of organic molecules - the ability to undergo spontaneous chemical transformation - with the uncommon property of synthesizing a copy of that system. Biosignatures arise from this fundamental process in a number of ways.

Simplest to understand is that life, even microscopic life, leaves morphological traces of itself in the form of cellular or body fossils. There is presently considerable controversy around the question of the earliest terrestrial microfossils, so continuing research on this topic is very important. Such investigations will guide us as we look for microfossils in the first Mars sample returns expected in the 2010 - 2020 period.

Another type of biosignature derives from the fact that some organic compounds produced by the life process are very stable and can be detected as "molecular fossils", even in very old rocks. Examples from the Archean fossil record on Earth include hopanes and terpenes preserved in ancient sediments.

Other chemical biosignatures are based on the fact that living systems choose between carbon isotopes when metabolizing single carbon species, such as carbon dioxide. This results in a characteristically "light" ratio of C^{13}/C^{12} compared to inorganic minerals, such as calcium carbonate. Similar patterns occur for sulfur and nitrogen isotopes.

On a global scale, life can move an entire planetary environment away from chemical equilibrium. In the case of the modern Earth, the presence of molecular oxygen arising from oxygenic photosynthesis is a clear indication of the existence of surface life. Oxygens coexistence with methane reflects a dynamic equilibrium mediated by life. The recent observation of methane in the Martian atmosphere is potential example of this type of process elsewhere in our Solar System, and should be given high priority for further investigation.

High resolution images of the surface of Europa, obtained by the Galileo mission fly-bys, have revealed a complexly fractured and largely uncratered surface, where blocks of water ice crust appear to have foundered, tilted and become frozen in the leads between diverging plates of ice. Ice mounds appear to have formed where "volcanic" eruptions of water or ice were sustained at one place for some time. These features suggest the possibility of a kind of "cryo-tectonic" cycle driven by tidal flexing and internal frictional heating, which could maintain a zone of liquid water or a fluid ice-brine mixture beneath the crust up to three times the volume of the Earth's oceans. The movements of the ice crust would be sustained by density-driven, upward flows of warm water, or ice-brine mixtures from beneath the crust. Where the crust was breached, water or brines erupted and froze out at the surface. This hypothesis is consistent with magnetometer measurements obtained from orbit at Europa (as well as the other icy Galilean satellites, Ganymede and Callisto), which require the presence of conducting brines beneath the surface of these moons. In addition, spectral mapping of the surface of Europa from orbit shows the presence of magnesium salts, supporting the presence of interstitial brines. Additional orbital measurements of Europa's surface are needed to determine the mineralogical and organic composition of the surface ice and to probe the interior for evidence of a subsurface ocean. In addition, landed robotic missions directed to sites of recent up-flows, are needed to explore for evidence of pre-biotic organic chemistry, potential energy sources for life and biosignatures preserved within surface and subsurface ices.

Titan is a planet-sized moon of Saturn with a dense atmosphere of nitrogen and methane. Over geologic time photochemistry has converted methane and nitrogen into a diverse suite of hydrocarbon and nitrile products, which sediment out onto the surface. We do not know whether these hydrocarbons and nitriles remain on the surface as solids and liquids, or have been gardened into the crust by impact and other geologic processes. Regardless, exposure of any of this material to transient liquid water or ammonia-water would be extremely interesting from the astrobiological viewpoint because synthesis of monomeric, or even polymeric, building blocks of life might be possible. Impacts or internal processes on Titan are capable of creating localized, transient bodies of liquid water or water-ammonia. Determination of the existence and distribution of surface organics on Titan, and evidence for past geologic activity consistent with the melting of the water ice (or ammonia-water) crust, are goals that can be met with the ongoing Cassini explorations during its four year prime mission, though an additional 2-3 years to allow for more Titan flybys would ensure mapping of much of the surface of this diverse world. If merited by Cassini and Huygens probe studies, a follow-on mission to sample organic deposits on Titan's surface could permit the search for and detection of amino acids, peptides, purines/pyrimidines, and other molecules of prebiotic or protobiological interest. Were such to be found on Titan, the notion that life forms wherever salubrious conditions are found would be greatly bolstered.

Investigation 5.1a: Develop reliable, universal methods for the in situ detection and characterization of pre-biotic organic chemistry and biosignatures present in surface and subsurface rocks, soils and ices, over a broad range of conditions that are representative of the extreme environments that exist on other planetary bodies in our Solar System.

Developing methods for the reliable identification of biological and chemical biomarkers is criticially important for this objective. Although considerable progress has been made in recent years, clarification of the nature, preservation potential and interpretation of potential biomarkers is urgently needed. Such methods are needed on Mars, Titan, comets and possibly meteorite parent bodies.

Investigation 5.1b: Explore Mars for potentially habitable environments (past or present) using orbital and surface missions.

Search for surface and subsurface reservoirs of water (in all of its forms), energy sources, mineralogical indicators of past aqueous environments, pre-biotic organic chemistry and biosignatures of fossil or extant life. Use orbital and in situ investigations to create a context for multiple targeted sample returns. This will require support for technology developments needed to pursue both broadly based orbital and in situ surface robotic exploration to search for biosignatures present in surface or subsurface environments.

Investigation 5.1c: Conduct orbital remote sensing of Jupiter's icy moons to test alternative models for the presence of subsurface brines.

Map surface geomorphology and composition at high spatial and spectral resolution in preparation for surface missions that will explore pre-targeted sites for pre-biotic organic chemistry, energy sources and biosignatures preserved in surface/subsurface ices and brines.

Investigation 5.1d: Explore the atmosphere and surface of Titan for environments conducive to complex pre-biotic synthesis and life.

Determine the nature of pre-biotic organic chemistry, energy sources and aqueous environments present and explore for biosignatures in surface materials.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
SOLAR SYSTEM EXPLORATION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Solar System Exploration Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on conducting robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

Administrator

Date

MEMBERSHIP ROSTER

Solar System Exploration
Strategic Roadmap Committee

Committee Members
Orlando Figueroa, NASA Science Mission Directorate, ***co-chair***
G. Scott Hubbard, NASA Ames Research Center, ***co-chair***
Jonathan Lunine, University of Arizona Lunar and Planetary Laboratory, ***co-chair***
Andrew B. Christensen, Northrop Grumman
Jerry Chodil, Ball Aerospace (retired)
Ben Clark, Lockheed Martin Astronautics
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Wes Huntress, Carnegie Institution of Washington
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Thomas D. Jones, Consultant
Melissa McGrath, NASA Marshall Space Flight Center
Karen Meech, University of Hawaii
John Niehoff, Science Applications International Corporation
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Carl Pilcher, Directorate Coordinator, ***Designated Federal Official***
Judith Robey, Advanced Planning and Integration Office Coordinator

Ex Officio and Liaison
Andrew Dantzler, NASA Science Mission Directorate
Heidi Hammell, Space Science Institute, Education Roadmap Committee Liaison
Chris Jones, Jet Propulsion Laboratory
Jason Jenkins, NASA Exploration Systems Mission Directorate

Final 12/22/04
Updated 3/4/05

Strategic Roadmap #4: “To conduct advanced telescope searches for Earth-like planets and habitable environments around neighboring stars.”

Executive Summary

“Is there life elsewhere in the Universe?”, “Are there other planetary systems like our own?, “How do planets and stars come into being?”, “Are we alone?”. In the vast blackness of the Universe, our home planet is a sparkling oasis of life. Whether the Universe harbors other worlds that can support life is a question that has been asked for millennia. However, we are privileged to live in a time marked by scientific and technological advances so rapid and so brilliant that these elusive questions can now be pursued not only with philosophical speculation, but also with scientific observation. While the questions are simple, the scientific and technical capabilities needed to answer them are challenging. In this Roadmap, we articulate the scientific case for exploration beyond the Solar System and map out a set of implementing strategies and missions that will lead to the answers to these and other central questions concerning humanity’s place in the Universe.

This Roadmap is a framework for Exploration on the grandest scale, leveraging NASA’s considerable experience to achieve what only NASA can. It is an answer to NASA’s Vision “... To find life beyond.” It is the response to NASA’s Mission statement “ ... To explore the Universe and Search for Life” and “ ... To Inspire the Next Generation of Explorers.” If fully implemented, it would be the partial realization of the Space Exploration Vision, as described in the “President’s Commission on Implementation of United States Space Exploration Policy,” which challenges NASA to Search for Earth-like Planets. “The President's Vision for United States Space Exploration (2004)” has made the “advanced telescope searches for Earth-like planets and habitable environments around other stars” one of the foundations of NASA’s exploration goals.

Our central theme is the quest for Earth-like planets, habitable environments, and signs of life outside the Solar System. To fully realize this vision requires measurements in both the visible and the infrared, and the determination of planetary masses. Therefore, we have designed a staged program of space missions, *Kepler*, the Space Interferometry Mission (SIM), the Terrestrial Planet Finder-Coronagraph (TPF-C), the Terrestrial Planet Finder-Interferometer (TPF-I), and Life Finder, each building on the legacy of and information derived from the previous one. *Kepler* will find signs of terrestrial planets shadowing distant stars; SIM will measure the motion of nearby stars caused by planets, and the masses of those planets; TPF-C in optical light will image a dim Earth from under the glare of its bright companion star and probe its atmosphere; TPF-I, the even more sensitive infrared counterpart to TPF-C, will extend these studies in detail and range; and, finally, the spectroscopic telescope, Life Finder, will study the atmospheres of even more distant planets to seek definitive evidence of life. Planets and planetary systems are formed in the context of stellar birth. This Roadmap describes the mysteries of formation and birth and explains how missions such as the *James Webb* Space Telescope (JWST), the Stratospheric Observatory for Infrared Astronomy (SOFIA), and the Single Aperture Far-InfraRed mission (SAFIR) will unravel them. Each mission in this ambitious series builds on the technological and scientific legacies of those that precede it.

A guiding principle is that the flagship missions must represent quantum leaps in performance. JWST will be 100 to 1000 times as sensitive as *Spitzer*. It will have 10 times the collecting area of Hubble. In the far-infrared, SAFIR will be more than 100 times as sensitive as SOFIA. TPF-I will have 100 times the contrast capability of JWST, and TPF-C will have 10^5 times that of Hubble. With all these missions, the opening up of new "discovery spaces" is a major theme. What energizes the explorations described in this Roadmap is not only that known territory will be probed deeply and with precision, but that unanticipated new territories must inevitably be revealed.

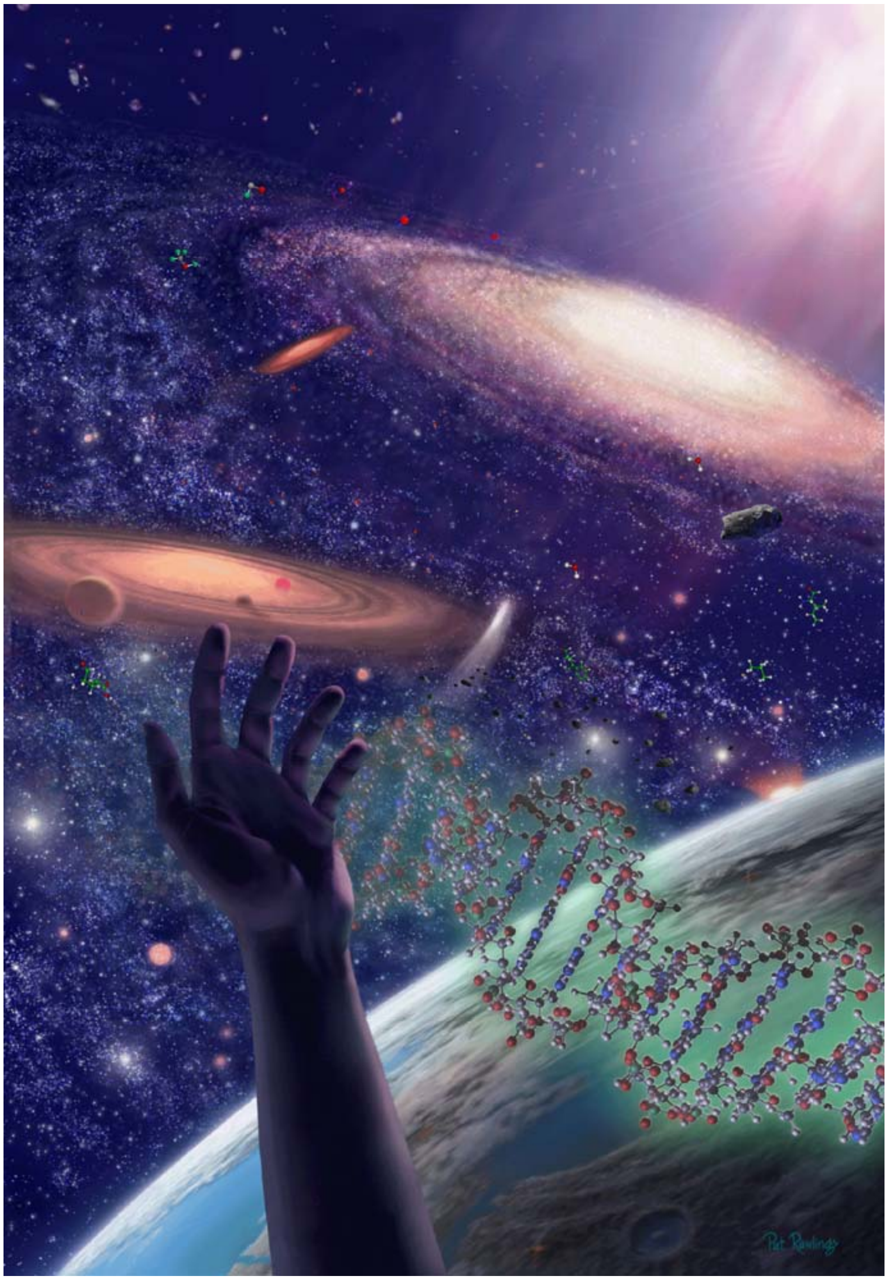
It is crucial that investment for a mission reduce the risks and costs of its successor missions. Detectors in the far-infrared developed for SOFIA will pave the way for those on SAFIR. Cryogenic research for *Spitzer* and JWST will lead to the low-temperature capabilities necessary for TPF-I, SAFIR, and Life Finder. Interferometric capabilities for SIM will be incorporated into technologies needed for TPF-I and Life Finder. Advances in large telescope apertures for JWST will also be employed for the TPFs, SAFIR, and Life Finder. In the realms of detectors, telescopes, coolers, and distributed spacecraft, technology for a given mission must pay off multiple times in subsequent missions. Therefore, an integrated plan of crosscutting technology investment is one of the pillars of this Roadmap.

Beyond the strategic space missions, NASA's scientific success depends on rapid and flexible response to new discoveries, inventing new ideas and theoretical tools leading to tomorrow's space science initiatives, converting hard-won data into scientific understanding, and developing promising technologies that are later incorporated into major missions. These activities are supported through a balanced portfolio of competed Research and Analysis (R&A), Universe Probe, and Discovery programs, which collectively are designed to guarantee the continued vitality of NASA's overall space science vision, reduce major mission risks, and optimize the return on NASA's capital, technology, and manpower investments. Importantly, NASA, through its Education and Public Outreach programs and through the R&A program's support of student and postdoctoral researchers at America's universities, plays a critical role in educating the Nation and training the next generation of explorers.

Some of the discoveries to emerge from this Roadmap could fundamentally shift our understanding of our place in the Universe, with implications as profound as the early work of Copernicus, Kepler, and Galileo. A viable Roadmap must take full advantage of this potential to ignite the public imagination, while fulfilling its obligation to inspire the students of the future who will carry out its programs of discovery. This Roadmap is a legacy to them.

I. Agency Objective Statement, Strategic Roadmap #4:

"To conduct advanced telescope searches for Earth-like planets and habitable environments around neighboring stars."



Strategic Roadmap #4, "**The Search for Earth-like Planets,**" builds on a strong legacy of scientific advances and policy heritage (see Appendix 1) and represents NASA's *only* plan for realizing these exploration goals.

II. Key Science Goals: The Search for Habitable Planets, the Development of Habitable Environments

Are we alone? In the vast blackness of the Universe, our home planet is a single sparkling oasis of life. Whether the Universe harbors other worlds that can support life is a question that has been pondered, yet remained unanswered, for thousands of years. While we continue to search for sub-surface life on other worlds in our Solar System, we are privileged to live in a time when technological advances allow us to expand the search for life beyond the confines of our own Solar System, and out into the wider Universe. Over the next two decades, NASA will launch a series of spaceborne telescopes that will build on a foundation of existing observatories and progressively advance humanity's ability to detect and characterize Earth-like planets around other stars, and examine those planets for signs of life. This program directly supports *The President's Vision for US Space Exploration* (2004) that calls for *"advanced telescope searches for Earth-like planets and habitable environments around other stars"* as one of NASA's exploration goals in the 21st Century.

Within the first 10 years of this Roadmap, we will know whether Earth-like planets are common or rare. We will also know whether any nearby stars have Earth-mass planets, and we will be on the verge of knowing whether any nearby exoplanets show biosignatures indicating the possible presence of life. Missions in later decades will successively reveal the presence, formation, and diversity of Earth-like planets and any life they may harbor.

This Roadmap has two scientific themes that will lead to these and other discoveries. The first theme is the search for extrasolar planets and their direct detection and characterization, and the second is the study of the formation and evolution of exoplanetary systems from stellar disks. This Roadmap will delineate the investigations and the missions that make up these two themes.

A. Do other stars harbor planets like Earth?

The search for extrasolar planetary systems is well underway, and we now know of over 150 planets outside our Solar System, most discovered by NASA-supported ground-based telescopes and with the help of NASA-supported grants.

While some of these planets are gas giants similar to Jupiter and Saturn in our Solar System, some of the newly discovered planets have masses as small as 15 times the mass of the Earth.

These recent discoveries have already revealed important insights:

- Planets are quite common. Roughly 7% of all nearby stars harbor a giant planet within 3 AU.
- The number of planets increases as mass decreases towards the mass of an earth.
- Stars that contain higher abundance of metals are more likely to have planets

- Multiple planets are common, often in resonant orbits
- The number of planets increases with distance from the star.
- Eccentric orbits are common, with only 10% being nearly circular.

The increasing number of planets with smaller mass suggests that planets with masses below 15 Earth masses, currently undetectable, are even more numerous. Moreover, the correlation with heavy elements supports current planet formation theory that suggests rocky planets would be more numerous than the gas giants. *The observations suggest that many nearby stars harbor rocky planets.*

Doppler planet search techniques have found all but 5 of the ~150 known extrasolar planets. Over the next few years, these Doppler planet searches are poised to discover Jupiter-mass planets orbiting at 4-7 AU, providing the first direct comparison of planets in our Solar System to those orbiting at comparable distances from other stars. Jupiter analogs, those in circular orbits having no giant planet inward of them, may be signposts of rocky planets orbiting closer in, thus serving to prioritize target stars for SIM – PlanetQuest, Terrestrial Planet Finder-Coronagraph (TPF-C), and Terrestrial Planet Finder-Interferometer (TPF-I). Doppler work with a precision of 1 m/s would allow detection of planets having mass as low as 10 Earth masses, but most easily if they orbit within 0.1 AU of a solar-mass star, a region that is hotter than the corresponding habitable zone. Earth-mass planets orbiting at roughly 1 AU induce a stellar wobble of only 0.1 m/s, a factor of 10 below the detection threshold of even future Doppler work. Thus, other space-borne techniques are needed to find Earth-like planets, first indirectly with SIM and then directly with TPF-C and TPF-I.

While current observations suggest that rocky planets *may* be common, their abundance is quite uncertain. *Kepler* will address this question statistically by surveying stars 200-600 parsecs away (one parsec is equal to 3.26 light-years). *Kepler* will detect Earth-sized planets (and larger) through their rare alignment with the host star, dimming it by one part in 10,000. Planets found by *Kepler* will be too distant for follow-up by SIM-PlanetQuest or TPF. SIM-PlanetQuest and TPF will survey nearby stars and determine the abundance of nearby Earth-like planets.

B. What are the properties of these planets?

Discovery will be but the first step in our exploration of extrasolar rocky planets. Next, we will want to learn the basic properties of each newly discovered planet. The diversity of rocky worlds is likely much greater than that represented by Mercury, Venus, Earth, and Mars. SIM-PlanetQuest, TPF-C and TPF-I will begin the process of exploring these new planets by measuring their fundamental properties:

- *Mass.* The SIM-PlanetQuest mission will directly measure the masses of the larger rocky planets. The mass of a rocky planet determines whether it can retain molecules in its atmosphere. The presence of greenhouse gases in the atmosphere determines the planet's temperature. Mass also sets the geochemical and thermal structure of the interior of the planet, which dictates the presence of plate tectonics (affecting the cycling of surface material), active volcanism, and magnetic dynamos (that provide magnetic protection from cosmic rays). Mass discriminates ice-giants from rocky planets that otherwise differ little in radius.

- *Surface Temperature and Radius.* The temperature of rocky planets will be measured unambiguously by the combination of TPF-C and TPF-I. The direct images themselves provide orbital distances, which imply temperatures from radiative equilibrium, albeit with an uncertainty due to the unknown albedo (light reflection fraction) and greenhouse effects. By combining measurements of the reflected visible fluxes (setting albedo) made by TPF-C and of the mid-IR fluxes (setting planet luminosity) made by TPF-I, we can uniquely determine the radius and surface temperature of the planets. These measurements by TPF-C and TPF-I will establish the habitability of each detected rocky planet. Table II-1 summarizes the scientific synergies between SIM, TPF-C, and TPF-I.

- *Atmospheric Composition.* TPF-C and TPF-I will acquire low-resolution spectra of rocky planets enabling the first measures of the chemical composition of their atmospheres. The spectroscopic observations will be designed to detect oxygen, ozone, carbon dioxide, and methane in the planet's atmosphere. These spectroscopic observations will also be essential for our search for biomarkers (next section).

- *Surface Properties.* TPF-C/TPF-I will search for temporal variability in the brightness of the rocky planets caused by the rotation of surface features and clouds. TPF-C can get direct spectral measurements of planetary surface composition (rock, ocean, ice, vegetation) and TPF-I will be able to discriminate CO_2 ice-covered worlds with thin atmospheres. By measuring such variations over many rotation periods, these observations will reveal whether the planet has clouds, oceans, and continents. These temporal observations will also reveal the rotation period of the planet and could detect annual global variations in planetary properties. Remote observations of the Earth would reveal significant daily variations in its brightness.

By measuring these basic properties, the planned suite of missions will determine whether any of the nearby planets are suitable environments for detectable life.

Table II-1: Physical Parameters Determined by SIM, TPF-C, and TPF-I. Red plus signs mean that all the missions are required to determine the parameter; black checks mean that the indicated parameter can, in principle, be obtained by the one mission alone.

	Parameters	SIM	TPF-C	TPF-I
Orbital Parameters				
–	Stable orbit in habitable zone	✓		
Characteristics for habitability				
–	Temperature			✓
–	Temperature Variability due to distance changes	✓		
–	Radius		+	+
–	Albedo		+	+
–	Mass	✓		
–	Surface gravity	+	+	+
–	Atmospheric and Surface Composition		✓	✓
–	Atmospheric conditions		✓	✓
–	Presence of water		✓	✓
–	Temporal Variability of composition		✓	✓
Solar System Characteristics				
–	Influence of other planets	✓		
–	Presence of comets or asteroids		✓	
Indicators of Life				
–	Atmospheric Biosignatures (e.g., O_2, O_3, CH_4)		+	+
–	Surface Biosignatures (e.g., vegetation red edge)		✓	

C. How will we detect the presence of life?

Our search plans assume that the effects on a planet of even the most basic forms of life are global, and that biosignatures from the planet's atmosphere or surface will be recognizable in the disk-averaged spectrum of the planet. Observations and exploration of our own and other planets in our Solar System, and ongoing astrobiology research, have taught us that signs of life can *only* be conclusively recognized in the context of the overall planetary environment.

The Earth has known surface biosignatures from vegetation, and several atmospheric biosignatures, including the characteristic spectra of life-related compounds like oxygen – produced by photosynthetic bacteria and plants - and its photochemical product, ozone. A more robust atmospheric biosignature is the simultaneous presence of oxygen or ozone and a reduced gas, such as methane (CH_4) or nitrous oxide (N_2O), which are also produced by life. Although these latter two gases are difficult to detect in the Earth's current atmosphere they and other biogenic compounds may be more detectable on Earth-like planets around other stars or during different stages of a planet's history.

Life, and the conditions under which life thrives, may not be identical to those found on Earth. Correspondingly, we must design missions that are as robust as possible in thoroughly characterizing planets of unknown composition, and in searching for the byproducts of metabolisms that may not be familiar to us. To do this, we must observe over the largest wavelength range possible, to provide confirmation detections of the same molecular species, and to increase our overall chances of detecting and interpreting biosignatures in the context of their planetary environment. This will maximize the probability of success in our search for extrasolar life and provide crosschecks and verification tests for what could be the most important scientific and cultural discovery of the century. A marginal detection of oxygen in the visible could be verified with a follow-up detection of the stronger ozone in the mid-IR. Having data in two different wavelength regions would also help with the identification of the secondary biomarker gases such as CH_4 and N_2O. CH_4 can be observed in both the visible and the thermal infrared, although detection in the mid-IR can be problematic in the presence of strong absorption from water vapor, whereas N_2O can only be seen in the mid-IR. In addition, many metabolic byproducts of life have absorption features that are accessible only in the mid-IR. On the other hand, surface signatures of life, such as those from leafy plants on Earth, can only be detected in the visible range. Thus, robust detection and quantification of biosignatures from the widest possible range of potential metabolisms would require data in both wavelength regions. Not only does this allow access to a more comprehensive array of potential biosignatures from different types of life, the two wavelength regions also provide the crucial characterization of the planetary environment required to identify the biomarker in context. It is very clear that if we do eventually make a tentative identification of life in one wavelength region, the information that we will need to corroborate it is data from the other wavelength region.

Beyond the TPF missions, the next generation "Life Finder" mission would use a greater collecting area to provide enhanced spectral resolution, better temporal resolution, and improved overall sensitivity. This would enable a more sensitive search for additional biosignatures, and extend our search for Earth-like worlds to perhaps thousands of stars. The dual goals of extending our search to further planetary systems and providing greater resolution, time-resolved, spectral information will challenge our imagination and technical prowess, particularly in the area of large, lightweight space optics, for decades to come.

To support these observational missions, it is very important to explore possible biosignatures in great detail, both theoretically and in the field or laboratory, to better understand those signs of life that might be remotely detected in the spectrum of another planet, especially for habitable planets that differ from our own modern Earth, in age or composition. It is also important to identify potential "false positives," the non-biological generation of planetary characteristics that mimic biosignatures. The NASA Astrobiology Institute and the TPF-Foundation Science program support research that will help determine the design and characterization strategies for the TPF and successor missions. This research will determine the most robust characterization strategy via the synergistic use of planetary mass from SIM, and the complementary optical and infrared spectral information provided by the TPF and Life Finder missions.

To ultimately understand whether we are part of a living Universe, we can only extrapolate outward. If life is found anywhere within our stellar "neighborhood," then we can conclude it to be highly probable that life is common in our galaxy, and surely so in the wider Universe. Conversely, if present or past life is found to be absent from our stellar neighborhood except for here at home, then this information surely will inform our view of how rare life is anywhere in the Universe, and how precious it is on Earth.

The Extrasolar Habitable Zone

The Habitable Zone classically refers to that range of distances from a star in which an Earth-like planet can maintain liquid water on its surface. The inner edge of the habitable zone is governed by the catastrophic loss of surface water into the atmosphere, and the outer edge is governed by the freezing out of water on the planetary surface.

Our exploration of our own Solar System suggests that the habitable zone may be larger. There is growing evidence that sub-surface environments on Mars and Europa, regions outside of the classically defined Habitable Zone, might be conducive to life. However, life deep under rock or ice would be extremely difficult to detect via remote sensing, even from orbit. Thus, the "Extrasolar Habitable Zone", the region where life could both exist and be remotely detected, is used for planning the astronomical remote-sensing reconnaissance to be undertaken by the TPF missions and LifeFinder.

D. How does star formation lead to planet formation?

The Sun, our home star that provides our planet with warmth and light, was formed from a dense cloud of dust and gas 4.5 billion years ago and will continue to shine at nearly the same brightness for another 5 billion years. Our Sun is only one of 100 billion stars that populate our home galaxy, the Milky Way, and is by no means the oldest or youngest. This realization that the Sun is in many ways average – of ordinary mass, and common composition – implies that if the conditions of our star's formation were universal, then perhaps so are planets. We therefore want to investigate the processes of star formation throughout the Universe. In the foreseeable future, we will know details of planets only in the Solar neighborhood. In contrast, we can study the ubiquitous process of star formation over large distances throughout the Milky Way, and even through the history of the Universe by looking at distant galaxies, to understand what types of star-planet systems may exist elsewhere.

By observation, computer simulation, and theoretical calculation, astronomers have posited a star formation scenario. After a dramatic initial collapse, a protostar grows for a few hundred thousand years as gas and dust flow onto it from the surrounding cloud. A swirling flattened disk of gas and dust forms, through which additional mass flows onto the young stellar object. Eventually the new star stabilizes, the fusion of elements in its core producing energy that counteracts the compression of gravity. In broad outline, observations from the ground and from space (e.g., using the *Hubble* Space Telescope [HST] and *Spitzer*) have verified this scenario. However, significant questions remain within this paradigm. What triggers the cloud to collapse at all? What sets the mass of the final star? How does the presence of neighboring protostars affect the material left in the disk? For how long does the disk retain material that might form a planetary system? What determines if the surrounding material forms a planetary system, a second star, or merely escapes back into empty space?

- **How do stars and disks interact?**

If star-forming cores did not spin as they collapsed, there would be no disks in which to form stars or planets. Yet, if the rotation rates were too great the disks would spin apart. Is rotation controlled by a universal process that makes all disks hospitable places for planet formation? Once the disks form, they influence the ultimate characteristics of stars, such as mass and rotation speed, while the stars drive mixing and chemical processes in the disks. X-rays and ultraviolet photons generated as stars pull in gas from the disk return to the disk and ionize its upper layers, feeding the star even faster and producing complex chemical reactions in the disk. Simultaneously, energetic photons from neighboring stars may be penetrating the disk, so the final planetary system may depend on stellar environment. The Stratospheric Observatory for Infrared Astronomy (SOFIA), *Herschel*, the *James Webb* Space Telescope (JWST), the Single-Aperture Far-InfraRed mission (SAFIR), and a future Large UV/Optical mission (generic name LUVO) will address how the presence of terrestrial and giant planets is related to disk dynamics, stellar mass, age, and magnetic activity, stellar binarity, and/or the presence of surrounding stars in a cluster.

- **When do planets form?**

Millimeter wavelength observations reveal that significant amounts of gas and dust can be left in disks around new stars, but are not yet sensitive enough to show whether this is always the case. Observations of the masses and composition of disks, from the initial massive disks surrounding young stellar objects through to the remnant disks around main sequence stars, will determine how planets get their ultimate configurations.

The most abundant gas in protostellar disks is molecular hydrogen, but this symmetric molecule is notoriously hard to observe. Future direct measurements using SOFIA, *Herschel*, JWST, SAFIR, and LUVO of molecular hydrogen via infrared emission lines or ultraviolet absorption and fluorescence will probe gas disks directly and with increasing sensitivity and angular resolution. The classic picture is that solid particles of dust coalesce early and stick to each other in collisions, slowly building a core around which a planet grows: gas giant planets do so quickly, in less than a million years, before the system loses most of its gas, and Earth-like planets do so over a longer period of tens of millions of years. This picture explains many characteristics of the Solar System, but it is now running into trouble because disks appear to dissipate too quickly to form all known planets. The eventual detection of proto-planets growing in their disks is essential to refine this picture. Initial observations could take the form of studies of the motions of H_2 gas in the disk to detect regions where gas is flowing onto pre-planetary cores.

- **Where do planets form?**

Knowledge of planetary system architectures, that is, the nature and position of all component planets, and the presence of comets and asteroids, is important for understanding the likelihood of habitable planets. Giant planets, which are unlikely to directly harbor life, dynamically constrain the orbits available for terrestrial planets. Giant planets are the older siblings – both the bullies and protectors of the terrestrial planets. How they stir up the disk determines how many comets and asteroids survive to bombard smaller worlds with either sterilizing intensity or with life-bringing chemicals. Giant planets in eccentric orbits are less likely to allow terrestrial planets to orbit stably in the habitable zone. However, gas giants might be necessary for shielding terrestrials from life-damaging impacts of comets.

One of the exciting and unexpected results of the planet searches to date is the large number of systems unlike our own. Gas giant planets have been found to orbit closer to their stars than Mercury about the Sun. Among the unsolved problems in planet formation today is not just how to form giants, but how to move them to their present locations. Some appear to have migrated large distances while others, such as Jupiter, appear to have mainly remained in place. Many gas giants also have substantial eccentricities – coming closer and further from their stars over their orbits. However, these systems exist only for a minority (10-20%) of stars, leaving open the possibility that many stars have planetary systems more like our own. Only with missions such as SIM will we obtain an unbiased view of planetary architectures.

Initial disk conditions, interactions between multiple young planets and between planets and their disks may all contribute to the final system architecture. Tracing the dynamics, densities, and temperatures of disks with high precision may betray these processes in action. If giant planets sweep up disk material, they may leave a disk devoid of the raw materials for terrestrial planets. We want to inventory the planetesimal population at the conclusion of planet formation and relate it to the architecture of the system.

The compositions and atmospheric attributes of the planets in our Solar System change dramatically from the rocky inner worlds to the hydrogen and helium dominated gas giants, to the heavy element enriched ice giants and back to the dirty ice members of the Kuiper belt. The compositions of giants will reflect their formation and migration histories.

E. How do the components of life come to reside on terrestrial planets?

Life, as we know it, depends entirely on the complex chemistry of compounds built around carbon atoms, known as organic compounds. We live on the rocky Earth with abundant silicates, iron-bearing minerals, and surface water. We now know that the Universe was not born with these materials, but that the stars themselves are the sites of their manufacture. This discovery that the heavy elements essential for life come directly from stars demonstrates the importance of understanding the creation and distribution of heavy elements and organic molecules throughout the Universe.

- **When did the Universe form the raw materials necessary for planets and life?**

The buildup of these heavy elements did not happen all at once. We have learned how these elements are made in stars and how they can be recycled into future generations of stars and potential planetary systems. At the ends of their lives massive stars explode and less massive stars slowly shed gas enriched with these heavy elements. In each cycle the abundance of heavy elements increases as the "ash" of nuclear burning in the centers of stars is added to the mix. We can roughly chart the increase in heavy elements over the generations of stars born over the 12 billion year lifetime of our Milky Way Galaxy and compare it with similar processes in other nearby galaxies. With infrared spectroscopic observations of very distant galaxies using JWST, we will soon be able to measure the buildup of elements over cosmic time. In turn, we will better understand the importance of heavy elements for the formation in the Milky Way of planets and, ultimately, life. Such observations will also trace the buildup of gas, solid-state molecules, and dust over cosmic time. This will lead us to understanding the possibility of planets and ultimately life in the Milky Way and the universe as we understand better the importance of heavy elements for the formation of planets. We already know that stars with more heavy elements are more likely to have close-in giant planets. We want to know what metal content is required for various types of planets to form and whether any particular elements are needed to make geologically-active planets such as Earth and the early Mars. JWST and the TPFs will tell us.

When and how did pre-biotic molecules necessary for life form in the history of the Universe? The infrared spectral signatures of hydrocarbon chains, hydrocarbon rings, and simple molecules (i.e., oxygen, water, carbon monoxide, methane, methanol) have been found in many regions of our Milky Way galaxy. We know that these basic components of organic molecules exist now (and likely did so 4.5 billion years ago, when the Sun and Earth formed), but at what earlier time did they come to exist in the Universe? Which materials were produced first, and when did they combine to produce the more complex molecules? Using SOFIA, JWST, and SAFIR, if we probe similar, but much more distant, galaxies when they were much younger, when the Universe was about a billion years old (less than 10% of its present age), we will see if they exhibit any hydrocarbon or ice features (redshifted to mid-infrared wavelengths) and, thus, will likely constrain the period in cosmic time when materials important for life were first created.

- **What is the origin of the interstellar medium composition?**

The atoms, dust grains, and hydrocarbon molecules released by dying stars in the Milky Way must follow long circuitous paths in order to be swept up into star forming clouds and eventually processed into materials necessary for life on planets. These newly created materials must spend large amounts of time drifting in the diffuse interstellar medium before they are eventually swept up into dense clouds of gas and dust by gravitational forces. Clouds shield these materials from damaging external radiation, allowing the carbon-nitrogen-oxygen group to form simple volatile molecules such as carbon dioxide, methane, ammonia, and water when they combine with hydrogen atoms (which are all-pervasive) and each other. This combination of volatiles, dust grains, and hydrocarbons is key to forming the chemical building blocks of life in the environments around young stars and their nascent planetary systems.

- **How do chemical/physical processes in disks create the molecules necessary for life?**

Observations from *Spitzer* are now showing that simple volatile molecules can freeze onto dust grains in circumstellar disks. Moreover, gaseous molecular hydrocarbon rings are observed to be in star-forming regions, and it is very likely that they also stick to icy dust grains in circumstellar disks. Laboratory experiments show that when these chemical mixtures are exposed to ultraviolet light – as in a disk around a young star – complex organic molecules form. Experiments have produced compounds that are needed for life, including ketones, ethers, aromatic alcohols, and even amino acids. It is logical, and now possible, to obtain infrared spectra of young stars in nearby dark clouds to see whether such materials are forming in their pre-planetary disks.

To understand the crucial steps towards the creation of life, we need to 1) conduct systematic searches for and inventory the molecules in planet-forming disks, and 2) improve our knowledge of the physical conditions in this environment. SOFIA and, particularly, JWST will be able to detect and study complex carbon-bearing molecules and water, the raw materials for life. A far-infrared and submillimeter interferometer (generically named FIRSI) will have high enough spatial resolution to see whether water vapor and more complex molecules are present in disks in regions where terrestrial planets form.

- **How are volatiles and organic molecules delivered to terrestrial planets?**

As noted above, physical processes during stellar evolution modify the disk and its constituents. Interstellar dust contains amorphous silicates, but the comets in our Solar System and dust in debris disks around other stars contain a significant fraction of crystalline silicates. These crystals must be formed in hot regions of the disk. Determining where and how these crystalline grains are produced will tell us how the disk is mixed by turbulence, inward accretion, and stellar winds, giving insight to the creation of our own Solar System, as well as others. Near-to-far-infrared spectra with high spatial resolution are necessary to trace the distribution of these important planetary constituents, requiring the *Keck* and Large Binocular Telescope (LBT) Interferometers, SOFIA, JWST, and SAFIR. As gleaned from the impact record of the early Solar System, while the disks around young stars are clearing, it is likely that these remnant rocky, crystalline asteroids and comets intensely bombard their terrestrial planets. Does this bombardment deliver the carbon-rich material to start the development of life?

Missions such as the Wide-field Infrared Survey Explorer (WISE), JWST, *Herschel*, and SAFIR that can measure the dust content of disks with time can be combined with theoretical studies to explore this phase of planetary system development. We will learn how giant planets direct material from one part of the disk, perhaps water-rich, to the inner regions where Earth-sized bodies are growing. This process may have brought volatile materials and organic compounds to the early Earth and allowed life to form on our planet.

III. Recommended Missions, Implementation Framework, and R&D Programs

A. An Integrated Program to Address the Core Questions

Discovering planets around other stars and then exploring them remotely are difficult and complex tasks, requiring many kinds of information from many sources in order to guide the search and to interpret what has been found. Determining how common Earth-like planets are in the galaxy (the frequency of Earth-like planets or $\eta_{\oplus}$) helps set mission strategies by determining the number of stellar systems that must be explored to have a reasonable chance of success. Similarly, understanding the nature of the dust disks around stars informs the theories of how systems of planets form and evolve around stars, and also helps determine the sensitivity that an observatory must have to pick out a planet from the dust background. Knowing the stellar background behind a target star tells us how difficult it will be to extract the planet signal from the confusion of other signals. This preliminary, near-term program is summarized in Figure III-1 below:

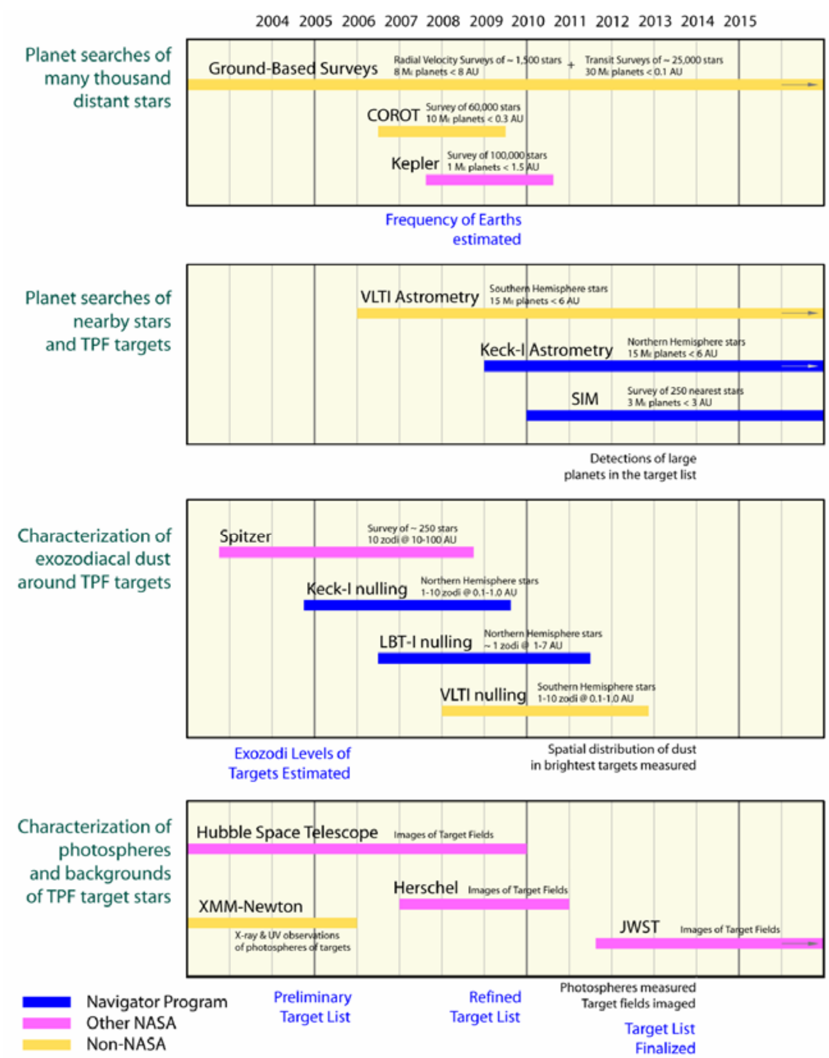


Figure III-1. The search for Earth-like planets can benefit not only from NASA's program of missions, but also from the work of scientists around the world using a variety of space- and ground-based assets.

The technology required to detect and characterize potentially habitable worlds is so challenging that no single mission can provide all the measurements needed. Nor can any one mission be as productive operating alone as it would be working as part of a carefully planned program. Consequently, the search for Earth-like planets is composed of missions that independently take intermediate observational steps, providing valuable scientific results each step along the way. These results, in addition to contributing to the overall scientific body of knowledge, are used to mitigate the risk and uncertainties inherent in the other missions, improving operational efficiencies and measurably increasing the probability of mission success.

The flagship mission to carry out a census of planets around nearby stars will be the Space Interferometry Mission (SIM PlanetQuest). SIM PlanetQuest will be the first instrument to detect Earth-like planets around the closest stars – those that we can then follow up with direct detection of light, to learn more about the planet's physical properties. SIM surveys the nearest stars and determines gross physical properties of planets such as mass and orbital eccentricity essential to establishing habitability. SIM will add critical information to our growing knowledge about the nearest stars and, thus, help to identify targets most suitable for subsequent observation by Terrestrial Planet Finder (TPF) missions. The knowledge from SIM that particular stars have (or do not have) planets of various masses and orbits, and continued radial-velocity studies, will focus the targeting choices for TPF, thereby increasing the early tempo of direct detection and characterization. A hypothetical SIM observing program might focus on the 60 most promising nearby stars. For a planet in the middle of the habitable zones of these stars, Figure III-2 provides a histogram of the cumulative number of such stars versus minimum planetary mass detectable. The potentially large number of near-Earth-mass planets SIM might detect in the habitable zone is impressive. The *Kepler* Discovery mission will provide statistics on the frequency of Earth-sized planets using distant stars, which will help set the scale of the TPF missions by suggesting how large a stellar population must be sampled to obtain data on terrestrial planets.

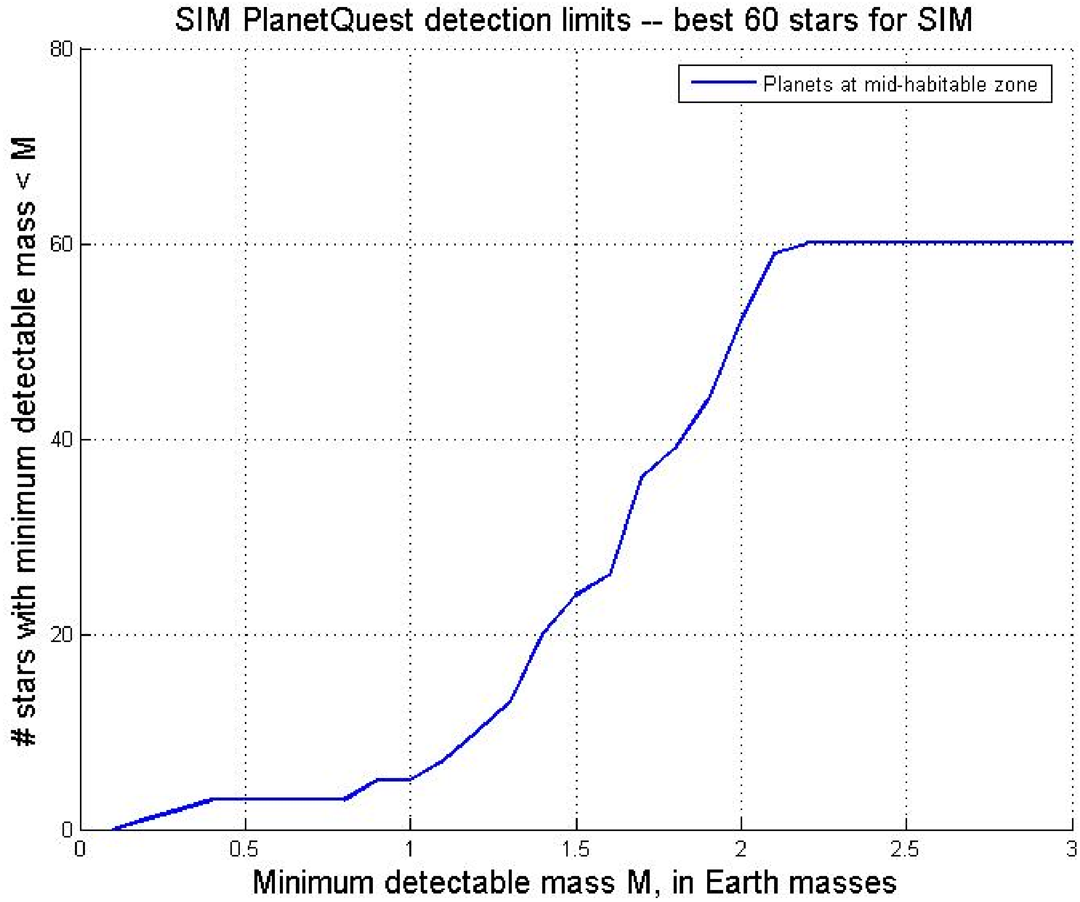


Figure III-2. SIM's capability for finding terrestrial planets. This is a histogram of the number of stars versus minimum mass for a planet in the middle of the habitable zone of the 60 best nearby stars for the SIM mission. This hypothetical observing program would concentrate ~17% of SIM time on these 60 stars. Minimum detectable mass is defined as the mass whose astrometric signature is bigger than the threshold set for a 1% false alarm probability.

Direct imaging detection and spectroscopic characterization of nearby Earth-like planets will require the Terrestrial Planet Finder (TPF) missions. The first, the TPF Coronagraph (TPF-C), planned for launch in 2014, will suppress the light of the central star to unprecedented levels, allowing it to search for terrestrial planets in ~120 nearby planetary systems, and thoroughly study 35. TPF-C will be followed by the TPF Interferometer (TPF-I) about five years later. TPF-I will operate in the mid-IR, will search for terrestrial planets around approximately 500 stars, and will characterize all of those it finds.

Once a terrestrial planet is detected, TPF-C and TPF-I will determine which planets have conditions suitable for life, e.g. a warm, wet atmosphere, and which, if any, show global signs of life, e.g. an oxygen-rich atmosphere due to the effects of photosynthesis. Theoretical, laboratory, and field studies are already under way to learn which “biosignatures” —identifiable features in the spectrum of the planet’s light—can reveal the presence of life on a distant planet. This research will guide the requirements for the Terrestrial Planet Finders, and help in the design of future telescopes, such as Life Finder.

Existing infrared telescopes, such as *Spitzer,* the LBT-I, and the *Keck* Interferometer, will investigate exo-zodiacal dust clouds for both their intrinsic scientific interest as by-products of planet formation and to help optimize the target list for TPF. Future mid- to far-infrared telescopes such as SOFIA, JWST, *Herschel*, and SAFIR will allow us to determine the evolving location and composition of dust in planet-forming disks. Observations of ice and organic compounds in disks with JWST, TPF-C, and SAFIR with spectroscopic capability can be combined with theories of organic chemistry, volatile processing and orbital dynamics to place constraints on the formation and evolution of pre-biotic compounds, and their delivery to terrestrial planets.

Once TPF-C and TPF-I have completed their investigations of the characteristics and habitability of Earth-like planets, and made first-order attempts to detect the most obvious global biosignatures, the next important scientific step will be a more thorough and capable search for life by Life Finder on a larger number of planets. After that, a far-future Planet Imager can be envisioned to obtain coarse images of exoplanets to detect their basic land and ocean surface features. Such a mission would be extraordinarily difficult and expensive, probably requiring multiple launches of 10-20 m telescopes whose light could be combined interferometrically. Planet Imager will continue to be evaluated and refined as the search for other Earths proceeds over the next decades. The overriding consideration for the long-range future of this mission concept is the will and commitment of the Nation, or of the community of space-faring nations, to invest the resources that will be required for such an epochal exploration.

B. Implementation Philosophy

The explorations described in this Roadmap will require the development of missions with unprecedented capability. The challenges this presents have led to adoption of certain philosophical principles in the implementation of the Universe investigations. These include:

- The most challenging investigations will be carried out through strategic missions identified and endorsed through the strategic planning process and the National Academy of Science Decadal Survey of astronomy. These strategic missions will be led by NASA flight centers, with science teams, key investigations and instruments drawn from the broad scientific community through open peer-reviewed competition.

- Strategic missions will be initiated through an extended pre-formulation (pre-Phase A) period where all of the high-risk technologies will be developed before the mission is allowed to proceed into the higher cost-rate period of formal formulation and implementation. This provides an essential cost-risk mitigation strategy that has served NASA well.

- Where important scientific investigations can be accomplished without significant new technology development, and without excessive development risk, a series of competed PI-led mission opportunities at a variety of cost levels will be invoked. These investigations may be identified through the strategic Roadmap, or may be proposed *ab initio* by the PI. Mission lines exist at low- (~$200M Explorer Program), medium- (~$400M Discovery Program) and high- (~$600M Universe Probes) cost levels. The proposed Universe Probe line of the Universe Division would be a competed mission on a scale between a Discovery and a Strategic mission that is an essential component of a well-balanced program that can take advantage of new developments as they arise.

In order to focus the complex relationships of the scientific and technological activities involved in carrying out the science described in this Roadmap, NASA has organized the implementation of closely related missions of extrasolar planet exploration into the Navigator Program: Exploring New Worlds. Navigator is responsible for conducting the precursor and supporting science activities, technology development and implementation of these missions. Figure III-3 below encapsulates the implementation plan for this integrated Roadmap, the place of the Navigator Program within it, and very approximate timelines.

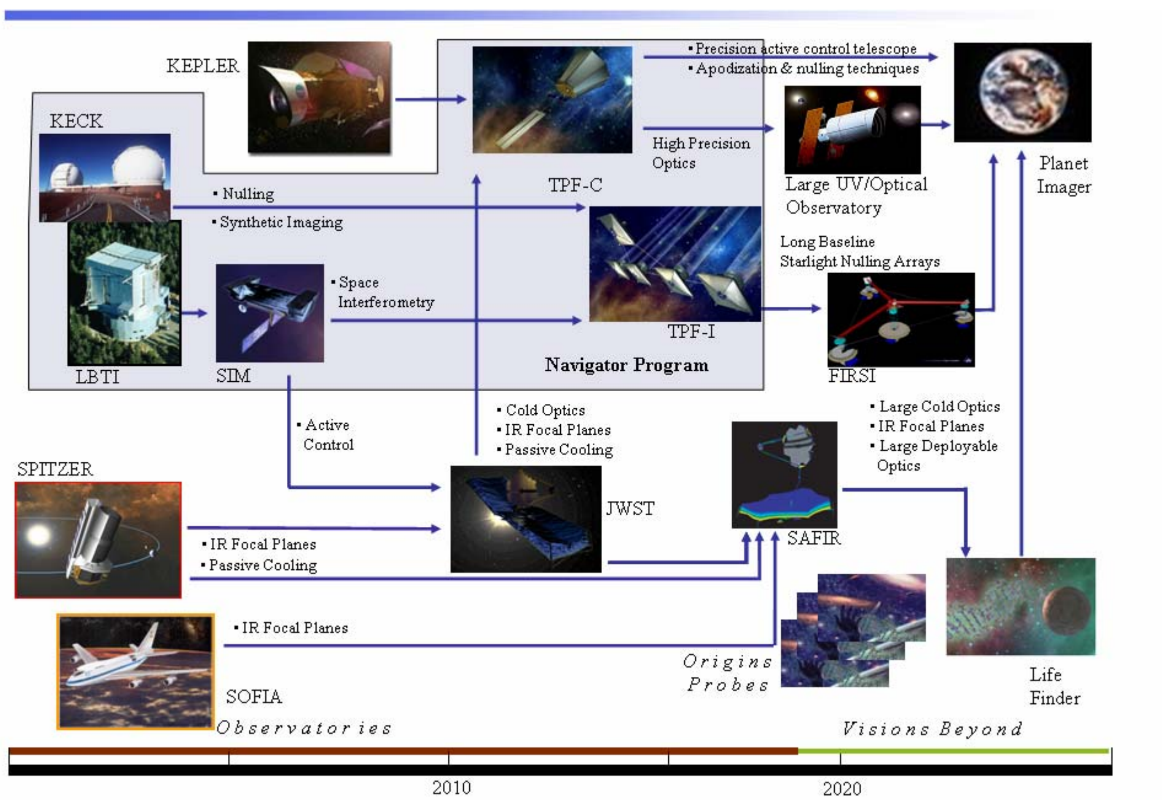


Figure III-3. Mission implementation roadmap, including the responsibilities of the Navigator Program and approximate timelines.

C. Ground-based Initiatives, R&A, Theoretical Challenges, and Astrobiology

With bigger telescopes, more observing time, and better instruments, the ground-based Doppler method of planet detection is poised to achieve precision better than the existing 1 m/s. For comparison, an Earth-mass planet at 1 AU induces a wobble of 0.1 m/s in a solar-mass star. Though Earth-like planets in the habitable zone around a solar-mass star are not currently detectable, Doppler precision is likely to be improved with superior spectrometers and spectroscopic analysis. Furthermore, low-mass planets could preferentially be found in the habitable zones of low-mass stars. The allocation of more telescope time permits averaging over photospheric turbulent "jitter" to approach a precision of 0.3 m/s, rendering detectable planets with masses down to 3 Earth masses orbiting in the habitable zones of solar-mass stars. The US government investment in *Keck* and in other ground-based telescopes will be particularly valuable for continued Doppler work.

NASA should remain vigilant and support new technologies that are still under development, such as astrometry at the south pole, microlensing from space, and transit-planet spectroscopy with *Spitzer*. This Roadmap also requires continued technology development for coronagraphs, ultra-lightweight, high-contrast optics, formation flying and interferometric nulling, detectors, and improved Doppler instruments. Furthermore, the theory of planet formation is poised to make predictions about the occurrence and properties of rocky planets, constrained by the properties of the observed giant exoplanets. To support TPF, theoretical work on the formation of rocky planets, their dynamical evolution, and the diversity of their interiors and atmospheres should be strongly supported. Theoretical and laboratory work on the origin and evolution of the atmospheres of rocky planets, both with and without biological feedback, should be vigorously pursued.

Detecting and characterizing extrasolar terrestrial planets poses both considerable technological *and* scientific challenges. While substantial investments in large space-based telescopes will be required to make significant progress in this field, the ultimate scientific payoff from these missions will require not only the technological capabilities, but a strong scientific foundation from an active, interdisciplinary scientific community. Both precursor and supporting observations from space-based and ground-based telescopes, as well as a rich program of theoretical and interdisciplinary research will be needed. Theoretical, laboratory, and field research will provide end-to-end mission support by supplying crucial new ideas, context and information relevant to mission planning, design and science priorities, and by providing the expertise and tools to convert the hard-won spacecraft measurements into new scientific understanding. NASA will build and maintain this interdisciplinary science community via competed R&A programs, of which the TPF Foundation Science program, NASA Astrobiology Institute, the Astrophysics Theory Program, the Origins of Solar Systems Program, the Astrophysical Data Program (ADP), and the Interdisciplinary Exploration Science program are current examples. Theoretical and multidisciplinary scientific research should also be integrated into the fundamental mission design to address scientific challenges that are critical to the mission's key goals.

To meet our objective to find and characterize habitable planets around other stars, we will need theoretical research and modeling to understand the plausible range of solar system architectures and planets that we may find, to understand the relationships between the host star and environments of its orbiting planets, and to interpret the photometric and spectroscopic signatures of life. Modeling can be used to understand the formation and evolution of habitable planets, including volatile delivery throughout a planet's lifetime, and to explore how planetary processes affect habitability over time. The interiors and atmospheres of rocky planets having masses 1-10 Earth-masses are not represented in our Solar System, and therefore require modeling to predict their characteristics. The modeled characteristics will inform our understanding of how to best discriminate observationally between planets of different compositions and stages of development. To that end, modeling is also required to understand the detectability of planetary characteristics in the low-resolution, full-disk spectra that will be available to the Terrestrial Planet Finder and Life Finder missions.

The relatively new field of astrobiology uses intrinsically interdisciplinary approaches to study the origins, evolution, distribution, and future of life in the Universe. This fundamental research will allow us to explore biosignatures in great detail, both theoretically and by obtaining field or laboratory data, to better understand those signs of life that might be remotely detected in the spectrum of another planet, especially for habitable planets that differ from our own modern Earth, in age or composition. This research must also identify potential "false-positives," the non-biological planetary characteristics that mimic biosignatures. The results of this research will help determine the design and characterization strategies for the TPF and successor missions, and the breadth of the research will enhance mission success by increasing our overall likelihood of detecting and correctly interpreting biosignatures in the context of extrasolar terrestrial planet environments.

IV. Key Milestones and Decision Points

A. Milestones

Accomplishing the mission set recommended in this Roadmap requires both an ongoing interaction with the developing body of scientific knowledge and technological achievements along the way. Scientific knowledge feeds into the design concepts and the scaling of the system designs. Technologies needed by a mission must be developed to the point where feasibility is demonstrated with a high degree of confidence by the time the mission enters Phase A, where the design concept is set. The technology must be demonstrated in terms of performance in a flight-like environment before the mission can proceed with implementation. The milestones summarized in Figure IV-1 will provide input at key decision points and opportunities to mitigate risk and adapt to new findings.

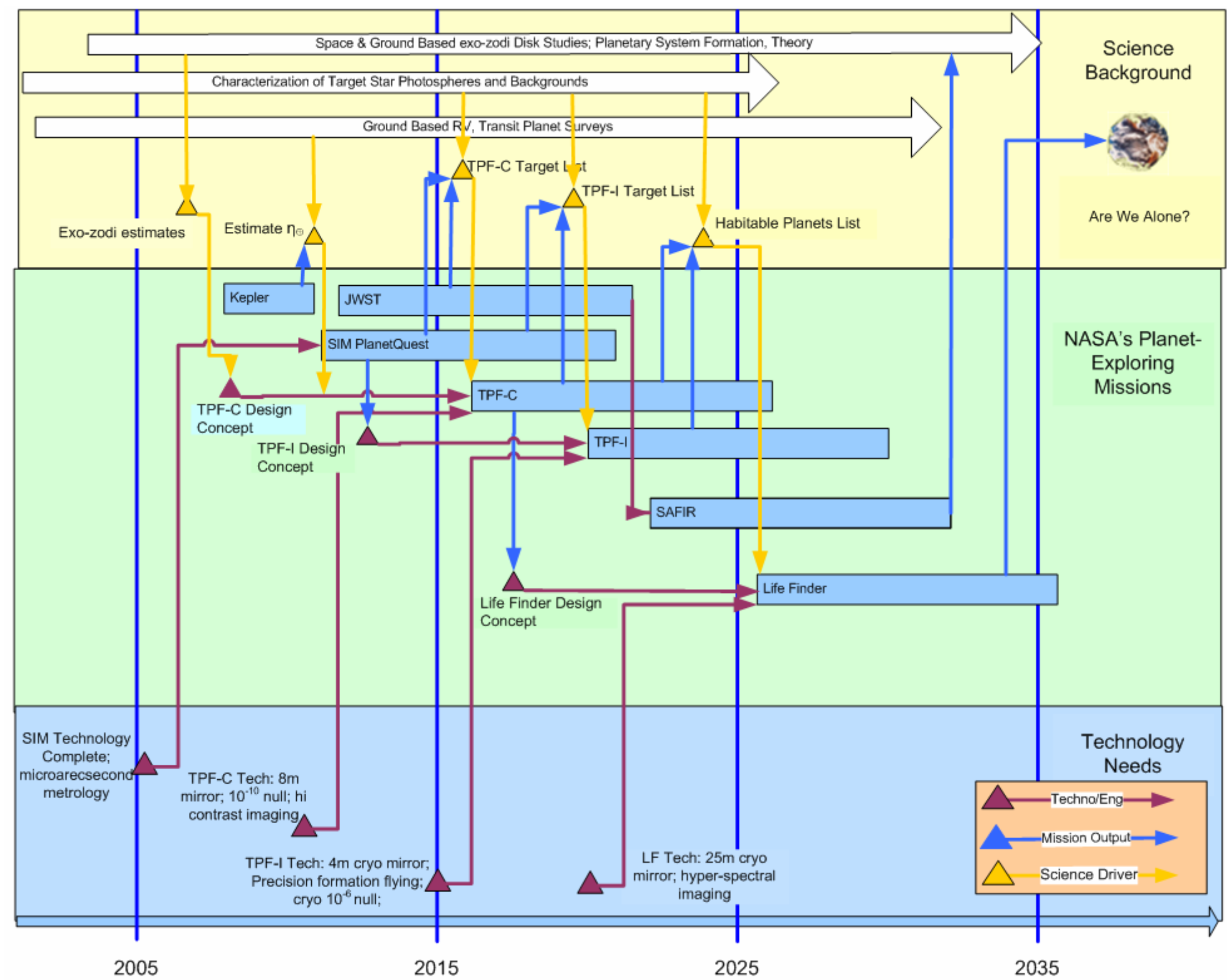


Figure IV-1. Key milestones on the road to other worlds.

The Navigator Program has been carrying out a focused set of technology development activities to enable the missions to explore exoplanets. Examples of milestones concerning the integrated program to discover, explore, and characterize exoplanets that have been, or soon will be, met include:

1. Development of interferometric techniques using the Palomar Testbed Interferometer for application on the Keck Interferometer and SIM PlanetQuest. (**Complete**)
2. Implementation of initial interferometric operational capability (fringe visibilities) between the two Keck 10-m telescopes. (**Complete**)
3. Development of techniques and ground testbeds to demonstrate ultra-precision metrology and system stability to a picometer accuracy for SIM PlanetQuest, at both component and system-level. (**On Schedule**)
4. Development of 10^{-10} contrast ratio for visible nulling for TPF-C, and demonstration of 10^{-9}. (**On Schedule**)
5. Development of 4-way beam combination IR nulling for TPF-I and demonstration at 10^{-5} level. (**On Schedule**)
6. Development of robust ground testbed demonstration capability for precision formation flying to enable TPF-I as well as a number of other future missions in astronomy. (**On Schedule**)

Conduct advanced telescope searches for Earth-like planets and habitable environments			
	Phase 1: 2005-2015	**Phase 2: 2015-2025**	**Phase 3: 2025 +**
Planet Detection	a) Measure the frequency of Earth-like planets in a statistically representative sample [COROT, *Kepler*] b) Radial velocity surveys detect additional Jupiter analogs and nearby planets with less than 10 M_{earth} [Ground] c) First SIM planet detections	a) Astrometric detection of M>3 M_{earth} planets in habitable zone within 10 parsecs [SIM] b) Photometric detection of M > 0.5 M_{earth} planets in stellar habitable zone within 10 parsecs [TPF-C] c) Photometric detection of M > 0.5 M_{earth} planets in stellar habitable zone within 100 parsecs [TPF-I]	a) At least an order of magnitude increase in the number of directly-detected terrestrial planets [LF] b) Direct detection of moons in nearby extrasolar planetary systems [LF]
Planet Characterization	a) Measure atmospheric spectra of hot Jupiters seen in transiting events [Ground, HST, *Spitzer*, JWST] b) Measure spectra of brown dwarfs and giant planets [JWST]	a) Measure Mass [SIM] b) Measure radius and surface temperature [TPF-C+TPF-I] c) Detect basic atmospheric composition and presence of clouds [TPF-C+TPF-I] d) Determine gross surface properties [TPF-C, TPF-I] e) Detect new classes of planets [SIM, TPF-C, TPF-I] f) Detect provisional indications of life [TPF-C, TPF-I]	a) Confirmation of biomarkers [LF] b) Search for life on a larger sample of planets [LF] c) Search for a variety of different metabolisms [LF] d) Enhance characterization of planetary systems [LF]
Planet Formation and Habitability	Observe the formation and evolution of stars, galaxies, and planetary systems, from the first luminous objects to debris disks in our own neighborhood [*Spitzer*, SOFIA, *Herschel*, JWST]	Observe the development of conditions for life, from the first release of the chemical elements in the first stars, through the formation of protoplanetary disks, to the chemistry and physics of the Solar System [SOFIA, JWST,SAFIR]	a) Observe proto-planetary disks with the resolution needed to detect Earths in formation [FIRSI] b) Trace the chemical evolution of the early Universe [Large UV/Optical Imager]

Table IV-1. Expected scientific achievements in the near-, mid-, and far-term of this Roadmap and the missions that will accomplish them.

B. Potential Decision Points

The nominal architecture of the program of missions in this Roadmap incorporates the minimum mission set necessary to conduct a complete, but initial, exploration of planets around other stars up to and including the search for signs of life. It starts at the simplest point – a look at a very large sample of stars, far away, to see how many have planets and how many of those could be Earth-like (*Kepler*). While most of these will not be stellar neighbors, they comprise a large sample that can be observed together to determine overall exoplanet statistics. The program then goes on to provide the necessary survey of gross physical properties of nearby planets and their systems (SIM PlanetQuest). Following SIM, TPF-C and TPF-I will conduct mutually complementary and confirming spectral imaging investigations to identify potentially habitable planets and to make a first search for signs of life. Finally, Life Finder will execute a refined and thorough spectroscopic investigation of the most promising candidates determined by TPF, providing robust confirmation of signs of life, as well as searching for different types of life on a larger sample of terrestrial planets. The scale and timing of these missions are predicated on an assumption that Earth-like planets are modestly common – i.e., the fraction ($\eta_\oplus$) of Sun-like stars that have Earth-like planets (both in terms of size and position in the habitable zone) is greater than or equal to 10%.

Each of the milestones for scientific knowledge or technological capability represents a decision point in terms of design parameters for the particular mission that is affected. However, there are also events that could affect the overall architecture of the program. Surprising early discoveries of very nearby terrestrial planets might be an opportunity to solicit proposals for rapid-development, low-cost missions designed to study just that planet. Well-developed methodologies for such solicitations, coupled with emerging technologies for rapid, low-cost optics development, will enable agile responses to such serendipitous discoveries.

What if the key assumption that $\eta_\oplus$~10% should be wrong? Or what if one of the missions in the sequence fails for technical or programmatic reasons? At the program-level, there are a few key eventualities for which alternate architectural paths have been identified. These are represented in Figure IV-2.

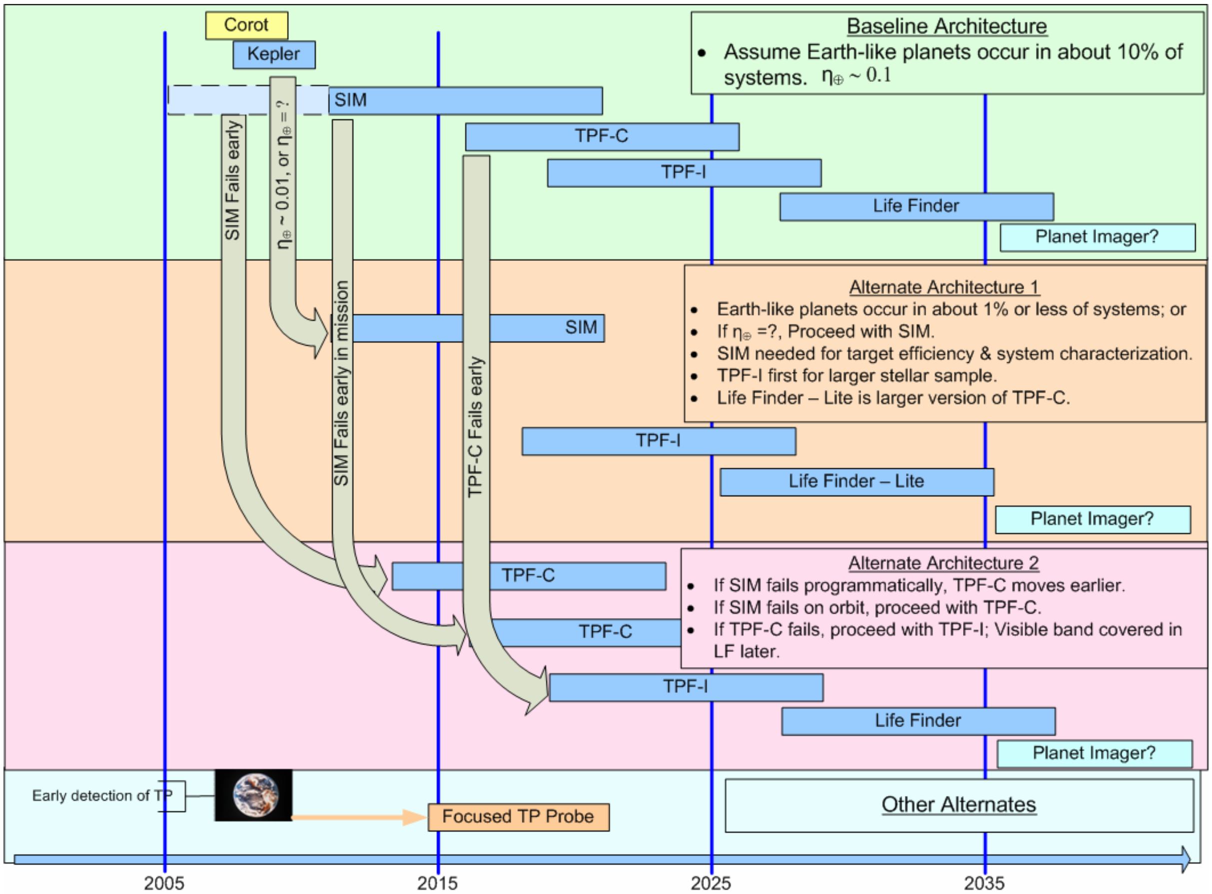


Figure IV-2. Some alternate architectures, branch points, and options.

None of the missions in the program is a <u>necessary</u> precursor to others in the early part of the sequence; however, the sequence represented in the baseline architecture is important because the knowledge gained from one mission helps subsequent ones. For example, in the case of SIM, it not only provides vital data on physical properties of exoplanets, but can enhance the early targeting efficiency for both TPF-C and TPF-I. In particular, SIM discoveries can focus subsequent TPF targeting choices to ensure that the practical yield of terrestrial planets that are well-characterized by TPF-C is optimized during TPF-C's finite lifetime, thereby increasing the scientific return of that mission. Similarly, TPF-C images combined with SIM-derived orbits can help interpret TPF-I data. Later in the sequence, if, for example, no habitable planets had been found, there would be no scientific driver to proceed with a Life Finder (although observatories of comparable capability would certainly be needed for other scientific purposes).

1. If *Kepler*/COROT show that Earths are common or rare?

A rapidly growing dataset on exoplanets is leading astronomers to feel increasingly comfortable with the expectation that at least 10% of solar-type stars will have Earth-like planets. The sequence and scale of the baseline mission architecture is predicated on this assumption.

Should the early transit missions, *Kepler* and COROT (a mission of the French space agency, CNES), show that the fraction is much lower, say around 1%, it will call for a reexamination of the sequence. In particular, SIM would still proceed, not only because it would already be nearly ready for launch, but also because its ability to probe a fairly large number of nearby stars in a target-poor environment would enable the best possible determination of the target list for TPF-C or TPF–I to pursue. Consideration would then be given to deferring further development of TPF-C, and instead accelerating TPF-I, with its long baseline able to achieve angular resolution at larger distances, and, thereby, able to investigate a larger stellar population. These data would provide the IR coverage of the observed systems, and would also provide information useful for targeting of a subsequent visible band mission (LUVO). In this scenario, Life Finder would be accelerated as a "LF-Lite" mission, taking advantage of advances in large aperture space telescope technology available by then. This is depicted as Alternate Architecture 1 on Figure IV.2.

2. If SIM-PlanetQuest can not do better than 5 μas?

Should the on-orbit performance of SIM PlanetQuest fall significantly below its design value, it could still greatly augment radial-velocity studies in characterizing extrasolar planetary systems, as well as carry out groundbreaking programs in general astrophysics. However, its value as a TPF-C precursor in identifying target stars and target epochs for viewing Earth-like planets (e.g., knowing when a target planet is visible at elongation) would be severely diminished. At that point, the best response would likely be a replanning of the TPF-C observing sequence to compensate for the greater uncertainty of targets and timing of observation.

3. If, for whatever reason, some mission does not proceed?

A number of alternate routes and off-ramps are available in the case of mission deferral or failure. All of these assume that the cause of the failure is known, and has been factored into subsequent developments to preclude a repeat of the same failure. If either of the early transit missions (COROT or *Kepler*) fails, the other provides a backup. If for some reason both fail, then we are proceeding with a large uncertainty in $\eta_\oplus$. While knowledge of the statistics of planets around a distant stellar population would be valuable for planning the TPF missions, SIM would not be making statistical studies of $\eta_\oplus$ for the nearby stars. Rather, it would determine directly what TPF needs – the locations and properties of planetary systems around nearby stars. So in this case, SIM would proceed. Depending on SIM's early results, if $\eta_\oplus$ should turn out to be ~1%, then consideration would be given to switching between TPF-C and TPF-I, as case 1 above, since TPF-I has a larger range.

If for some reason SIM does not proceed on the current schedule, then TPF-C could be moved a bit earlier. If SIM has proceeded on the current schedule, but for whatever reason fails early on orbit, one option would be to reset and build another SIM; however, since TPF-C will be well along on its development path, it would be more economical to proceed with TPF-C and rely on its imaging capability to provide snapshots of the most likely stellar systems for subsequent use by TPF-I. However, the need for masses is so central a feature of our Roadmap, that an astrometric mission such as SIM must still eventually be done.

If TPF-C fails early, then the most logical thing would be to proceed with TPF-I and to make the subsequent Life Finder mission an optical mission. If TPF-I should fail early, Life Finder could still proceed, targeting those planets identified by TPF-C as satisfying the conditions of habitability, but Life Finder would then be an infrared mission. In any case, data in both the infrared and the optical are necessary for the complete characterization of terrestrial planets that is a central cornerstone of this Roadmap.

4. If there are surprising discoveries?

If $\eta_\oplus$ is found to be one or greater, the closest Earth-like planets could be only a few parsecs away. As a result, the scientific emphasis of the program might shift to emphasize characterization of these nearby planets. Even though the requirements on angular resolution needed to survey more distant habitable zones could be relaxed, large apertures would still be required for spectroscopic analysis. While SIM and TPF-C would proceed as planned, the TPF-I architecture might change from the free-flying spacecraft needed for higher angular resolution to a shorter-baseline, connected structure with a large collecting area for spectroscopy.

The discovery of a terrestrial planet around a very nearby star (such as α Centauri) through a “lucky transit” or other such event could trigger a call for a competed mission designed to study just that planet. “Universe Probes” can be part of a “rapid-response” strategy to exploit opportunities afforded by such surprising discoveries. Invoking a low-cost architecture, such as a pinhole camera, enabled by emerging low-cost rapid-fabrication optical technology, would bring to bear a focused mission to study the new planet in parallel with the ongoing strategic flagship missions designed to look much more broadly for other planets in our neighborhood.

5. Role for smaller, competitively-selected missions and new technology

The path towards characterizing planetary systems includes important roles for smaller, competitively selected missions. Technological breakthroughs already in sight are the lifeblood of this Roadmap, but not all can be predicted in advance. Some additional possibilities include improved methods for suppressing starlight in coronagraphs and nulling interferometers, improved concepts for operating SIM to improve its accuracy, or improved detector technology. Such improvements would enhance the performance of the planned mission sequence, or could be incorporated in competitively selected smaller missions, but do not change the basic scientific approach or requirements. The technical challenges facing TPF-C and TPF-I could be tested at reduced risk in the space environment with smaller scale, space-borne missions: either an optical coronagraphic imager or an structurally connected infrared interferometer. Both have been discussed and/or proposed for $350-450M Discovery line, either as US-only, or in conjunction with other countries. A space telescope with an aperture of 2 meters, outfitted with adaptive optics and a coronagraph, can't detect Earths, but can detect analogs of Jupiter and Saturn orbiting between 5-20 AU from nearby stars. Similarly, a nulling interferometer operating at 3-5 microns over a 10-m baseline could study infrared emission from hot Jupiters. In both cases, a modest spectrometer could detect many of the molecular constituents of the atmospheres of giant planets, yielding insights about the chemical composition and origin of these planets. The light rejecting technologies by which these telescopes would block the starlight would be similar to those necessary for TPF-C or TPF-I, providing valuable technical insights about the more difficult goal of detecting Earths. A proof of concept for either approach might be feasible at the cost of a Discovery-Class mission.

V. Technological Dependencies, Linkages, and Infrastructure Requirements

A. Key technology requirements for each mission concept

In this chapter (which should be read in conjunction with Chapter VI on "Critical Inter-Roadmap Dependencies"), we provide a more detailed summary of the technology requirements and plans for missions that advance the science of exoplanets, from discovery, to understanding their formation and evolution, to determining the conditions for life, back to the beginning of time. Many of the key technologies have been reviewed and presented in the Advanced Telescopes & Observatories Capability Roadmap, but there are also dependencies on the launch vehicles, propulsion, communications, and servicing Capabilities Roadmaps, as articulated in Chapter VI.

The missions in this Roadmap are entirely dependent on new technologies, largely enabled by the application of computer modeling and closed-loop control systems to correct errors and allow the use of lightweight optics. In addition, the critical detector systems are dependent on investments made over many years, and require continued funding.

There are four core missions currently under development, ***Kepler*, SIM, JWST**, and **TPF-C,** that will take us through the 2015-2020 time frame. There are then two missions specifically devoted to planet finding and characterization that are undergoing conceptual development, **TPF-I** and **Life Finder**; these missions are critically dependent on the technologies to be developed during SIM and TPF-C. A parallel thread of our Roadmap dealing with the formation of planets and stars and protostellar/protoplanetary disks is accomplished not only by **JWST**, but by the strategic missions **SOFIA** and **SAFIR**. In the distant future, a far-infrared and submillimeter interferometer ("**FIRSI**") could provide high-resolution imaging of an unprecedented character. These would be powerful tools to understand the formation and evolution of planetary systems. Also, a future general-purpose **Large UV-Optical telescope** would extend the Hubble Space Telescope's (HST's) observations of planetary systems. These mid- and far-IR missions and UV-optical missions are also strong components of the SR#8 ("Universe") scientific area with explicit dependencies. We now proceed to a mission-by-mission discussion of technological linkages and dependencies.

The ***Kepler*** Discovery mission will view about 100,000 distant stars to discover terrestrial planets via dimming of the star because of the planet's transit of the star. This mission requires photometry at one part in 100,000. Since the occultations typically take 4-8 hours, the spacecraft has three multi-hour driving requirements: the pointing jitter must be 100 milliarcseconds or better, the optical system must be sufficiently stable in order to have a stable point spread function, and the CCDs must have stable relative performance. The hardware development is proceeding to plan and all of these driving requirements will be met or exceeded.

The **SIM** mission will find planetary systems around nearby stars by detecting changes to the stars' proper motions due to planetary perturbations. There are two very difficult requirements that must be met. The first is picometer metrology, which will be accomplished interferometrically. The second is end-to-end verification of system performance on the ground in 1-g; modeling will need to be developed to a new level of sophistication so that the hardware subsystems will be verified, and then the subsystems will be tied together via the system model to provide the confidence needed before committing to launch. These capabilities must be developed on SIM in order to confidently proceed into TPF-I. In fact, metrology and sophisticated modeling are required for all of the future missions that rely on interferometry and/or long-baseline/multi-spacecraft optical systems. SIM will validate this technology and modeling to a high degree in the flight environment in preparation for these still more challenging missions. The related European astrometry mission, *Gaia,* will not have the sensitivity to measure the masses of Earth-like planets.

The **JWST** mission will provide imaging, spectroscopy, and basic coronagraphic capabilities at wavelengths from 0.6 to 28 microns. JWST requires deployment of precision optical components, and it has benefited from the development of mid-infrared detector arrays and the passive cooling technologies of *Spitzer*. Key technologies being completed for JWST include the ultra-light deployable segmented beryllium primary mirror, wavefront sensing and control, a multilayer deployable sunshield, radiative cooling to the 30 – 50 K level, advanced large format IR detectors of HgCdTe and Si:As with much lower noise levels than achieved before, micro-shutter arrays for multi-object spectroscopy, and a mechanical cryocooler to cool the mid-IR detectors to 7 K. JWST decided to use a cryocooler to reduce mass, and will fund one design for flight. Cryocoolers are required for most of the IR missions in this Roadmap. They have been developed at industrial labs worldwide, and at NASA centers. The ACTDP (Advanced Cryocooler Technology Development Program) held competitions and selected winners for further development, aiming to support JWST, Con-X, and TPF-I. The design for the JWST cryocooler may be sufficient for TPF-I, but future far-IR missions and Constellation-X (SR#8) will need additional stages to reach temperatures much below one Kelvin.

The **TPF-C** mission (Terrestrial Planet Finder-Coronagraph) will directly detect (at visible wavelengths) Earth-like planets around nearby (~30 light-years) Sun-like stars. There are several driving requirements for this mission. The brightness ratio between the visible star and its reflected light from the planet is 10^{10}, while the angle subtended between the star and Earth-like planet will be on the order of 100 milliarcseconds. The flux from an Earth-like planet is estimated to be roughly 0.05 photons/m^2sec over the full visible wavelength band from 0.4 to 0.9 microns. Therefore, a mirror of ~ 25 m^2, with a 5 nanometer rms surface, and with 20-picometer wavefront control will be required to achieve a flux of about 1 photon/sec with sufficient contrast and signal-to-noise ratio to actually "see the planet." Innovative processes to fabricate low-scatter surfaces and precision masks are some of the many advanced telescope technologies underway today. TPF-C will inherit a portion of the SIM optical bench and structures metrology that gives 200-picometer precision. A monolithic mirror is required because a segmented mirror's edge-scattering effects will degrade the contrast ratio. ITT/Kodak is under contract to develop techniques for the large lightweighted mirror and for the surface finish. (See section B below for further discussion of the optical technology readiness.) Improved detectors in the visible (and, possibly, in the near-infrared) are essential for spectroscopy of the detected objects. The scientific benefits of array detectors that detect individual photons would be immense, and there are promising ideas that could succeed with continued funding.

The **TPF-I** mission (Terrestrial Planet Finder-Interferometer), best done jointly with ESA as TPF-I/*Darwin*, will detect Earth-like planets around nearby Sun-like stars, but will have a greater range than TPF-C. This mission builds on SIM technologies in very important ways in that nanometer metrology will be used, but at longer wavelengths of 6-17 microns. Such wavelengths ease the requirements somewhat for nulling of the radiation from the Earth-like planet's star. The current baseline configuration of this mission is 5 spacecraft, one combiner and 4 collectors with about 4-meter diameter apertures in a linear array, with a maximum separation of a few hundred meters. JWST technologies are basic to the optics, detectors, and cooling. TPF-I is the first planned mission that requires precise formation flying and will require perfect precision formation flying techniques so that the light from its independent telescopes can be combined and controlled to an accuracy of much less than one wavelength. In fact, TPF-I, in addition to requiring large aperture telescope technology, will need that special set of technologies unique to interferometry, which includes formation control algorithms, optical beam combiners, micro-Newton thrusters, laser metrology, and intersatellite navigation. This set of capabilities will also be needed for the Black Hole Imager and Big Bang Observer missions of the *Beyond Einstein* program highlighted in SR#8.

The **Life Finder** mission will require many more photons than TPF-C to perform robust spectral analysis of biological signatures. There is now discussion among scientists as to whether visible or mid-infrared spectroscopy will yield the best spectral evidence for the existence of life. We expect that a roughly 100 times increase in aperture area will be needed over TPF-C or TPF-I to provide unambiguous identification of biological markers. The technical requirements will depend on the scientific results from TPF-C and TPF-I, and in particular on the then-known characteristics of the most observable targets. The Life Finder and the Large UVO (LUVO) telescopes will build on the success of the TPF-C telescope technologies to produce a telescope system with an aperture in excess of 10 meters diameter that will need to be precision-deployed and autonomously aligned. In any case, the much larger apertures required are impossible with today's technology, and a significant effort for a long period of time will be required. On the other hand, other Government agencies (NRO, DOD) also have requirements for very large apertures, and there is no fundamental reason that computer control could not manage such large apertures. The Life Finder is the first in this series of missions that might require complex in-orbit assembly and test, and would strongly benefit from technology development in remote manipulation, robotic servicing, and even human servicing. Life Finder would also benefit strongly from larger launch vehicles, as well as technologies that reduce vibration and acoustic disturbances in the launch environment. These technologies would also benefit earlier large observatories.

The **Planet Imager** mission will attempt to image roughly 25 pixels across each dimension of a planet at 10 parsecs. This may require about 12 spacecraft separated by an average of 100 km, each with a 10- to 20-meter diameter primary mirror. The success of this mission hinges critically on technology to achieve extremely high-contrast images, such as is being developed for TPF-C, and the formation flying capabilities of TPF-I and Life Finder. While there is no law of nature preventing such a mission, we have no clear path for the needed technology. Nevertheless, the extraordinary cultural importance of such a project and its role as a long-term technology driver will keep it in the Vision until it can be completed by future generations.

Mid- and Far-IR missions. The Stratospheric Observatory for Infrared Astronomy (**SOFIA**) will have a 2.5-meter airborne telescope that is optimized for infrared to submillimeter observations. SOFIA will observe dust, gas, and molecular ices in the envelopes and planet-forming disks around young stars, as well as other obscured regions in the local Universe. SOFIA is nearing the completion of its development, and it will operate until after 2020. Many of its 9 first generation science instruments have technologies related to *Spitzer*, JWST, and *Herschel* instruments, and its instruments will be frequently updated with new capabilities that will allow SOFIA to maintain state-of-the-art performance. SOFIA has also developed some new detectors for its instruments, and it will serve as a very versatile platform to develop and test instrument technologies (primarily detectors and coolers) that would otherwise have to be tested in space. A vigorous instrument program will ensure that SOFIA maintains state-of-the-art instruments and develops new technologies upon which future missions such as SAFIR can build.

The Single Aperture Far-InfraRed (**SAFIR**) mission will study star and planet formation with imaging and spectroscopy. Its telescope is expected to have an aperture of about 10 meters, and it will observe emission from molecules and grains at wavelengths from 20-500 microns. Its telescope will be both actively and passively cooled to below 4K, requiring the development of long-life mechanical coolers that operate at low temperatures and have large capacities. SAFIR will benefit from the passive cooling architecture of JWST, which will also find application in the Life Finder and future missions. SAFIR will need large format arrays of far-infrared and submillimeter detectors, prototypes of which are to be developed on SOFIA. However, SAFIR will still require an aggressive development program of its own for mid- and far-IR detectors.

Advanced far-infrared and submillimeter interferometric missions (such as the generically named **FIRSI)** are also being studied for development after SAFIR. These missions would require unique technology development for advanced cryocoolers, lighter-weight and lower-cost optics, and advanced detectors. Unlike detectors and coolers for shorter wavelengths, there are no funds outside of NASA for development in the far-infrared. As a result, these missions are critically dependent on NASA technology development funding.

The **Large UV-Optical Telescope (**generically named **LUVO)** is also of importance to this Roadmap. Indeed, HST, a UV/optical telescope, is the only telescope that has observed a spectral line of another planet. The need for a separate large UV-Optical telescope might depend on the ability of TPF-C to carry out science outside the specific coronagraphic objectives.

Alternative Concepts and Competed Missions are still under consideration for future strategic missions, as well as the less-costly Universe Probe missions. NASA has supported these through HQ competitions, TPF project-managed competitions, and the NIAC. As an example, we cite the idea of an external coronagraph, with a blocking body or a pinhole on a separate payload, flying in formation on the line of sight between the telescope and the star, which might be brought to bear as a single-planet deep study mission in response to a surprise discovery of a nearby terrestrial planet (see Chapter IV.B.4 under "Decision Points"). We endorse the continued search for new ways to accomplish the goals of this Roadmap, through new technologies, new mission concept studies, and competitions for Explorer, Discovery, and Universe Probe missions.

Missions like TPF-I that require precise formation flying of separated spacecraft will demand a serious space engineering effort. Telescopes significantly larger than JWST will demand a very serious investment in lower cost mirror fabrication and in deployment, robotics, or human-aided assembly. For all missions, sensitive detectors must be developed to ensure maximum return on investment in large apertures.

B. Technological Readiness and the Ordering of TPF-C and TPF-I

The 30-year history of proposed searches for other Earths is the history of the debate between advocates of visible coronagraphs and infrared (nulling) interferometers. In the early 1990's coronagraphs were dismissed when it was realized that making a large (>4 m) primary mirror with ~λ/3,000 surface quality was not possible with existing or foreseeable technology. The focus shifted to interferometry and sufficient technical progress was made on infrared nulling that a mid-IR interferometer was presented to the NAS/NRC Decadal review committee for its consideration. However, NASA continued to invest in starlight rejection technologies, "the physics experiments," and mission concept studies at both wavelengths to ensure finding at least one good solution. Starting in 2000, through a competitive peer-reviewed process, NASA utilized the efforts of over 100 scientists and engineers at dozens of universities, NASA Centers, and aerospace companies to survey a very broad range of approaches (59 separate concepts) and finally to arrive at two viable solutions for planet detection: a 3x6 m visible coronagraph and a formation flying interferometer using four 3-4 m telescopes separated by 100-200 m. The latter project was investigated in collaboration with ESA's Darwin project.

With respect to the critical question of starlight rejection, laboratory testbeds of both techniques have shown that rejection to the required level can be achieved either today or with credible extrapolations of existing technology: IR nulling has demonstrated null depths of 10^{-5} to 10^{-6} in reasonable pass bands ($\lambda/\Delta\lambda$<10-100) at 10 μm; at visible wavelengths, the development of highly precise, short-stroke deformable mirrors with 4096 actuators has made it possible to achieve the required output wavefront accuracy (~λ/3,000) and stability (~λ/10,000) using a small deformable mirror to correct a large primary mirror that can be built with conventional techniques to an accuracy of ~λ/100.

With roughly comparable states of readiness for the "physics experiments" needed for starlight rejection at the two wavelengths, the issues in deciding which project, TPF-C or TPF-I, might go first became higher-level system trades. In the case of TPF-C, important issues include setting tolerances of the optical system, vibration control, and the manufacture of the primary mirror. In the case of TPF-I, the issues include formation flying to centimeter-level accuracy, beam transport between spacecraft, the manufacture of 3-4 m cryogenic mirrors, significantly larger than the JWST mirror segments, and testability on the ground. Studies by the TPF project suggested that a coronagraphic mission of limited scope, but still capable of making complete searches for Earths around 35 stars and partial searches of another 120 stars, could be executed more quickly and at a lower cost than an interferometric mission of comparable or greater scope. The natural ordering of the missions appears to be a first reconnaissance and detection of Earths using TPF-C. Subsequently, TPF-I would add mid-IR wavelengths to the visible data obtained with TPF-C, as well as extending the search to more stars, taking advantage of the better angular resolution of the formation-flying system. Thus, in response to the NASA Exploration Vision, the Universe Division elected to proceed with TPF-C, tentatively scheduled for launch in 2014, to be followed by TPF-I, which might be conducted jointly with ESA (and its *Darwin* mission), in the 2015-2020 timeframe, depending on the budgets available at the two agencies.

C. Required Talent

The talent necessary to carry out the missions in this Roadmap currently resides at academic, industrial, and government laboratories throughout the world, and future talent to carry out this program will have to be attracted and developed. The education and public outreach portion of this Roadmap is essential to the future of NASA and to these missions in particular, since the most difficult of them require innovations that we can barely imagine. Experience shows that the extreme challenge of these missions has already attracted top researchers and brilliant students, and will be an excellent way to recruit the next generation of scientists and engineers. Experience also shows that students and researchers respond to the sustained availability of funding. A strong commitment of NASA to a program calls forth the needed talent.

Specific areas of technical expertise required to implement this Roadmap include: mission design, optics, cryogenics, detector physics, low temperature electronics, thermal engineering, and sensing and control systems. Specific areas of required scientific expertise required for planet and planet formation studies include: comparative planetology; paleogeology; star and planet formation processes; interstellar chemistry; astrobiology; astrodynamics and planetary system evolution; atmospheric chemistry, spectroscopy, and evolution; weather and climate; high-pressure solid and liquid-state physics; and laboratory astrophysics. Probing the origins of the conditions for life requires expertise in galactic structure and evolution, the nature of dark matter and energy, stellar structure and evolution, stellar outflows and explosions, interstellar magneto-hydrodynamics, stellar collisions and interactions, and cosmic-ray propagation and effects. In other words, almost every area of planetary sciences and astrophysics is important for full exploration of the two great questions: How did we get here? Are we alone?

D. Required Facilities

At present, the large optics technology needed by these missions is also required by other government agencies, and has been developed primarily in industrial laboratories as a result of competitions. Extremely innovative ideas for large optics are also being developed at optics research universities, and the ground-based community is exploring ways to build 30-m to 100-m telescopes. Significant breakthroughs may come from many directions.

Facilities for testing large optics in vacuum exist at both industrial and government labs. However, each new mission has unique requirements, and each will have its own trade studies to select the most appropriate facilities based on the selected teams and the technical requirements. Temperature, size, and vibration isolation are the most important issues. The largest such facility is NASA's Plum Brook facility, but it is not being used for JWST, partly because of logistics issues, involving the distance and obstacles between the airport and the test chamber, and partly because of the cost to upgrade the facility for optical testing. If Plum Brook is needed for future missions, these problems could be overcome, but at significant cost.

Facilities for detector development are also major investments. Currently astronomical-quality detectors for wavelengths between about 0.3 and 28 micron are primarily available from industrial sources, based largely on semiconductor technology developed for other users. Astronomers typically do acceptance testing because the requirements for dark current and noise are so stringent, and test chambers are so difficult to build at the required performance levels. Vendors that specialize in astronomical detectors are critically dependent on astronomy funding. Detectors for shorter and longer wavelengths are in a very different situation. Astronomy missions are the main customers for the necessary technologies, and consequently NASA is usually the only source of funding for the organizations and facilities that develop them. The recent loss of non-program-specific NASA-wide advanced technology development funding jeopardizes the entire range of UV and far-IR missions in this Roadmap.

E. Unique Requirements

The coronagraph-type missions may require large lightweight monolithic mirrors with surface finish and stability significantly better than is currently available. This issue depends critically on the ability of small deformable mirrors to correct the errors on a sufficiently rapid time scale. Thus, large and very stable structures with active metrology control will be required. The system-level performance of these large structures with picometer metrology can not be fully verified on the ground, so system modeling to predict on-orbit performance will have to advance significantly beyond its current state.

Ultra-precise formation flying of two or more spacecraft with centimeter control is completely new territory. A detailed roadmap for this technology will be needed from the TPF-I project, based on actual flight requirements. Considering the stakes involved, an extensive series of laboratory demonstrations will be needed, ranging from scale models to proof of flight hardware. A decision on the need for a space demonstration of relevant technology will be required when the concept has been further developed.

VI. Critical Inter-Roadmap Dependencies

In the near-term and mid-term, the Search for Earth-Like Planets Roadmap has no architectural dependencies on other strategic roadmaps that would impede its implementation. There are enhancing dependencies with the Transportation and Education roadmaps related to selection of near-term Earth-To-Orbit (ETO) transportation options and effective communication with the public at large. The "Search for Earth-Like Planets" Roadmap has strong programmatic linkage with the "Exploration of the Universe" roadmap (Strategic Roadmap #8) because both roadmaps are to be implemented by the Universe Division of the Science Mission Directorate.

In the far term, alternate observatory architectures would be enabled by enhanced ETO launch capability and deep space nuclear power sources. The Roadmap anticipates telescope apertures that are larger than existing launch vehicle shrouds. JWST will be the first example. The maximum size of stowable aperture segments has a significant influence on the telescope design and aperture deployment or assembly technique. Larger shrouds will enable larger apertures and fewer individual segments – both of which directly affect performance. The ultimate sensitivity of cryogenic infrared observatories could be enhanced substantially if they could be located beyond the main belt asteroids and outside the bulk of our Solar System's cloud of zodiacal particles. Nuclear power for electric propulsion maneuvering and orbit circularization, active cryogenic refrigeration, and operational support would potentially enable this enhanced infrared and submillimeter observatory architecture.

There are synergistic scientific dependencies with a number of other science roadmaps. In general, these dependencies have the character of information transfer. For example, the possible discovery of extra-terrestrial life in our Solar System will influence the interpretation or focus of remote observations of other planetary systems. The absence of life on certain solar planets could expose the possibility of false-positive biosignatures. We may also learn that habitability is strongly influenced by the presence or absence of planetary magnetic shielding and that water, alone, is insufficient for life.

There are no identified dependencies related to the International Space Station and no expectation to establish a lunar-based observatory as part of the Roadmap plan.

Identified Strategic Roadmap dependencies are listed in Table VI-1. This table summarizes significant external relationships between this Roadmap (SR-4) and other Strategic Roadmaps. Following the guidelines of the relational database, events between roadmaps are characterized as *dependent* (exclusively), *enabling* (necessary, but not sufficient), *enhancing* (beneficial, but not critical), or *synergistic* (of mutual benefit). Arrows point toward the roadmap which accrues the benefits from the event dependency; arrow colors indicate the status of linkage resolution (*red*=fundamental disagreement, *yellow*=resolution process pending, *green* = event compatibility achieved for both roadmap committees. Specific technology dependencies and linkages of the missions roadmapped in this report are detailed in Chapter V above.

Key Dependency	Linked Roadmap			Nature of Relationship and Status	SR-4 Roadmap Event	Time-frame
	Name		Event			
Expanded launch vehicle shroud size, capability	SR-5	Transportation	New or improved ETO capability	Enhancing ⇨	Observatory archicture designs	Far
Science and programmatic linkage - understand joint capabilities	SR-8	Universe	Detection of extrasolar planets and evidence of biologic activity	⇦ Synergistic ⇨	Discoveries related to origin, evolution, and structure of the Universe	Near, Mid, Far
Expansion of biosignatures	SR-2	Mars	Develop Mars science strategy	⇦ Synergistic ⇨	Investigations or discoveries of biosignatures	Mid
Expansion of Habitable Zones (Icy Moons)	SR-3	Solar System	Knowledge of range of habitable conditions on Jupiter icy moons	⇦ Synergistic ⇨	Special Habitable Locations	Mid
Mission requirements influence transportation design	SR-5	Transportation	Transportation architecture designs	⇦ Enhancing	Identify future transportation requirements	Near
Understanding Earth as example of terrestrial planet	SR-9	Earth Science	Enhanced understanding of biomarkers	⇦ Synergistic ⇨	Enhanced understanding of biomarkers	Near, Mid
Habitability; planet star connection	SR-10	Sun-Earth	Magnetosphere	⇦ Synergistic ⇨	Role of planetary magnetic fields	Near, Mid
Public interest and support	SR-12	Educate	Public outreach, engagement	Enabling ⇨	Mission advocacy, Science Discoveries	Near, Mid, Far
3 AU IR Observatory deployments; telescopes far from Earth	SR-13	Nuclear	Deep space power generation, nuclear-electric propulsion	Enhancing ⇨	Observatory archicture designs	Far

Table VI-1. Inter-roadmap dependencies between SR-4 and the other Strategic roadmaps.

Capability Roadmap Dependencies

Suggested Capability Roadmap dependencies are listed in Table VI-2. This table summarizes the proposed relationships between this Roadmap (SR-4) and the various capability roadmaps. The SR-4 Roadmap committee has held discussions with CR-4 (Advanced Telescopes and Observatories) and CR-12 (Scientific Sensors and Instruments) and generally accepts the proposed capability needs from these roadmaps. The proposed products from other capability areas are not sufficiently well defined by database information to be immediately accepted. Additional information is required.

SR-4 expects that system level test and verification of future very large space optical systems will be difficult, if not impossible, on the ground or in low-Earth orbit. The adverse effects of gravitational loading, terrestrial environments, LEO thermal instability, and physical size are the sources of these testing issues. Advanced precision modeling and simulation tools and materials properties data will be required to stitch complex subsystem verification data together to achieve system level confidence. These tools should be a product of CR-14. Capabilities related to exploitation of the moon as a site for planet search observatories are not required. There is no expectation of a lunar observatory in the planet search roadmap.

Key Dependency	Linked Roadmap			Nature of Relationship	SR-4 Roadmap Event and Status	Time-frame
	Name		Event			
Precision Low-Thrust	CR-3	In-Space Transport.		Enabling	Observatory Design	Mid, Far
Micro-Newton thrusters				Enabling	Observatory Design	Near, Mid
Control of flexible structures	CR-4	Advanced Telescopes and Observatories		Enabling	Observatory Design	Near, Mid
Interferometer systems				Enabling	Observatory Design	Near, Mid
Algorithms and sensors for formation-flying				Enabling	Observatory Design	Near, Mid
Wavefront sensing and control				Enabling	Observatory Design	Near, Mid
Large lightweight optics				Enabling	Observatory Design	Near, Mid, Far
Rendezvous and docking	CR-10	Autonomous Systems and Robotics		Enhancing	Observatory Design	Mid, Far
Repair and servicing				Enhancing	Observatory Design	Mid, Far
Deployments				Enhancing	Observatory Design	Mid, Far
Operations planning and scheduling				Enhancing	Observatory Design	Near, Mid, Far
Detector technologies and performance	CR-12	Scientific Instruments and Sensors	Improved performance of science detectors	Enhancing	Sensitivity estimates to support observatory designs	Near, Mid
Cameras, detectors, spectrometers				Enabling	Observatory Design	Mid, Far
Cooling				Enabling	Observatory Design	Mid, Far
System modeling tools	CR-14	Advanced Modeling, Simulation, Analysis	Tools for system modeling and verification	Enabling	Observatory Designs, Test and Verification	Near, Mid
Science / engineering data processing and fusion				Enhancing	Science Extraction	Near, Mid, Far
Complex systems integration and test	CR-15	Systems Engineering Cost/Risk Analysis		Enhancing	Observatory Design	
Ensure outcome or optimize performance within constraints				Enhancing	Observatory Design	

Table VI-2. Inter-roadmap dependencies between SR-4 and the Capability roadmaps.

Appendix 1: National Policy Framework and External Constituencies

The Search for Earth-like Planets was highlighted in *A Renewed Spirit of Discovery –The President's Vision for U.S. Space Exploration,* and reiterated as a key NASA objective in the Space Exploration Vision articulated in the *President's Commission on Implementation of United States Space Exploration Policy* (the "Aldridge Report"). That report called for "advanced telescope searches for Earth-like planets and habitable environments around other stars" as one of the foundations of its exploration goals. In fact, all recent NASA planning documents have included as one central strategic goal to "conduct advanced telescope searches for Earth-like planets." The NASA Vision Statement includes the charge "**To find life beyond**." The NASA Mission Statement expressly challenges us "To explore the Universe and **Search for Life**." The National Academy of Sciences Decadal Survey: *Astronomy and Astrophysics in the New Millennium* endorsed the search for and characterization of Earth-like planets as an exciting frontier for space astronomy in the coming decade. The *Origins 2003* Roadmap, the *NASA Astrobiology Roadmap 2003*, and the 2003 Strategic Plan of the former Space Science Directorate each had as centerpieces the discovery and exploration of planets, habitable environments, and signatures of life outside the Solar System.

Strategic Roadmap #4, "**The Search for Earth-like Planets,**" builds on a strong legacy of scientific advances and policy heritage and represents NASA's *only* plan for realizing these exploration goals.

External constituencies for this Strategic Roadmap include the aerospace industry, astronomical researchers in academia, planetary scientists, the ground-based astronomical community interested in large telescopes, astrobiology researchers, K-12 schools, the NRO, DOD, OMB, and Congress. For instance, NASA is partnering with the DOD, NSA, and NRO in pursuing large, advanced space optics for the purpose of furthering the state of the art in lightweight mirror fabrication and space assembly. International constituencies include ESA, the Canadian Space Agency, and JAXA.

Appendix 2: Bringing the Universe down to Earth: Education and Public Outreach (EPO)

The discovery of Earth-like planets that may host life is a stunning prospect for people of all ages and cultures. The subject and its lexicon is broadly accessible to the uninitiated. The first confirmed Earth-like planets around another star will fundamentally alter our place in the cosmos, with implications as profound as the work of Copernicus, Kepler, and Galileo. This decades-long endeavor has the potential to ignite public excitement and stimulate the public imagination akin to the greatest discoveries in the history of culture.

Unique Education and Public Engagement Opportunities

The missions and programs that support the telescopic search for Earth-like planets and habitable environments around other stars present distinct opportunities to advance NASA's Strategic Objective # 13:

> *Use NASA Missions and other activities to inspire and motivate the Nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the Nation.*

This lofty goal serves down-to-Earth needs. We must generate and sustain an ample workforce of scientists and engineers—some of those who will implement the missions in this Roadmap are now only in elementary school. A strong education program provides 1) a necessary return on the public's investment in science exploration; 2) develops pathways for students to enter the fields of science, technology, engineering, and mathematics (STEM) careers, and 3) stimulates the public appetite for NASA Missions. Beyond the STEM careers themselves, the broader public must achieve a basic level of scientific literacy. This is not only good for the Nation and our democracy, but it may well be a prerequisite for the support that a multi-decadal program of exploration and discovery requires. The final report of the Moon-to-Mars Commission identified sustaining public interest as possibly the single greatest challenge facing NASA's overall Space Vision.

Public Engagement: Sharing Exploration and Discovery

NASA will need to plan proactively for the worldwide interest that the discovery of Earth-like worlds will cause. The quest has the potential to enter the mainstream of popular culture, capturing the public imagination at levels unmatched since the height of the Apollo program. Yet, the 30-year research timeline and attendant capital investment requires sustained public support. Unlike Apollo, this will be a journey, not a race. To support this major effort, the public needs to be emotionally engaged in the excitement of the Missions, and to be rationally informed about the goals and accomplishments along the way. This may require new and novel approaches to public engagement, as science and engineering compete for public attention, in addition to the traditional formal and informal education programs that serve complementary goals.

Public engagement builds grass-roots support that can sustain the search for Earth-like planets and habitable environments. Examples of how this has worked in the past include SETI@home, the distributed computing phenomenon initiated by UC Berkeley, and the many billions of hits received on the Mars Rover web site. Both cases demonstrate a burning desire of the public to be authentically involved in the search for life beyond Earth. Strategies that allow members of the public to participate in the discovery of Earth-like planets have the potential to generate national and international support for the Missions and programs, and such opportunities should be fundamentally linked to the Mission requirements where possible.

Public engagement encompasses the media, individual participation, and events. Examples include:

- Multi-media products for home, at school, and in public spaces like planetaria engage the public in NASA's discoveries
- Kiosks in public spaces like libraries, national parks, and shopping malls that interactively provide current news
- Volunteer networks such Solar System Ambassadors and the Night Sky Network that enable trained individuals to reach broad public audiences on NASA's behalf
- National and local events that highlight missions, such as the Year of the Telescope in 2009
- Mission launches that are strategically broadcast live via science centers and museums
- Websites like the PlanetQuest that offer engaging interactives and story-telling visualizations that carry the story to ever larger audiences.
- Electronic, broadcast and print media that carry news of the discoveries
- Online gaming communities that build new planetary systems inhabited by creatures of the imagination that interact sending parties of exploration, invasion, and colonization.
- Individuals modeling of planetary systems, and habitable worlds on home computers
- Yet-to-be-invented interactive experiences that will allow people to explore NASA data via the National Virtual Observatory (NVO) or the future sensor net.
- New cultural phenomena, such as blogging.

Public interest in astronomy, space science, and NASA is often fed by local science centers and museums, where exhibits, planetarium programming and IMAX films explain the process of science and share the thrill of exploration and discovery. These institutions offer opportunities of high leverage for NASA to communicate with the public. Their innovative programming and exhibits make them significant partners in public engagement, especially when the content is disseminated to other, smaller communities.

Education: NASA Science in the Classroom:

> "Everyone involved in exploring space today can make a difference for tomorrow by using the excitement of space exploration to engage the broadest possible cross section of America's children in learning math, science, and engineering." *Report of the President's Commission on Implementation of United States Space Exploration Policy,* p. 42

Exploration, discovery, and understanding are communicated to teachers and students via formal curriculum, instruction, and experiential learning. A coherent program for education will thread through the successive missions, sharing legacy resources and developing new products, partnerships, and strategies as national education goals and communications technologies evolve.

Education programs that will leverage NASA's investment by focusing on professional development for educators who support public science literacy include:

- K-12 teachers, especially STEM teachers,
- informal educators at science centers and planetariums,
- undergraduate faculty who instruct the "science for citizens" general education courses in astronomy, astrobiology, geology, geobiology, etc.

The goal of such programs will be to enrich the talents of educators, who in turn inspire students to support the scientific enterprise and/or pursue studies that lead to STEM careers. Community colleges and institutions that serve historically underrepresented groups are important partners, since most K-12 teachers take their STEM coursework at these institutions. The NASA Center for Astronomy Education professional development workshops now serve these faculties with great success.

> "The Commission finds that the space exploration vision offers an extraordinary opportunity to stimulate mathematics, science, and engineering excellence for America's students and teachers—and to engage the public in a journey that will shape the course of human destiny." *President's Commission on Implementation of United States Space Exploration Policy: A Journey to Inspire, Innovate, and Discover*, p. 41.

As college-age students prepare to join the NASA workforce, their education will necessarily require both breadth and depth in the classroom as well as laboratory and hands-on experiences with NASA missions and programs. The integration of many disciplines is required to explore Earth-like worlds and habitable environments; this points to a need for cross-trained teams of scientists, technologists, and engineers. The planet-finding missions utilize a variety of space-based and ground-based telescopes, as well as a rich program of research and analysis, laboratory astrophysics, and theoretical investigations supported by Research and Analysis (R&A). This is a diverse environment in which to train the STEM workforce who will actually conduct missions in the future. Programs of scholarships, fellowships, and training for undergraduate, graduate, and post-doctoral scientists and engineers should be supported via academic and research institutions, NASA centers, and in industry. Programs could include:

- National Research Council Fellows
- TPF Foundation Science program
- Michelson Science Fellowships
- NASA Astrobiology Institute Internships and Fellowships
- NASA's proposed university-based Virtual Space Academy
- Programs similar to NSF's Research Experiences for Undergraduates and Research Experiences for Teachers

Core EPO Values and Principles

To create quality education and public outreach, NASA programs share core values: 1) coherence to meet varied audience needs; 2) coordination with other NASA initiatives, 3) leverage via national and international partnerships; 4) scientific and technical participation by the NASA team; 5) hands-on experiences involving real research and data; and 6) engaging diverse people with NASA and in the NASA workforce. To achieve excellence, EPO programs require: dedicated resources (~2% of a mission's or program's total cost), comprehensive planning, implementation of EPO requirements in the design and development of missions, alignment with broader Agency efforts, and reliable assessments of the effectiveness of all EPO activities. Together, public engagement and education and outreach programs can reach the broadest audiences to achieve NASA's strategic objectives.

Appendix 3: External Partnerships: Engaging the Nation and the World

In the last ten years we have discovered over 150 extrasolar planets, the existence of water on Mars, and the possibility of water below the crusts of Jupiter's moons Europa and Ganymede. We have discovered complex connections between Earth's atmosphere, oceans, and continents that drive Earth's weather and make it habitable for highly diversified forms of life. We have quantified the Sun's decadal variability and its influence on Earth's biological, chemical, and physical processes. Public interest in the exploration of our Solar System and beyond is very high, but is tempered by cost and feasibility concerns. Maintaining the momentum of discovery and keeping the exploration initiative on a viable and productive path will require a global effort of partnerships among USG agencies, US industry, and international partners (both government and industry). This partnership of discovery will fuel economic, social, and intellectual growth worldwide and foster technical development at a faster rate than NASA might accomplish on its own.

A. A Balanced Program between NASA, Academia, and Industry

The first step in laying out a roadmap is to set the vision. The US Space Exploration Vision provides the overarching context for the Nation's and NASA's plans for future space missions. The fundamental scientific questions and required technological innovations are defined by academia and industry, and these in turn enable the goals and objectives of this Vision. Answering the fundamental science questions through a series of targeted missions to explore these questions is NASA's mission. Garnering and sustaining support for these missions will be difficult if there are visible space program failures. There have been a series of special reports in the last few years (e.g., the Young Panel, the CAIB report) that not only focused on hardware failures that resulted in loss of a mission, but on failures of program management that resulted in program plans that were overly ambitious and unrealistic from the beginning, resulting in significant cost and schedule overruns. Industry's role is to work in partnership with NASA and the science community to create a realistic program within the cost and schedule boundaries dictated by NASA's budget. To do this requires that all three work in concert from the outset to establish a comprehensive systems engineering approach that balances the program's parameters, costs, schedule, and science requirements simultaneously and that efficiently addresses the risks and trade-offs. To maximize our investments we will need simple, elegant solutions that progressively build on previous technology, while never sacrificing safety. Successful program planning and execution requires proactive management of such complex projects. This necessitates an active dialogue throughout program planning, development, and operational phases that constantly factors in the evolving scientific requirements, enabling technologies, and engineering practices. Such a dialogue will result in realistic scientific goals consistent with the state of the requisite technologies and, hence, in realistic cost, schedule, and risk plans. Re-engineering programs like SIM when they are years into development is otherwise an inefficient and costly use of resources. Industry can play a stronger role in the formulation of programs by being an equal partner early in concept formulation and definition.

B. The Importance of Competition

Competition is a fundamental tool in soliciting a broad spectrum of ideas for mission implementation. Competition has a multitude of dimensions in this context:

1) There is the competition between PIs who propose innovative missions, thus affording NASA the broadest set of options to further its scientific goals. Similarly, there is the competition of ideas for strategic missions, too large for PIs, which are presented to NASA committees and reviewed by NAS committees.

2) There is the competition among contractors to become NASA's industrial partners in selected missions. Industry will often match investments made by NASA in pre-Phase A and Phase A studies, providing NASA with a broad range of technical and programmatic ideas for implementing these missions. During Phase C/D proposals, competition can be used judiciously to explore options for balanced technical development and risk reduction, within budget and schedule margins. If this is not done, contractors are unduly encouraged to make overly optimistic assumptions in order to be competitive. As a result, safety and program realism suffer. The recommendations of the Young Panel should be reviewed before any RFP is written for an ambitious new program.

and

3) There is the competition between NASA and its international counterparts, such as ESA, the Canadian Space Agency, JAXA, and the Chinese space agency. Such competition promotes a global debate on where humankind should focus its space exploration resources. Often ESA and NASA have similar mission goals and in the interest of leveraging resources will decide to collaborate, rather than compete. However, early competition creates a plethora of ideas, from which partners can later choose the best set of options and define their respective roles and responsibilities. The technical and resource challenges of a program like TPF-I will require employing all aspects of the above. Engagement between NASA, industry, academia, and international partners cannot begin early enough.

C. USG agencies

NASA has a history of working effectively with other agencies, which will be essential to achieve its Exploration vision and in the search for Earth-like planets. The NSF is NASA's partner in furthering American science and technology and should work with it to promote an expanded view of Earth and Space science. For example, the NSF is partnering with a European consortium to build the Atacama Large Millimeter Array (ALMA) to study the formation of solar systems around very young stars in relatively nearby dark clouds. The NSF is also the largest single partner in the GEMINI 8-meter optical / IR telescopes, and GEMINI is now making significant investments in detecting extrasolar planets. These new investments include developing an extreme adaptive optics system to image extrasolar Jupiter-like planets orbiting nearby young stars and an infrared spectrograph which will be optimized to detect Earth-mass planets in the solar neighborhood. The NSF is also investing in visible-light ground-based radial-velocity studies that are identifying ever lower-mass extrasolar planets around nearby Sun-like stars.

NASA should also strengthen its ties to other agencies. For instance, it is formulating a long-term plan with NOAA to gather environmental data through joint missions that also can provide operational forecasting capability for NOAA and Earth science data for NSA. Similarly, NASA needs to build strong ties to DOE, DOD, DARPA, and the NRO to multiply the return on the Nation's investment in fundamental sensor, mirror fabrication, optics, space assembly, and propulsion technologies that will be crucial to executing the extrasolar planet discovery missions of this Roadmap. In this vein, NASA is coordinating technology efforts in large advanced space optics through the Large Optics Working Group of the Space Technology Alliance, an affiliation of the Federal Space-Faring Agencies. Specifically, collaborations are being pursued in lightweight, rapid, and low-cost mirror fabrication.

D. Importance of International Collaboration

NASA has a long and successful history of collaboration with the space and research agencies of other nations. In fact, almost all of NASA's Earth observation missions include substantial international participation. The Global Earth Observation System of Systems (GEOSS) includes over 60 nations and more than 40 international research and environmental forecasting organizations. Likewise in space science, ESA and CSA participation in JWST is a fundamental part of the cost strategy of that program. ESA is providing the Ariane launch vehicle and the Near-InfraRed Spectrograph (NIRSpec) instrument, with NASA providing the detectors and microshutters. ESA is also organizing a European partnership to produce the opto-mechanical assembly of the Mid-Infra-Red Instrument (MIRI). The whole MIRI effort is a 50-50 partnership with ESA, with NASA/JPL assuming project leadership and the US providing the science team lead. The Canadian Space Agency is also a partner and provides the Fine Guidance Sensor. ESA and CSA are to get guaranteed allocations of observing time of 15% and 5%, respectively.

Two other missions, which are important to this Roadmap and which are currently in development, have significant international participation. The *Herschel* mission is led by ESA, with 20% participation from NASA. The US provides *Herschel* with advanced detectors and coolers, which have helped advance these technologies in the US. SOFIA is led by NASA with a 20% contribution from the German Aerospace Center (DLR) in the form of the SOFIA telescope and a portion of the SOFIA operating needs. Both of these missions will be very important for the planet formation and habitability science objectives of this Roadmap.

The search for Earth-like planets will require continued international participation and cooperation to leverage resources, share scientific data and responsibilities, and promote continued funding by the various government agencies involved in the emerging scientific field of planetary exploration outside the Solar System. This is particularly true with regards to TPF-I and NASA has begun discussions with the ESA/Darwin project. Likewise, industry is becoming more and more global and is partnering across borders to provide the best overall technical and cost solution to its customers. America will benefit from more international scientific and technical cooperation.

Appendix 4. Synopsis of Missions to Explore Extrasolar Planets

The rich science program described in this Roadmap draws upon a vast array of activities including ground- and space-based observations, data analysis, theory, and modeling. The sources of observations include ground observatories, balloon and sounding rockets, small and medium size competed missions, and the major strategic missions. This appendix of the Roadmap summarizes the core and strategic missions that are called for to implement this exploration vision. First, Figures A4-1 ("Exoplanet Detection and Characterization") and A4-2 ("Formation & Evolution of Exo-Planetary Systems from Disks") lay out the general time sequence of the missions for the two major scientific themes and identify key relations and products. Then, each mission is described in turn and its unique role in this Roadmap is summarized.

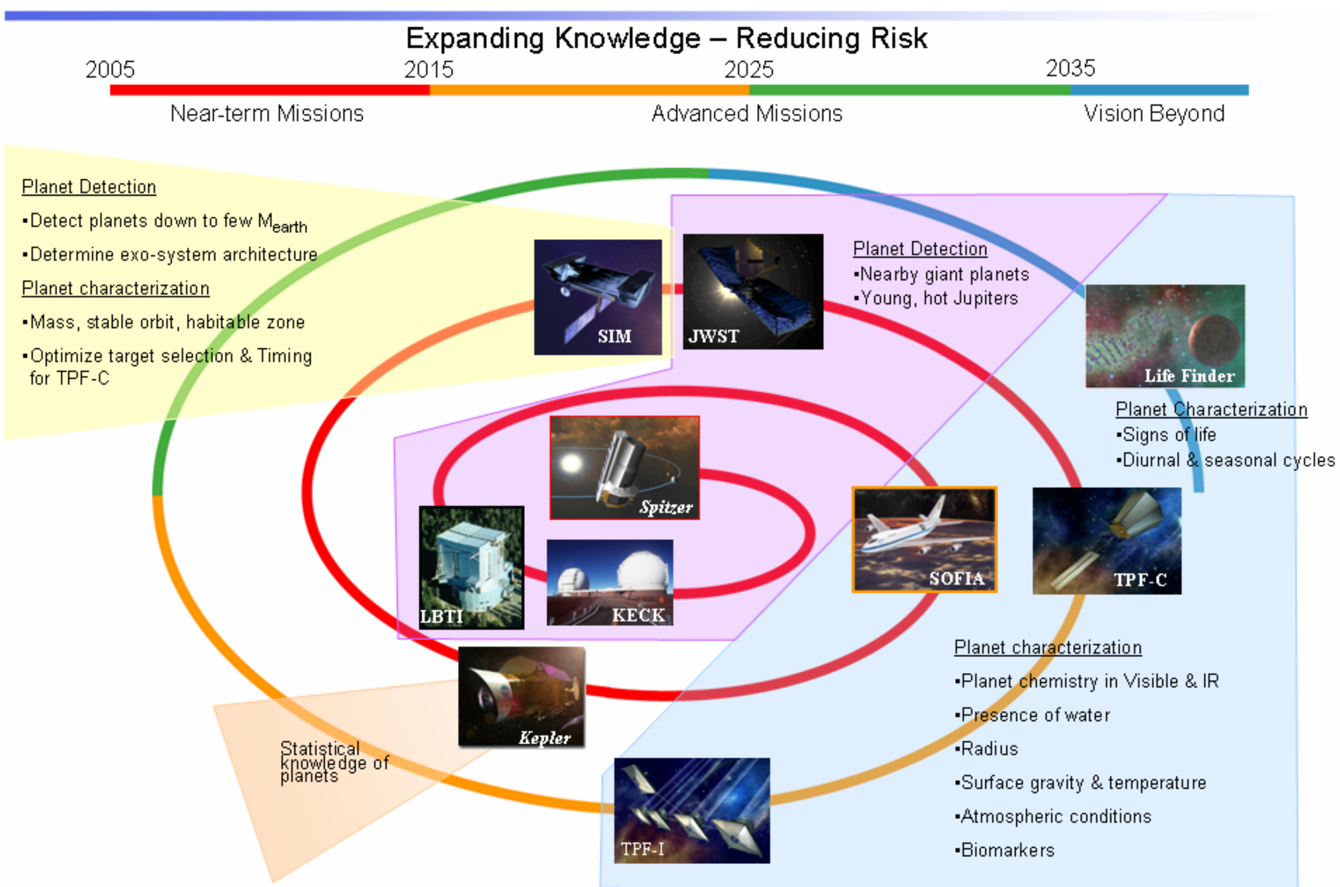


Figure A4-1. Key products and relationships of recommended missions that focus on exoplanet detection and characterization. Colors indicate launch decade as indicated at the top.

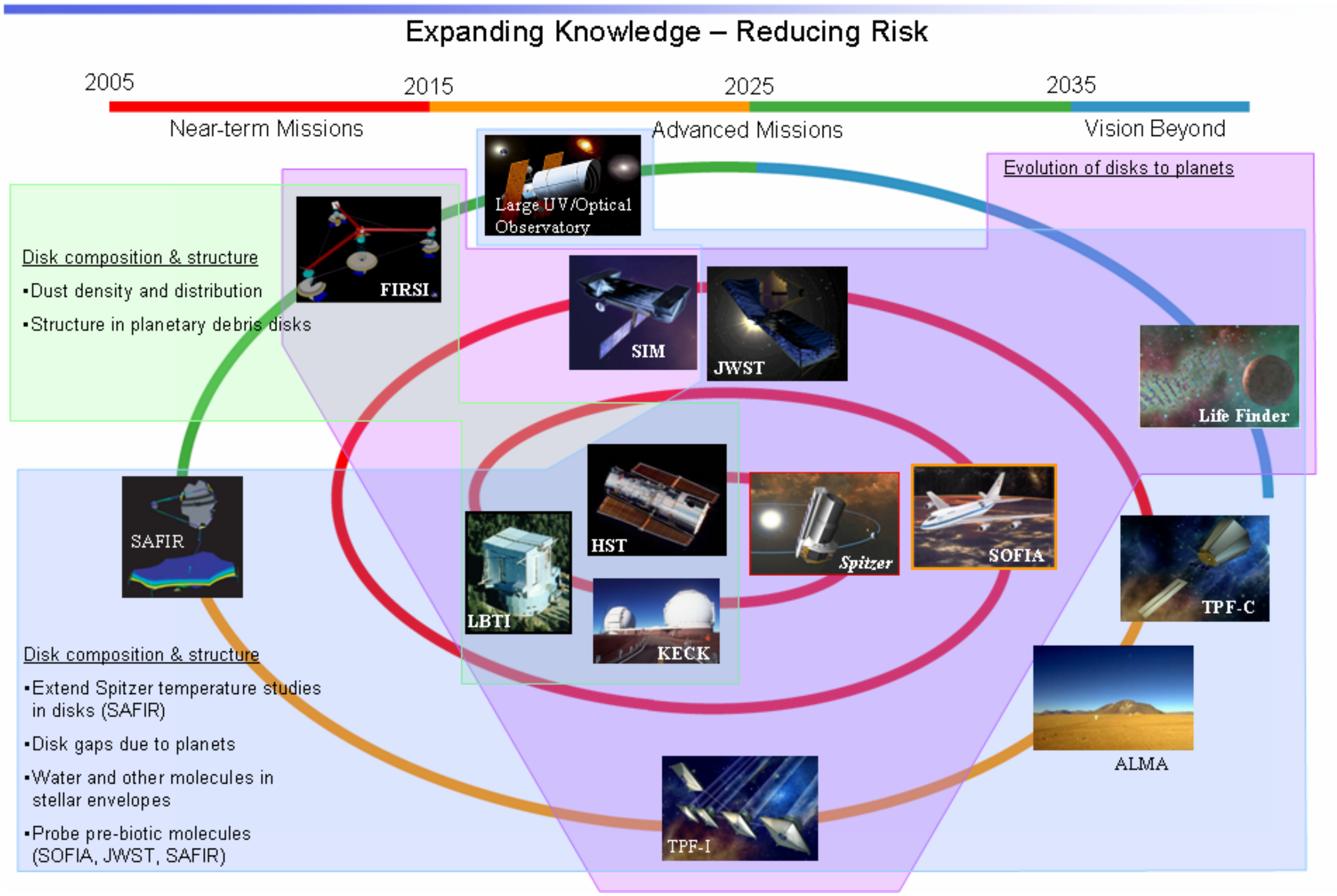


Figure A4-2. Key products and relationships of recommended missions that focus on planet formation and evolution. Colors indicate launch decade as indicated at the top.

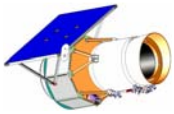
Missions for 2005 – 2015

NASA supports a broad science program in conjunction with the W.M. Keck Observatory in Hawaii. This program has two main thrust areas: first the sponsorship of community-accessible time on single Keck telescopes to pursue Roadmap science goals; and second, the development and operations of the **Keck Interferometer (KI)**. The single-Keck program has been in place since 1996, and has been extremely successful in producing important scientific results such as radial velocity exo-planet detections, spectral characterizations of L and T dwarfs, and mid-infrared imaging of planetary debris disks. KI has combined the infrared light collected by the two 10-meter Keck telescopes to undertake a variety of astrophysical investigations. Among the issues addressed by KI will be the location and amount of zodiacal dust in other planetary systems and, possibly, the astrometric detection and characterization of exo-planetary systems around stars in the solar neighborhood. This first in-depth and long-term census of planets will be an important contribution to our understanding of the architecture and evolution of planetary systems, and will be key in helping to define the requirements and the architecture for TPF.

The **Large Binocular Telescope Interferometer (LBTI)** will further a variety of Roadmap goals in star and planet formation through both nulling and wide-field imaging interferometry. Primary among these goals is a planned systematic survey of nearby stars to understand the prevalence of zodiacal dust and gas giant planets and to determine a system's suitability for terrestrial planets. The modest baseline and common mount design of the dual 8.4-meter LBTI allows uniquely sensitive infrared observations of candidate planetary systems through nulling interferometry. The development of nulling technology and observing techniques will help create a mature technological basis for a TPF mission. The LBTI also allows wide-field, high-resolution imaging of objects down to brightness levels similar to filled aperture telescopes.

The **Stratospheric Observatory for Infrared Astronomy (SOFIA)** will study sites of star formation, formation of new solar systems, survey the debris disks which are planet-forming regions, and study Neptune-sized and larger extrasolar planets through the transit technique. In addition, SOFIA will conduct a number of other astrophysics investigations such as observations of the cold interstellar medium, and the center of our galaxy at high spatial resolution at far-infrared wavelengths. It is a joint U.S. (80%) and German (20%) observatory that consists of a 747 aircraft with a telescope as large as HST (2.5m). SOFIA will also function as a unique platform for developing, testing, and reducing risk of new IR instrument technologies, particularly detectors for future missions such as SAFIR. It will have a prominent education and public outreach program, including involving high school teachers and students in its flights and observations. SOFIA will be making observations in 2006.

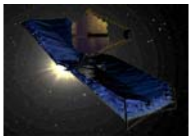
Kepler is a Discovery Program mission scheduled for launch in 2008. This provides an excellent example of the kind of moderate scale missions that can contribute to the Roadmap in important ways. The *Kepler* mission is specifically designed to photometrically survey the extended solar neighborhood to detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone and provide fundamental progress in our understanding of planetary systems. The results will yield a broad understanding of planetary formation, the frequency of formation, the structure of individual planetary systems, and the generic characteristics of stars with terrestrial planets. These results will be instrumental in determining how deep TPF will have to look to find an adequate sample of planetary systems to find and characterize habitable planets. *Kepler* is a simple 0.95-m Schmidt telescope, with a very challenging detector array consisting of 42 CCDs, each with 2200 x 1024 pixels.



WISE. WISE (Wide-field Infrared Survey Explorer) is a MIDEX class explorer mission to conduct an all-sky survey from 3.3 to 24 microns up to 1000 times more sensitive than the IRAS survey. Among other things, WISE will measure the local mass function of brown dwarfs down to a few Jupiter masses. WISE has a 40-cm telescope and reimaging optics, giving 6" FHWM resolution. It consists of a single instrument with HgCdTe and Si:As arrays at 3.5, 4.6, 12 and 23 microns. WISE is scheduled for launch in 2009 aboard a Delta rocket.

The **Space Interferometry Mission (SIM): PlanetQuest** will be the first observatory capable of detecting and measuring the mass of planetary bodies with a few times the mass of Earth in orbit around nearby stars. SIM PlanetQuest will take a major step forward in answering some of the defining questions in our exploration of the Universe: “Are we alone?” Are there other worlds like our own home planet, existing within planetary systems like our own Solar System? SIM will extend mankind’s exploration of nearby planetary systems into the range of the rocky, terrestrial planets for the first time, permitting scientists to refine their theories of the formation and evolution of planets like Earth. This census will form the core of the observing programs for subsequent missions that will investigate in detail the nature of these newly discovered worlds. SIM will aid in defining the early “target list” for TPF by identifying systems to focus on, i.e. those with candidate planets of a few Earth masses or a dynamical void that would imply the presence of such planets, as well as those systems to avoid, i.e. systems with gas or ice giants near the habitable zone. Orbital information from SIM could help in detailed planning of TPF observations. SIM will provide for the first time the properties of planetary systems in orbit about young stars where imaging is limited by photospheric activity and rapid rotation, helping to answer questions about the formation of systems of these systems. SIM will provide all-important data on planetary masses, which when coupled with data from TPF-C/I will yield densities and surface gravities crucial to complete physical characterization. In addition to its scientific goals, SIM will develop key technologies that will be necessary for future missions, including precision location of optical elements to a fraction of the diameter of a hydrogen atom (picometers) and the precise, active control of optical pathlengths to less than a thousandth the diameter of a human hair.

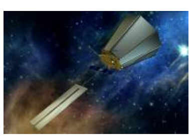
Beyond the detection of planets, SIM’s extraordinary astrometric capabilities will permit determination of accurate positions throughout the Milky Way Galaxy. This will permit studies of the dynamics and evolution of stars and star clusters in our galaxy in order to better understand how our galaxy was formed and how it will evolve. Accurate knowledge of stellar positions within our own galaxy will allow us to calibrate luminosities of important stars and cosmological distance indicators enabling us to improve our understanding of stellar processes and to measure precise distances throughout the Universe.



James Webb **Space Telescope (JWST)** will have an aperture 2.7 times that of HST and about an order of magnitude more light-gathering capability. Because the prime science goals for JWST are to observe the formation and early evolution of galaxies, JWST's greatest sensitivity will be at mid- and near-infrared wavelengths, where the expansion of the Universe causes the light from very young galaxies to appear most prominently. JWST will be a powerful general-purpose observatory capable of undertaking important scientific investigations into a very wide range of astronomical questions, including those that are central to the Roadmap themes. JWST will be a powerful tool in the exploration of extrasolar planetary systems by studying planet forming regions, dust disks and their dynamics, birth of stars and formation of early systems, and studying how the chemistry that can lead to life is delivered to planetary systems.

The telescope diameter of JWST will be 6.5 meters and JWST will be celestial background-limited between 0.6 and 10 microns, with imaging and spectroscopic instruments that will cover this entire wavelength regime. JWST has a requirement to be diffraction-limited at 2 microns. With these capabilities, JWST will be a particularly powerful tool for investigating fundamental processes of stellar formation and early evolution, as well as the later stages of evolution. In both cases, dust almost completely blocks our ability to observe the light from rapidly evolving stars, so that detailed observations have to be carried out at longer wavelengths.

The European Space Agency and the Canadian Space Agency have agreed to contribute significantly to the JWST project. These contributions will be important in significantly enhancing the overall capabilities of the observatory.



The **Terrestrial Planet Finder Coronagraph** (TPF-C) will directly detect and study planets outside our Solar System from their formation and development in disks of dust and gas around newly forming stars to their evolution and even potential suitability as an abode for life. By combining the high sensitivity of space telescopes with revolutionary imaging technologies, TPF will measure the size, temperature, and placement of terrestrial planets as small as Earth in the habitable zones of distant solar systems as well as their gas giant companions. In addition, TPF spectroscopic capability will allow atmospheric chemists and biologists to use the relative amounts of gases like carbon dioxide, water vapor, ozone and methane to find whether a planet someday could or even now does support life. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, including gas giants, terrestrial planets and debris disks. TPF's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new solar systems is an important scientific motivation for the mission. However, TPF's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an Earth orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest.

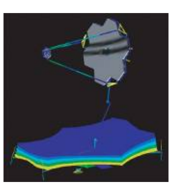
The visible-light coronagraph will use a single telescope with an effective diameter near

8 meters, operating at room temperature, and required to achieve a billion-to-one image contrast in order to isolate the signal from a planet from that of the star. Very precise, stable control of the telescope optical quality will be required. TPF-C has carried out an extensive program of technology development along multiple paths to enable this unprecedented capability, and has now demonstrated in laboratory conditions the ability to produce contrasts in the required regime. TPF-C is targeted for launch in 2014.

Missions for 2015 – 2025

The **TPF-Interferometer** (TPF-I) will be a long-baseline interferometer operating in the infrared. TPF-I will use multiple (≈4), 3–4-meter-diameter telescopes configured as an array operated on separated spacecraft over distances of a few hundred meters. The telescopes will operate at extremely low temperatures of ≈40 kelvin, and the observatory will necessarily be large. However, the image contrast requirement, "only" a million to one, and thus the required system optical quality, will be less challenging at infrared wavelengths than the TPF-C challenge of 1 billion to one at visible wavelengths.

The European Space Agency (ESA) has been actively studying an infrared interferometer with essentially the same science goals as TPF, referred to as Darwin. Under a NASA/ESA Letter of Agreement, scientists and technologists in both agencies are discussing ways in which the preliminary architecture studies can lead to effective collaboration on a joint mission.



The **Single Aperture Far-InfraRed** mission, consisting of a single 8–10-meter telescope and operating in the far infrared, will serve as a building block for the Life Finder while carrying out a broad range of scientific programs beyond JWST and *Spitzer*. These include probing the epoch of energetic star formation in the redshift range $1<z<10$ at a wavelength regime that can easily detect continuum and cooling-line emission from dust-enshrouded primeval galaxies with an angular resolution capable of isolating individual objects at or below the limits of the Hubble Deep Field; investigating the physical processes that control the collapse and fragmentation of molecular clouds to produce stars of various masses by mapping of cold, dense cores at <100 AU resolution at the peak of their dust emission and using gas phase tracers such as H_2, H_2O, CO, [OI], [NII]; learning about the era of cometary bombardment that may have determined the early habitability of Earth by making high spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars; and studying the nature of the recently discovered objects in the Kuiper Belt of our own Solar System which may be remnants of our own planet formation process.

Universe Probes: By the middle of the next decade, NASA will be in a position to call for a series of mid-scale missions with competed science that contribute in important ways to the overall exploration of extrasolar planetary systems.

Missions for 2025 – 2035

Two missions still far in the future because of their demanding technologies have strong relevance to Roadmap goals. The first is the **Life Finder**, which would provide high-resolution spectroscopy on habitable planets identified by TPF. This information would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth. Achieving that goal will require observations beyond those possible with TPF. For example, searching the atmospheres of distant planets for unambiguous tracers of life such as methane (in terrestrial concentrations) and nitrous oxide would require a spectral resolution of ~1,000, utilizing a version of TPF with 25-meter telescopes.

Finally, in the search for exo-solar planets capable of harboring life, a mission for the far future that will serve to challenge our imaginations and our technological inventiveness, is **Planet Imager**. Perhaps using a formation of a dozen ten-meter telescopes, this mission may some day return images our children or theirs could use to study the geography of a pale blue planet orbiting a star similar to ours across the gulf of space, time and imagination. While no clear path to accomplishing this mission currently exists, its appeal is so great that it will remain a distant vision on our Roadmap until future generations make the dream a reality.

Appendix 5: Bibliography of Key Agency and NRC Documents

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Appendix 6: Acronyms and Mission List

ALMA Atacama Large Millimeter Array
COROT COnvection ROtation and planetary Transits
FIRSI Far-Infrared and Submillimeter Interferometer
Herschel
HST *Hubble* Space Telescope
JWST *James Webb* Space Telescope
Keck-I *Keck* Interferometer
Kepler
LBTI Large Binocular Telescope Interferometer
Life Finder
LUVO Large UV/optical Observatory
MIRI Mid-Infra-Red Instrument
NIRSpec Near-InfraRed Spectrograph
NVO National Virtual Observatory
Universe Probes
Planet Imager
PTI Palomar Testbed Interferometer
SAFIR Single Aperture Far-InfraRed mission
SIM Space Interferometry Mission - PlanetQuest
SOFIA Stratospheric Observatory for Infrared Astronomy
Spitzer
TPF Terrestrial Planet Finder
TPF-C Terrestrial Planet Finder Coronagraph
TPF-I Terrestrial Planet Finder Interferometer
VLTI Very Large Telescope Interferometer
WISE Wide-field Infrared Survey Explorer
XMM-Newton

Appendix 7: Strategic Roadmap team, Search for Earth-like Planets

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
SEARCH FOR EARTH-LIKE PLANETS
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Search for Earth-like Planets Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on searching for Earth-like planets and habitable environments around other stars using advanced telescopes. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

Administrator　　　　　　　　　　　　　　　　　　　Date

Universe Exploration:
From the Big Bang to Life

A strategic roadmap of universe exploration to understand its origin, structure, evolution and destiny.

May 20, 2005

Table of Contents

Universe Exploration

1. **Agency Objective Statement:** Explore the universe to understand its origin, structure, evolution, and destiny.

2. **Flow-down to roadmap objectives**

Universe Exploration: From the Big Bang to Life

Science is now poised to answer some of humanity's deepest questions, such as how the universe came into being; how it formed the galaxies, stars, and planets that set the stage for life; and whether there is life on other worlds. The scientific pursuit of our origin, structure, evolution and destiny requires deep and detailed explorations into space and time, and challenges the limits of America's technical capabilities in space. This roadmap articulates a long-term plan for scientific exploration of the universe, from the Big Bang to life. It is composed of two program elements, the Beyond Einstein Program and the Pathways to Life Program.

The **Beyond Einstein Program** explores the ultimate extremes of nature: the birth of the universe, the edges of space and time near black holes, and the darkest and emptiest space between the galaxies. It will determine the initial conditions and natural laws that govern everything that happens in the universe, from beginning to end. This program takes up the challenge to explore the origin and destiny of the universe through three roadmap objectives:

1. Find out what powered the Big Bang.
2. Observe how black holes manipulate space, time and matter.
3. Uncover the nature of the mysterious dark energy pulling the universe apart.

The Beyond Einstein program's cornerstone missions are the Laser Interferometer Space Antenna (LISA), the first instrument in space to measure spacetime ripples called gravitational waves, and Constellation-X (Con-X), a path-breaking X-ray telescope that can study matter near black holes. A focused line of more specialized Einstein Probe missions is dedicated to specific studies of black hole discovery, the cosmic inflation that powered the Big Bang, and the dark energy propelling the cosmic expansion today. Forward-looking technology development, as well as foundational and exploratory studies in theory, modeling, and predictive simulation, aim ultimately toward two Vision missions: the Big Bang Observer, an ultrasensitive gravitational wave observatory, and the Black Hole Imager, an X-ray interferometer.

The simple Big Bang ultimately created a rich structure, giving rise to galaxies, stars and planets. Peering back nearly 14 billion years, this global history — from epoch to epoch, from the formless infant universe through nascent galaxy building to the formation of solar systems — can be traced by direct observations of distant space. For example, all-sky images from the Wilkinson Microwave Anisotropy Probe (WMAP) reveal the afterglow of the Big Bang, a remnant primordial radiation created by faint vibrations in matter and light half a million years after the Big Bang, triggered by the event itself. The more advanced ESA-NASA Planck Surveyor mission and eventually the Beyond Einstein Inflation Probe will measure these vibrations in exquisite detail. The weak ripples in gas and dark matter — a little more matter here, a little less there — later created the first stars, then the quasars powered by supermassive black holes, and finally the great cosmic web of galaxies linked by invisible rivers of dark matter and hot, tenuous gas. Con-X and LISA explore the era when massive black holes dominated; other Beyond Einstein missions will probe the era when dark energy became the dominant force in the universe.

As the universe evolved to the present day, stars played increasingly dominant roles in the evolution of matter and complex structure. Stars are the sources of the energy, light, and chemical elements that drive the cosmic cycling of matter into new generations of stars, planets, and eventually life. From hydrogen and helium created in the Big Bang comes carbon, oxygen, nitrogen and life itself. The **Pathways to Life Program** explores the formation and evolution of all of this grand system. It takes up the challenge to explore the structure and evolution of the universe through one overarching objective:

4. Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

This objective has three key components:

- Map directly the structure and evolution of the Cosmic Web.
- Map the flows of energy and matter between whole systems and their constituent parts, from galaxies to stars and planets.
- Trace the evolution of nuclei, atoms, and molecules that became life.

The Pathways to Life program builds on the historic legacy of the Hubble Space Telescope, and includes the airborne Stratospheric Observatory For Infrared Astronomy (SOFIA), the James Webb Space Telescope (JWST), the Gamma-ray Large-Area Space Telescope (GLAST), competed Probes, and the Pathways to Life Observatories. Con-X, LISA, and the Einstein Probes will contribute significantly.

All of these explorations require the development of complex space missions with unprecedented capabilities, from new ultrasensitive detectors and precision optics, to multiple spacecraft flying in formation to subatomic accuracy. New technology development is systematically incorporated into the multiple stages of the Beyond Einstein and Pathways to Life programs. The overall plan maximizes investment return by focusing on strategic technologies, where each development pays off multiple times.

Beyond the strategic space missions, NASA's scientific success depends on rapid and flexible response to new discoveries, inventing new ideas and theoretical tools supporting space science initiatives, converting hard-won data into scientific understanding, and developing promising technologies that are later incorporated into major missions. These activities are supported through a balanced portfolio of competed Research and Analysis (R&A), Probe, Discovery, Explorer, and sub-orbital programs, which collectively are designed to guarantee the continued vitality of NASA's overall space science vision, reduce major mission risks, and optimize the return on NASA's capital, technology, and manpower investments. Importantly, NASA, through its Education and Public Outreach programs and through the R&A program's support of student and postdoctoral researchers at America's universities, plays a critical role in educating the nation and training the next generation of explorers.

This roadmap describes a framework for exploration on the grandest scale. It lays out a scientific and technological agenda to discover the origin, evolution, structure and destiny of space and time, matter and energy, atoms and molecules, stars and galaxies, and ultimately life itself.

3. Implementation framework

Origin and Destiny of the Universe: Beyond Einstein

Our "common sense" about how things move works well on a human scale: a light beam travels a straight path; clocks tick at the same speed, whether in New York or London; an inch is an inch. But experiments have shown that our "common sense" fails spectacularly when we start to explore the extremes of Nature: the very small, the very fast and the very large — especially at the beginning and end of time, and the edges of space. Light bends, time slows, distances alter. Theories describing this non-intuitive natural world have been remarkably successful.

- Quantum mechanics describes the very small. Its weird predictions govern the operation of microcomputers, lasers and nuclear reactors. We know therefore that our theories of quantum mechanics are very precisely "right" on the scales of atoms and their components.
- Special relativity, Einstein's first unification of space and time, describes the very fast. Its predictions (such as $E=mc^2$ and the slowing of time at high velocities) have been tested to fantastic precision in particle accelerators, where small things move close the speed of light.
- General relativity, Einstein's great theory unifying space, time and gravity, also describes the behavior of very large and massive things: stars, black holes and the universe as a whole. The giant scale on which it works means that we need to go to space to explore nature's most outlandish violations of common sense. This is NASA's domain.

Einstein's general theory of relativity reveals the familiar "force of gravity" as an illusion. Instead, it views the whole world differently: Space and time are curved by matter, and the curvature of space and time determines how matter moves. An ant, walking in a straight line on a flat floor, will not return to his starting place. But an ant walking in a straight line on the curved surface of an orange will end up going around in circles. In Einstein's view, the Space Shuttle and the astronauts in it, like the ant on the orange, all move in the straightest lines they can on a four-dimensional spacetime curved by the matter of the earth. Experiments show that Einstein's description works better than Newton's more common-sense "force of gravity" description: for example, Einstein's theory predicts that identical clocks at different heights above the earth run at different rates, because time itself is distorted. Although the effect once seemed exotic, nowadays our global positioning system (GPS) satellites, which are used in all forms of navigation, must correct for this effect or their position errors would increase at about 8 miles every day!

Most checks of Einstein's general theory of relativity have been done in the Solar System, where gravity is weak, the curvatures of spacetime are small and everything moves much more slowly than light. These experiments include laser ranging from Earth to the Apollo astronauts' reflectors on the moon, radio ranging to the Viking and Cassini spacecraft, and the precession of LAGEOS orbits and Gravity-Probe B's gyroscopes. These have all so far confirmed that Einstein's theory works as perfectly as they can measure.

But in environments far more extreme than our solar system, Einstein's theory departs even more from common sense: not only can matter curve spacetime, but curved spacetime can curve itself. This leads to two breathtaking predictions: 1) there should exist vibrations in space and time, called gravitational waves, and 2) dense concentrations of matter or curvature should close off curved knots in space and time called black holes. So far, we have only indirect evidence that these two astonishing predictions are true. NASA's Beyond Einstein missions will obtain direct evidence by exploring the most extreme places in the universe, in ways never before attempted. Their quest will also explore the origin and destiny of the universe itself.

The Sound of Spacetime: Gravitational Waves

Since ancient times, astronomers have used one form of energy to study the universe. Called simply "light," it includes X-rays and radio waves and all the colors of the rainbow in between which humans have always seen with their own eyes. Light is made of vibrating waves of electric and magnetic fields traveling through space and time. In Einstein's theory of gravity, vibrating waves of space and time, which also travel at light speed, can carry energy. In the same way that black holes are made just of space and time, gravitational waves are also "pure" space and time, but behaving in a way that has not yet been detected. The new technology of Beyond Einstein will open up to science a whole new sense of the cosmos; suddenly, after centuries of silence, science will no longer be deaf to the sounds of spacetime.

Of all the outflows of energy in the universe, the most powerful are carried not by light but by the gravitational waves emitted when two black holes orbit, collide, and merge into a single black hole. In the final minutes or hours before the merging of just a single pair of supermassive black holes, a million times more power is radiated in gravitational waves than all the light from all the stars in all the galaxies in the entire visible universe put together. It is possible that the universe contains more of this gravitational radiation than it does light.

In spite of carrying enormous amounts of energy, gravitational waves interact very weakly with matter and penetrate anything without losing strength. While this makes them powerful probes of extreme conditions, it also makes them hard to detect — so hard that they have not yet been directly detected. They interact so weakly with any measuring apparatus that only in the past few years has technology advanced to the point that we are confident we can build equipment to detect them.

Detecting gravitational waves will give Einstein's theory a workout it has never had before. Through gravitational wave detection we will listen to collisions and mergers between black holes, the most violent events in the universe. The sounds of the universe will tell us how well Einstein's ideas still work in these extreme conditions, and yield detailed maps of the structure of space and time around both old and newly merging black holes. They will also allow us to penetrate times and places impossible to see with light, such as the birth of our universe, perhaps revealing startlingly violent events, such as the formation of our three-dimensional space from an original space with more dimensions.

Gravitational waves produce tiny jiggles in the distance between masses that are floating freely in space, isolated from all forces other than gravity. The distances between the masses can be monitored using laser interferometry. An early generation of such detectors has now been deployed on the ground—the NSF-funded Laser Interferometer Gravity-wave Observatory (LIGO) in the United States, and similar systems worldwide. It is hoped that these systems will make the first detection of gravitational waves from some sources of high-frequency waves. Beyond Einstein's LISA will operate in a broad band at much lower frequency. It will detect entirely different sources in great numbers and with exquisite precision.

The most powerful gravitational waves come from quickly changing systems with very strong gravity, so LISA's strongest signals will probably come from black holes spiraling into other supermassive black holes. In addition to detecting sources like these, which cannot be detected in any other way, LISA will break new ground in yet another way. By detecting for the first time gravitational waves from sources (such as orbiting pairs of white dwarf stars) that can be studied by optical telescopes, LISA will introduce gravitational waves as an entirely new way to study a wide range of astronomical objects.

The vision mission Big Bang Observer will study with unprecedented sensitivity the spectrum of gravitational waves at frequencies of 0.03Hz to 10Hz, in between those studied by LISA (0.0001 Hz to 0.03 Hz) and those studied by LIGO (30Hz-1000Hz), and extend the reach of gravitational wave astronomy towards its ultimate limit: detecting the quantum noise from the inflationary universe. In doing so it will enable detection of a vast range of astronomical sources.

Beyond Einstein: Exploring the largest and smallest scales

Two roadmap objectives explore relativity to the very largest scales and the very smallest scales possible: the size of the universe today, and the scale of the tiny point from which the Big Bang began.

The evolution of the universe predicted by the equations of the general theory of relativity has been spectacularly confirmed by measurements of the cosmic radiation background, the abundances of light elements, and the growth of structure in our universe. But theoretical inconsistencies, and disagreements with observation, arise if we try to use standard relativity to extrapolate back earlier in time `to the beginning', or to the physics of the emptiest space today. Physicists suspect that the general theory of relativity is not a reliable guide to exploration of space and time at these extremes. *To understand where we came from, or where we are going, we may need a theory beyond Einstein's.*

To fix the problem of cosmic expansion on the largest scales seems to require re-introducing to relativity something similar to Einstein's cosmological constant, a new form of `dark energy' permeating so-called empty space. Because measurements of the effect of dark energy on the universe are so difficult and fraught with possible systematic errors, it will be important to make several independent measurements of it. For example, LISA will use self-calibrating sources of gravitational waves to measure the universe, Constellation-X will use clusters of galaxies and growing structures to measure it, and the Dark Energy Probe may use supernovae or the deflections of light by growing structures as the measuring rods.

A theory describing something that is at once both very small and very massive — like the universe at the beginning of the Big Bang — has to include quantum mechanics and general relativity in one package. Many ideas of string theory and inflation models have been proposed, but only real data can tell us how nature actually works. Gravitational waves are the only signals that can escape the dense early universe to inform us directly about conditions at the earliest times.

Objective 1: Find out what powered the Big Bang.

Since ancient times, humans have sought to explain how the universe began. While a true scientific determination of our origins once seemed impossible, astounding recent discoveries have already started to a lead us to deep and mathematically rigorous understanding. Even more remarkable, we are not at a dead end; we know what measurements are needed to make further progress, and how to make them with the tools of space science.

In 1929 the great American astronomer Edwin Hubble made the surprising discovery that our universe is expanding. This discovery, and other abundant and compelling evidence, tied with Einstein's theory of space and time, now shows that our universe began in an unimaginably hot and dense condition and has been expanding and cooling ever since. This framework is known as the Big Bang theory. But what powered the Big Bang in the first place?

We are lucky to have an intact fossil of the beginning we can study directly: a faint glow of light left over from the Big Bang, which carries with it detailed evidence we can use to unravel the mysteries of our origins. This relic light from the earliest moments of the Big Bang, called the cosmic microwave background (CMB), has been traveling freely through space for over 13 billion years. Observations of the CMB reveal slight variations in the brightness of the otherwise remarkably smooth relic heat. These tiny deviations are thought to be direct imprints in the fabric of spacetime, dating to the moment of its creation.

They also mark congregations of matter and energy that have now grown into galaxies, stars, planets and life. Tracing the evolution of those small deviations into galaxies, stars and the complex living universe of today – driven first by the gravity of cosmic "dark matter", and later by the gas that eventually became stars, planets and life – is an exciting frontier of exploration addressed in the Pathways to Life Program.

We already have a definite model of how the Big Bang began. Many key facts can be explained if the universe started with a new form of energy whose gravity is repulsive. This "inflaton" field caused the infant universe to expand at a fantastic rate, made space large and nearly uniform, and gave the impetus to the expansion still seen among the galaxies. The inflaton energy then converted into the light energy, dark matter and atoms of the hot Big Bang that we see. This theory is called "inflation" because it describes a sudden dramatic growth of the infant universe.

The energy driving inflation had tiny imperfections due to the fact that all energy is quantized. As a result, during the dramatic cosmic inflation some parts of the universe got slightly bigger and faster than others. The effect of a single quantum fluctuation was inflated to an enormous size along with the universe itself. Sky maps of the CMB, such as from NASA's Cosmic Background Explorer (COBE) and WMAP missions, show a pattern of fluctuations very much like that predicted by inflation. They show the detailed ringing effect of primordial fluctuations resulting from the interaction of light and matter in the early universe – a "cosmic ultrasound" that images the infant universe. In much the same way that seismology on the Earth or the Sun reveals details of hidden composition and structure of those bodies, the primordial sound waves in light and matter visible on the sky reveal details of the composition of the universe as a whole, including the invisible dark matter.

As described below, cosmic evolution is studied in other very different ways, such as with supernova measurements of the cosmic expansion history, and three-dimensional maps of the galaxy distribution showing large scale structure of the cosmic web. One of the great scientific accomplishments of our time is that these experiments now all agree, with considerable precision, on a set of basic parameters describing the behavior of the universe on large scales: how old it is, how fast it is expanding, its composition (the amount of atoms and stars, dark matter and dark energy it contains), how close it is to being geometrically flat, and what kind of perturbations inflation left behind. This scientific accomplishment – the establishment of a precise ``concordance model'' of the universe – was recognized in 2003 by Science Magazine as the "Breakthrough of the Year," chosen over all fields of scientific study (as the discovery of the acceleration of the cosmic expansion was in 1998). The complete data set from WMAP, and the even more detailed maps to be made by the Planck Surveyor mission, will make our universe as a whole one of the most precisely measured of all physical systems.

While the Big Bang framework is well established, we are far from certain that the inflationary scenario is correct, or how it connects with new physics unifying gravity and quantum mechanics. Even if inflation is generally the right story, the details of the plot, and even the main characters, remain a mystery. We need new data to determine whether the early universe underwent a period of rapid inflation, and if so, to determine the mechanism responsible for driving it. Real data will teach us both about how the universe began, and about the new physics we need to understand it: the behavior and parameters governing new inflaton energy fields, and their relationship with the fundamental characteristics of space and time at the deepest level. That data will come from the Inflation Probe.

We already know a way to uncover these secrets. Calculations predict that in addition to tiny inflaton fluctuations already detected, inflation also generates gravitational waves. Since they originate as ``gravitons'' or quanta of spacetime itself, these waves deeply probe the new physics controlling the quantum beginnings of space and time. For this reason, detecting the signature of primordial gravitational radiation is one of the main strategic goals of Beyond Einstein. Primordial gravitons do not affect the formation of galaxies, but they do leave a subtle, distinctive pattern in the polarization of the light of the CMB that might be measured.

One candidate concept for an "Inflation Probe" is an ultrasensitive sky-mapping mission designed to discover this subtle pattern. The existence, strength, and details of the pattern will tell us whether inflation powered the Big Bang, and how it worked. It should tell us, for example, how fast the universe was expanding during inflation, and other details of the fields that controlled inflation. The data from WMAP is providing information about the levels and sources of contamination signals. Data from Planck, and from balloon polarization experiments, will help to refine these estimates. Thus, the tools are in hand to assess the feasibility and guide the design of an Einstein Inflation probe that uses the polarization of the microwave background to constrain the nature of inflation

While Inflation Probe may detect gravitational waves from inflation via their imprint on the CMB sky, LISA and the Big Bang Observer can directly detect many different kinds of cosmic backgrounds. Since gravitational waves are produced from motions of all kinds of mass and energy, and penetrate everything with almost no absorption, these experiments are a uniquely powerful exploration tool: they hear everything that has happened in the observable universe since inflation.

For example, it is possible that the early universe, after inflation but still in the first microsecond, has periods of roiling turbulence and chaos on small scales, perhaps associated with the formation of baryons during a phase transition, or with collapse of extra dimensions of space. These events generate high-frequency gravitational waves that would not affect the CMB (they are many orders of magnitude smaller wavelength), but may be strong enough to be detected by LISA in the millihertz band. If so, LISA will open a new window into a new episode of previously unknowable cosmic history.

Of course, such events, or other activity much later, may also create so much spacetime noise that it overwhelms fainter signals. Data from LISA, and its ground-based counterparts such as LIGO extending to higher frequencies, will directly measure the gravitational wave activity of the universe. This will help us evaluate the feasibility of the Big Bang Observer and guide its design. If the universe has been relatively quiet over much of its history at the relevant frequencies, its irreducible quanta of space-time – of the same kind as measured by Inflation Probe but at later stages of inflation – may be measured directly some day by the Big Bang Observer. Gravitational waves would then trace the origin of spacetime over eighteen orders of magnitude in length, spanning scales extending from the size of the observable universe right down to the size of our solar system.

It could be that the universe at all epochs is quiet enough to allow Big Bang Observer to make direct measurements of signals from as close to the beginning of time that we can ever, in principle, observe. This program carries human exploration to the most extreme science frontier that humans can currently imagine: a frontier that only NASA can explore.

Expected Achievements for Objective 1: Find out what powered the Big Bang.

In the 2005-2015 timeframe:

Assess astrophysical CMB foregrounds. The analysis of the complete WMAP dataset provides an understanding of astrophysical "foregrounds" sufficient to assess the feasibility of an Einstein Inflation probe that uses the polarization of the microwave background to constrain the nature of inflation. Results from the Planck Surveyor mission will add to that understanding with higher frequency studies.

Tighten constraints on inflationary models. Both WMAP and Planck Surveyor provide detailed images of fluctuations from inflation, revealing some details of the basic inflationary process.

In the 2015-2025 timeframe:

Detect gravitational waves. LISA reaches unprecedented levels of sensitivity for direct detection of gravitational waves. It may detect gravitational radiation generated around the first picosecond, when strong cosmic phase transitions are believed to have generated a slight excess of matter over antimatter in the Universe. (Later, all the antimatter disappeared after annihilating with matter, leaving behind this slight excess of matter, of which we and all the stars and galaxies are made.)

Observe the signature of gravitational waves from inflation. Informed by the WMAP polarization studies, the Inflation Probe finds correlations that indicate a unique signature of gravitational waves (tensor modes) from inflation. This data reveals details of which specific process powered the big bang.

In the 2025 and beyond timeframe:

Directly detect gravitational waves from inflation. The Big Bang Observer (BBO), building on LISA technologies, detects signals from all important sources of gravitational waves since the Big Bang, and directly detects gravitational waves from quantum effects during inflation. This data tests inflationary predictions at frequencies spanning 18 orders of magnitude and gives the first detailed spectral test of unified quantum gravity/string theory: BBO hears directly the beginning of time.

Objective 2: Observe how black holes manipulate space, time and matter.

Einstein's theory tells us that a black hole is made of pure gravitational energy. It tells us that a black hole should contain no actual surviving matter of the kind we are familiar with; anything whatsoever that falls into a black hole is quickly converted to pure gravity. The black hole should quickly radiate away as gravitational waves any bumps or mountains on its surface, leaving it smooth and simple, described only by a mass and a spin. Though we infer that the universe contains many black holes, we have yet to see one in detail. Einstein's general theory of relativity provides a mathematical picture of what one should be like: At a black hole's heart is a singularity, where space and time are infinitely curved and energy is infinitely concentrated. Surrounding the singularity is a region from which nothing can escape. The edge of this region is called the event horizon. There, time is so warped that it seems, from outside, to have stopped. How could we find out if such objects really exist, and if they do, behave in this weird way?

We could shake the black holes, and listen to the gravitational waves that Einstein's theory predicts should radiate away all the perturbations to the black hole. Fortunately we do not have to send astronauts to do the shaking: the giant black holes at the centers of galaxies are predicted to capture large numbers of stars and stellar mass black holes, and smaller numbers of their own relatives. As these orbit the giant black holes, they shake them and perturb their spacetime. LISA will observe the patterns of the resulting gravitational waves, and compare the wave patterns to those predicted, thus measuring precisely the properties of black hole and spacetime around it.

A second way to study black holes is to map the motions of clocks orbiting and falling into black holes. Again, nature provides a way to do this. We can observe the radiation from atoms of gas that falls into black holes. The frequency of the light they emit is like the ticks of a clock. Changes in that frequency are caused by the motion of the gas—the familiar "Doppler effect" change in tone you hear as an ambulance races past—and by the gravitational redshift due to spacetime curvature. Because the matter near the black hole is so hot, the atoms emit mainly X-rays. Constellation-X will measure the changes in brightness and frequency of these atoms as they orbit the black hole. Watching the spectra of these flows can reveal many details of how accretion of matter occurs, and the spacetime environment in which it orbits. If the things we call black holes are not actually the black holes of relativity, we may be so mystified by the results of LISA and Constellation-X that orbits and spectra alone may not be enough to understand them. In other cases the motions observed by Constellation-X may be so complicated (due to shock waves, ejected jets, instabilities) that more information is needed. The vision mission Black Hole Imager will address these problems by directly imaging the moving matter and its inward radial motion right down to the edge of the event horizon.

In addition to understanding the fundamental nature of black holes, and whether they exist as described by Einstein's theory, we would like to understand how they are made, how numerous they are, where they are located, how they grow, what properties they have, and how the matter and radiation they eject affect their host galaxies and their surrounding environment.

Black holes grow in two ways. One way black holes grow is by merging with each other. As two black holes approach each other, the two spacetime vortices spiral together faster and closer until they form just one rapidly spinning and pulsating hole, in the process broadcasting much of their mass into distant space as gravitational radiation. These events — the most powerful transformations of energy allowed by the laws of physics — can only be studied by their gravitational radiation, requiring the revolutionary capability of LISA.

The other way black holes grow is by swallowing gas. Matter falls into black holes in many ways. Whole stars can fall in, ripping apart as they approach. Streams of infalling gas can form bright hot torrents or delicate cool rivulets; sometimes, hot matter is splashed back out into space, or spewed at almost the speed of light in jets powered by the black hole's spin and magnetism. X-rays, such as those studied by Constellation-X, generally provide the best way to measure the motions of gas near black holes. Sometimes there is so much obscuring matter that even X-rays cannot get out, which is why the Black Hole Finder Probe observes in the more penetrating gamma-ray band.

The Beyond Einstein program will systematically explore this spectacular interplay of matter and gravity. The Black Hole Finder Probe will survey the universe seeking radiation from matter falling into black holes and mapping their locations; Constellation-X will study the spectrum of light coming from atoms as they fall in, collecting clues to the structure of spacetime in the neighborhood of the horizon; and in the distant future, the Black Hole Imager will create moving images of the swirling matter right down to the edge of the event horizon. The many forms of energy ejection from these events can even affect the evolution of a whole galaxy, including the formation of stars, planets, and life; these effects will be explored by GLAST, Constellation-X, and the Pathways to Life Observatories.

Expected Achievements for Objective 2: Observe how black holes manipulate space, time and matter.

In the 2005-2015 timeframe:

Observe the acceleration processes of relativistic jets emerging from black holes. Many black holes accreting matter spew some of it out in vast jets moving at relativistic speed. These affect the environment and the properties of the host galaxies, but we do not know how the jets are formed, nor even what they are made of. GLAST will measure the radiation from regions near the black hole where these jets are formed and accelerated.

Observe the merging and growth of the first black holes to form in the universe. The cosmological models that best describe current data predict that the first stars and black holes formed at a redshift of about 20, when the universe was about 100 million years old. The farthest we can now see black holes is to a redshift of about 6, when the universe was about 600 million years old, and by then they have already grown to enormous size. JWST will see the first black holes growing by swallowing gas in the intervening period. LISA will be lunched in this time frame; it will detect mergers between these first black holes at redshifts of 6-30 as their host galaxies coalesce into larger galaxies, and measure the properties of the black holes.

In the 2015-2025 timeframe:

Determine if the dense objects at the centers of galaxies, which we call "black holes," are truly the black holes predicted by Einstein's general relativity. LISA will measure the gravitational waves from stars and black holes shaking the spacetimes of the "black holes" they orbit. These waves encode a complete description of the spacetime and horizon properties. Comparing these properties measured by LISA with those predicted by Einstein's theory of relativity will tell us if these objects are the "black holes" of relativity.

Determine the precise masses and spins of a large sample of nearby galactic black holes. If the "black holes" at the centers of galaxies are the black holes of Einstein's general theory of relativity, all the properties measured by LISA for a given black hole will be determined by just two numbers: its mass and spin. LISA should measure these for about 100 supermassive black holes at redshifts greater than 0.2, using the gravitational waves from stars and stellar-mass black holes orbiting them.

Determine the spin and mass of black holes over a range of redshifts to constrain how black holes evolve. If the motions of the atoms observed by Constellation-X can be well modeled, we can infer from them the masses and spins of the black holes themselves, and do so for black holes in a wide variety of environments and redshift.

Measure the motions of matter orbiting close to black hole event horizons. Constellation-X will measure, through time-resolved spectroscopy, the speeds and changing brightness of iron and other atoms spiraling into black holes in galactic nuclei, from which we can infer how fast the black holes are growing, how they are ejecting matter and radiation, and perhaps also the mass and spins of the black holes themselves.

Determine how black holes grow by accretion in the local universe. There is evidence that a large fraction of the growth of black holes occurs while they are hidden behind dense clouds of gas and dust, and behind the glare of vast numbers of young stars. The Black Hole Finder probe will reveal these currently hidden black holes, and quantify their importance.

In the 2025 and beyond timeframe:

Directly image matter falling into a black hole. The Black Hole Imager will have the resolution to actually make a picture of the matter falling into the black holes identified by Constellation-X and the Black Hole Finder Probe. It will show us exactly where it is and what it is doing, and how fast it is moving at each point. This will enable us to investigate the nature of the black holes, the mechanisms of energy release in accretion disks, and the formation of jets.

Determine the cosmic history of formation of stellar-mass black holes. The Big Bang Observer will observe the mergers of tens to hundreds of thousands of intermediate mass (100-10,000 times the mass of the sun) and stellar-mass black holes (1-100 times the mass of the sun), and neutron stars, from redshifts of 0 to 5 and beyond.

Objective 3: Uncover the nature of the mysterious dark energy pulling the universe apart.

Deep as Einstein's general theory of relativity may be, it remains silent on a profound question: Is empty space really empty? Inflation models predict that it was not so in the past, and suggest that it may not be so today either. Einstein introduced a "cosmological constant" into his equations, to represent the possibility that even empty space has energy and couples to gravity. The unknown magnitude of the cosmological constant is set by parts of physics beyond Einstein's understanding – and, at present, our own. The recent discovery that the expansion of the universe appears to be accelerating suggests the presence of something dubbed "dark energy" that drives space apart. It seems likely that we have measured the value of a cosmological constant, or something like it.

The presence of dark energy is already widely accepted because it explains many observations. The first indication that the rate of expansion of the universe is increasing was revealed by observations of Type Ia supernovae and was confirmed in detail by WMAP. Supporting evidence for the increasing rate of expansion also comes from studies of global geometry, structure formation, cosmic age, galaxy clustering, and X-ray emitting galaxy clusters. All these observations leave little doubt that in some sense Einstein's "cosmological constant" is a reality: the energy of the universe is dominated by "empty" space whose gravitational effect is to pull the universe apart.

Given the crude state of our preliminary data on dark energy, a wealth of potential theories have been suggested which have very different implications for physics and for the future of the universe. Further more accurate measurements are essential for distinguishing this plethora of possibilities. Anything new we learn about dark energy would be an unexpected discovery. A simplistic unification of quantum mechanics and gravity predicts an amount of dark energy larger than that observed by a factor of 10^{120}. Some modern scenarios predict that the amount of dark energy decreases with time, instead of staying constant as in Einstein's conception. For these reasons dark energy is among the most exciting new developments in fundamental physics. *Because dark energy seems to control the expansion of the universe, we cannot predict the fate of the* *universe without understanding the physical nature of dark energy*. As we develop this understanding, we will be poised to answer the profound question: will the universe last forever?

We estimate that our universe today consists of about four percent ordinary matter, made of the familiar elements from the periodic table (in the form of stars, planets, gas, and dust); twenty-six percent “nonbaryonic dark matter”, thought to be a new kind of particle left over from the early universe; and seventy percent dark energy (which can be considered to have mass, too, because energy $E = mc^2$). To learn how dark energy really works, we need to measure its properties in more detail. It is spread so thin that it can only be studied in the enormous volumes of deepest space, where its cumulative effects make its presence evident. The first step in the exploration of dark energy will be to measure its density and pressure and how they change with time.

Initial and on-going observations from ground-based observatories and from the Hubble Space Telescope (HST) point the way toward a dedicated, special-purpose instrument that could provide much more accurate constraints on the expansion history of the universe. Such measurements could determine whether the dark energy is really constant, as Einstein conjectured, or whether it evolves over cosmic time, as suggested by some more modern theories. Real data on that question would help us discover where dark energy comes from, and what the future of our universe will be.

The Dark Energy Probe, which will be executed jointly with the Department of Energy as the Joint Dark Energy Mission (JDEM), will deploy the best available technology to study this effect. But other constraints will come from Constellation-X, LISA, Planck and the Inflation Probe. Constellation-X will make precision measurements of the matter and dark matter content of clusters of galaxies and constrain their abundance with cosmic time. These data can be used to determine distance/redshift relations and to chart the growth of structure in the universe, which depends on its expansion history. LISA, and later the Big Bang Observer with a much larger sample, will measure the rates at which binary black holes spiral together, because they lose energy to gravitational waves (i.e. it measures directly the wattage of the `wavebulb'). It also measures the amplitudes of those same gravitational waves. The ratio directly gives precise distances to the inspiralling binaries, from which one can measure the effect of dark energy on the expansion history of the universe. Planck and the Inflation Probe will refine our measurements of fluctuations in the CMB and the precision determination of the cosmological parameters.

Given the importance of this problem, it is essential that we invoke this wide variety of techniques to ensure that our inferences about the properties of dark energy are free from systematic uncertainties associated with specific measurements. On a longer timescale, the nature of future missions studying dark energy will depend on what we learn from these earlier experiments.

Expected Achievements for Objective 3: Uncover the nature of the mysterious dark energy pulling the universe apart.

In the 2005-2015 timeframe:

Measure cosmological parameters. The continued analysis of the WMAP dataset and the first analyses of the datasets acquired by Planck will yield improvements in the precision determinations of the global cosmological parameters like the global curvature, the Hubble constant, and the fractions of the energy density due to baryons, dark matter, and dark energy. Measurements of dark energy require knowing these parameters.

Constrain the nature of dark energy. Measurements with Chandra and XMM-Newton will benchmark the use of massive clusters of galaxies for cosmology. HST and ground-based observatories will increase our sampling of Type 1a supernovae, further refining our measurements of the acceleration of the cosmic expansion.

In the 2015-2025 timeframe:

Determine the cosmic evolution of dark energy. The launches of Con-X, LISA, and JDEM will allow a large number of complementary measurements of the dark energy equation of state. These will be cross-compared to improve precision and to search for possible systematic effects that could bias the results. Con-X will enable a large sample of massive clusters to be analyzed in detail, yielding accurate measurements of their number density as a function of redshift as well as the apparent variation of their baryon to dark matter content as a function of redshift. LISA will enable precision absolute luminosity-distance measurements to cosmologically distant black holes. Although the design of the JDEM mission has not been finalized, one possibility is that it involves a capability to acquire a large sample of well-calibrated Type 1a supernovae out to redshifts of about 1.5. Such a large data sample will test the use of these sources as calibratable standard candles and enable a precision measurement of the cosmic expansion. All dark energy measurement techniques (including supernovae, baryon acoustic oscillations, cluster counting, weak lensing, and galaxy correlations) will be extensively pursued by ground-based measurements as well.

In the 2025 and beyond timeframe:

Constrain the geometry and kinematics of the universe. The Big Bang Observer will measure precise absolute distances to over one million cosmological binaries containing neutron stars and black holes, simultaneously constraining both the geometry and kinematics of the universe.

Structure and Evolution of the Universe: Pathways to Life

The "Beyond Einstein" missions are designed to determine the initial conditions for the large-scale structure of the universe. They will also test the fundamental physics of Einstein's theories of gravity, and the exotic new ideas of cosmic inflation. From these fundamental starting points, astronomers can progress to a deeper understanding of how the modern universe develops the complex and rich structures we see today — clusters, galaxies, stars, and planets, at least one of which has produced life.

The early universe began as a nearly perfectly smooth ocean of matter and radiation, and has since developed into our complex modern universe, with clusters, galaxies, stars, and planets. Somehow the tiny primordial wrinkles grew into the structures and roiling activity that we observe today: a "cosmic web" of dark and ordinary matter, punctuated by galaxies and clusters, energized by successive generations of stars, supernovae, black holes, and quasars, and enriched by heavy chemical elements necessary for the formation of planets and life. How did the simple Big Bang develop such a rich structure?

The first stages of the structure formation in the cosmos were dominated by just one force, gravity. The gravitational pull of invisible cold dark matter (CDM) collected matter and atoms together, reversing the expansion in places and creating a cosmic web of clustered matter, distributed in knots connected by filamentary clouds. Atoms falling into the knots of this web produced the first stars and galaxies. The accompanying formation of stars and black holes transformed matter and released energy in many forms, creating a complex system structured by many interrelated components spanning a great range of scales. One byproduct of special importance to us was the synthesis inside stars of many elements of the periodic table not present in the simple Big Bang; those heavy atoms coalesced into earthlike planets, and were able to chemically combine in reactions that eventually gave rise to life. These processes have taken billions of years, much of it observable in the last 11-12 billion years. This critical epoch in the history of the modern universe is observable through optical, ultraviolet, and X-ray telescopes.

Objective 4: Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

The Pathways to Life program explores the interconnected evolution of systems on many scales: gas and galaxies (and their nuclei), stars and planets, atoms and molecules, from the pregalactic era to the present time. By looking deep into space, we can see back in time and study this cosmic evolution directly; we can also study modern fossils of past events. Because these systems cover a large dynamic range in many physical parameters, a comprehensive view of the transformation and flows of matter and energy demands high-resolution imagers and spectrometers on large telescopes extending from submillimeter to ultraviolet, X-ray and gamma-ray bands. For example, NASA is now building the James Webb Space Telescope (JWST), focusing on early stars in the first galaxies. The ultraviolet and optical radiation from these early stars is redshifted to near-infrared JWST wavelengths. However, comprehensive studies of stars extending from high redshift to the present will require access to large-aperture telescopes in the optical and ultraviolet; penetrating into their obscured star/planet formation regions requires far-infrared and sub-millimeter; and probing nuclear activity requires X and gamma rays. Access to the whole range of wavebands will bring detailed information about the entire cosmic ecosystem of matter, as it evolves from the relatively calm filaments of diffuse gas in the cosmic web and then cycles into galaxies, stars, planets, molecules and life. These deep, multi-band observations can only be carried out from space.

There are many unanswered questions about the complex pathways from the early universe to the present-day stars, planets, and life. For example, how did successive generations of stars and black holes form and coevolve with galaxies? What determines the mass distributions of stars and galaxies, how are they assembled, and how did they evolve with time? Why is cosmic star formation inherently episodic? What role is played by the vast reservoirs of matter in intergalactic space, and how is its distribution affected by the first stars, quasars, and chemical elements? In the local universe and within our own Milky Way galaxy, how does chemical enrichment affect the development of stars and planets? How do the radiation and magnetic activity of young stars impact the environment of newly forming stars, planets, and life?

Because of the great reach in scales and diversity of phenomena, it is natural to break down objective 4 into three key components, described in the following sections. Carrying out these investigations requires an implementation approach that is equally broad, involving competed probes and strategic missions called **Pathways to Life Observatories.** They will explore the history of star formation, both the visible stars at redshifts greater than 3 and those obscured by dust. They will chart the assembly and growth of galaxies and large black holes and gauge the impact these objects have on their host galaxies and surrounding gas. The Pathways to Life Observatories will allow astronomers to connect the observations of the early universe and first objects down to the present — a roadmap that leads from the Big Bang to the "Emergence of the Modern Universe".

The Pathways to Life Observatories encompass several possible approaches:

- A Far Infrared/ Submillimeter Interferometer (FIRSI), of which SPECS is an example
- A Large UV/Optical Telescope (LUVO)
- A UV/Optical Interferometer (UVOI), of which Stellar Imager is an example
- A large area, high spatial resolution X-Ray Observatory generically titled “Early Universe X-ray Observer” (EUXO), of which Gen-X is an example
- An advanced Compton gamma-ray telescope generically titled “Nuclear Astrophysics Compton Telescope” (NACT), of which ACT is an example
- The Single Aperture Far-Infrared Telescope (SAFIR)

Key Components of Objective 4:

4A. Map directly the structure and evolution of the Cosmic Web.

The CDM model, which succeeds very well in connecting inflationary cosmology with the modern distribution of galaxies, also makes predictions for the distribution of dark matter and atoms, or baryons, in the evolving universe as a function of time. Some baryons eventually form stars and other compact objects, but most of them are distributed on the largest scales in a cosmic web of diffuse filamentary clouds that grows steadily hotter and larger with time. The formation of the cosmic baryon web is the first step in the conversion from simple expanding behavior to rich and intricate complexity. Theorists have guessed at its structure, but only parts of it have as yet been detected directly.

Computer simulations predict that intergalactic matter is distributed over a range of different temperatures: warm photoionized gas (10^4 K), warm/hot shocked gas (10^5 - 10^7K), and much hotter gas ($T > 10^7$ K), the latter mostly associated with clusters of galaxies at the knots of the cosmic web. The warm and hot gas has stripped its atoms of most electrons, so those that remain bound have transitions visible only at high energies. In dense places, the hot phase is sometimes visible in X-ray emission; its composition and other properties will be studied in great detail with Constellation-X. Until recently, the warm/hot phase, containing most of the atoms in the universe, has been practically invisible, but is now starting to be observed through absorption lines in far ultraviolet and soft X-rays. The UV absorption lines are much more sensitive than their X-ray counterparts; however, only the X-ray features can probe the hottest gas at temperatures over a million degrees.

Theory tells us that the warm/hot medium is produced by shocks as gas falls into dark matter filaments. The medium is also affected by outflows: heavy elements are expelled from galaxies by winds and jets, whose shocks also contribute to the heating. To study this gas and the rich details of its behavior and composition, and its relationship to the surrounding environment of galaxies, we need large-aperture telescopes to deliver spectra of background quasars. These studies will determine the physical conditions and evolution of the intergalactic absorbers, and dissect galactic halos and outflows from galaxies. Both LUVO and EUXO will be needed to observe the faint quasars behind these structures.

4B. Map the flows of energy and matter between whole systems and their constituent parts, from galaxies to stars to planets.

Once stars form, energy feedback connects small systems with the larger ones they inhabit: galaxies and quasars energize the intergalactic gas, and stars energize the gaseous environment within galaxies. Outflows of radiation and matter from stars and black holes have powerful influences on subsequent generations of stars, and outflows from galaxies shape larger-scale structures. Energy flows, mediated by gas motions, magnetic fields, cosmic rays, and light, add to gravity to influence the formation of stars and galaxies and control the production of energy, radiation, and chemical elements. All of these processes create the cosmic weather systems that structure the living baryonic universe. Like weather on Earth, they display “butterfly effects”, where a tiny influence in one place can lead to huge effects, often millions of light years away. Since they directly connect phenomena spanning more than ten orders of magnitude in length, they can, like the atmosphere and oceans of our planet, only be understood by synthesizing results from a wide range of techniques. Studying the cosmic history of star formation and the role of feedback on the formation of stars and galaxies will require exquisite imagers at many wavebands (JWST, LUVO, SAFIR, EUXO), as well as powerful spectrographs (JWST, Con-X, LUVO, EUXO) to connect the transport of matter and energy with the larger-scale galactic and intergalactic environments.

Because stars are so important for cosmic transformations of matter and energy, a central strategy is to make observations of star formation everywhere: in nearby galaxies, over time in the past, and in diverse environments. This can be accomplished with high-resolution, sensitive imagers and spectrographs (JWST, LUVO, Con-X, SAFIR, FIRSI), from X-ray to far-infrared bands, that can probe dense and complicated star-forming regions containing both high-energy sources and cold molecular gas. Sensitive observations all the way to the sub-millimeter band will explore the substantial amount (perhaps half) of star formation that occurs in extremely dust-enshrouded environments. Even within our local neighborhood, normal galaxies reveal a bewildering variety of star formation and chemical enrichment histories. They can be addressed empirically by observations of a large sample of galactic populations in the full range of evolutionary states. To reconstruct the evolution of star formation, chemical abundances, and dynamics for a large sample of galaxies requires a large-aperture optical and ultraviolet telescope (LUVO).

Many stars are born in associations near massive stars, which rapidly erode the dusty molecular clouds that shroud the earliest phases of star birth. When shrouded, these regions are best penetrated by far infrared and sub-millimeter radiation. However, less than a million years after birth, the majority of young stars and their protoplanetary disks become accessible to high-resolution studies at optical wavelengths, allowing an investigation of early phases of planet formation, cluster evolution, and stellar youth. Infrared studies with JWST and SAFIR probe the earliest, dusty phases, while optical/UV observations with LUVO provide the combination of sensitivity and high spectral resolution necessary to deconstruct these objects. Through high-precision radial velocity studies of the fainter stars, astronomers will soon discover a vastly increased population of extrasolar planets. This population will improve statistical analysis of planetary and host-star characteristics, in the context of the many environments within the Galaxy, as well as their chemical history. This will give us much better idea of the possibilities for life in the universe as a whole.

Cosmic influences from outside the solar system extend right down to life on Earth. Galactic tides trigger comet storms that may cause extinction events; massive black holes can create hostile, sterilizing radiation reaching across an entire galaxy. Planetary atmospheres, including Earth's, are profoundly influenced by effects of high-energy radiation (UV, X-ray and paarticles) upon atmospheric photochemistry and photoionization. With the advent of space observatories, it has become clear that the ionizing radiation output of even normal, solar-like stars decreases by orders of magnitude over their lifetimes. As a result, the effects of stellar variations on climate are of great significance to the emergence and evolution of life forms on Earth-like planets. The details are still lacking, especially a comprehensive picture of magnetic evolution in stars. Observations of stellar magnetic activity with Con-X, LUVO, EUXO and UVOI will lead to an improved understanding of these phenomena and how they influence biological evolution in the nascent Earth and extrasolar planets.

4C. Trace the evolution of the nuclei, atoms, and molecules that become life.

In addition to energy flows, nuclear matter itself is transformed by stars into new elements, and then recycled into the interstellar and intergalactic gas. Galaxies and quasars in turn expel their interstellar gas, chemically enriching pristine intergalactic space with heavy nuclei. This enrichment with a variety of chemically active elements creates dust and molecules that strongly affect the cooling and collapse of gas into new stars, control the formation of planets, and ultimately form the basis of life.

The global natural history of nuclei will be traced on many levels. The production sites of heavy elements, hot young stars and supernovae, and their surrounding emission nebulae, as well as the acceleration sites of nuclei into cosmic rays, can be studied via X-rays and gamma rays (Con-X, GLAST, NACT, EUXO). Similar techniques can follow these chemical elements as they are transported into the interstellar medium and widely spread throughout our Galaxy and others. On the grandest stage of all, the flows of material from various types of galaxies out into the IGM and back into galaxies will be visible to a wide range of instruments, including UV and X-ray spectrographs (LUVO, Con-X, EUXO), probing interstellar and intergalactic gas via absorption of light from background sources. They will be diverse enough to capture a broad set of elements and ionization stages to provide nucleosynthetic signatures of the stellar sources, and sensitive enough to provide a densely sampled spatial and velocity map. Experiments will eventually comprehensively map chemical composition throughout galaxies, up into galactic halos, and out into the IGM. At the other extreme, as atoms combine with each other in cold and dense molecular phases, they become visible in the infrared to submillimeter bands, and start to reveal the development of the molecular complexity that presages true living molecules.

Expected Achievements for Objective 4: Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

In the 2005-2015 timeframe:

Determine the early history of stars and their environment. HST, Chandra, Spitzer, SOFIA, and JWST will provide comprehensive infrared through X-ray imaging and spectroscopy of protostars and their disks. This will allow us to develop a cohesive picture of stellar birth and youth, thus setting the stage for planetary formation.

Characterize evolution of surface activity of solar-type stars. HST and Chandra high resolution spectroscopy in the UV and X-ray will provide a survey of the ionizing radiation output and variability of aging solar-type stars. This will lead to a much better understanding of how the time history of such radiation influences biological evolution on the Earth and extrasolar planets.

Detect the hot intergalactic medium. Chandra and HST will provide early detection of the hot phase of the intergalactic medium. This will improve current models that predict that intergalactic matter exists at a range of different temperatures, including temperatures > 10 million degrees.

In the 2015-2025 timeframe:

Observe the formation of the first generation of stars. JWST will provide infrared imaging and spectroscopy that will allow studies of the history of star formation at high redshift. This information, combined with current UV measurements of start formation rates will provide an improved understanding of the evolution of star formation.

Confirm dispersion of heavy elements in the IGM. Constellation-X will build on the early results from Chandra and HST to measure the properties and composition of the hot intergalactic matter, providing the extent of dispersion of heavy elements in the IGM.

In the 2025 and beyond timeframe:

Map the missing baryons in the IGM. Some of the concepts for the Pathways to Life Observatories will be able to study the composition of the IGM through high energy spectroscopy of the radiation from background quasars.

Study the cosmic transformation of matter and energy. Star formation is key to the distribution of matter and energy in the Universe. The Pathways to Life Observatories will provide observations from X-ray to submillimeter, allowing the study of star formation in dense regions containing both high energy sources and cold molecular gas.

Trace the evolution of the nuclei, atoms, and molecules that become life. The Pathways to Life Observatories will provide imaging and spectroscopy in the infrared and sub-millimeter part of the spectrum, allowing the study of those spectral features that indicate the molecular complexity associated with life.

Universe Exploration Targeted Research and Analysis Needs

Without Research and Analysis (R&A) programs there would be no space science missions. R&A programs support the ground-breaking technology developments needed to enhance our ability to observe the universe, leading to new mission concepts. R&A programs support the analysis of mission data from which all discoveries are made. R&A programs support theoretical work that both explains what we see and predicts what we have yet to see; theory establishes the framework within which we understand the phenomena that we observe. R&A programs also support additional research needed for the success of space missions, such as laboratory measurements of physical parameters that must be known for space experiments (an example being the detailed X-ray spectra of iron-group isotopes). R&A programs, although costing a small fraction of the funds going to space missions, are an essential component of this roadmap.

Theory

Theoretical studies — here taken to include conceptual and analytical theory, development of software technologies supporting data exploration, astrophysical simulations, and combinations of these — were recognized by the National Academy's AASC decadal report as a central component of modern mission technology development. That survey recommended that supporting theory be explicitly funded as part of each mission funding line, because detailed modeling connecting the elements of a mission to the system under investigation is critical to design and even to conceive successful and cost-effective missions. Rigorous modeling is an important factor in reducing mission risk and evaluating competing mission strategies, and simulations can vividly demonstrate mission goals.

Beyond Einstein Theory Needs

Beyond Einstein explores to the boundaries of foundational knowledge as well as the boundaries of spacetime, so detailed and quantitative theoretical studies are indispensable, starting with the earliest design phases. To this end the Beyond Einstein Foundation Science (BEFS) program has been created to provide ancillary theoretical (and experimental) support for NASA's Beyond Einstein missions. In accordance with the AASC decadal report, a significant fraction of Beyond Einstein line funds are used for the BEFS program. Examples of the theoretical studies required by Beyond Einstein missions that are now being supported include:

• *Constellation-X*. Models of relativistic hydrodynamic flows in accretion disks, including radiative transfer models, leading to simulated, time-dependent spectra.

• *LISA*. Studies and simulations of signal extraction in the presence of multiple, overlapping signals; numerical relativity, aimed at accurate calculation of predicted gravitational waveforms for the whole range of merging and orbiting systems;

astrophysical modeling and simulations to connect binary population predictions with other data sets.

• *Inflation Probe*. Theoretical studies of early universe cosmology, including tensor and scalar mode predictions and their connection with fundamental theory; simulations of polarization effects, including the contamination effects of astrophysical foregrounds and gravitational lensing; development of optimal statistical signal extraction techniques.

• *Dark Energy Probe.* Theoretical studies of Type Ia supernovae and other candidate systems for calibrating cosmic distances, including realistic simulations of competing techniques for constraining dark energy models, with a view toward the development of a better understanding of the principal sources of systematic error and contamination in each case. This work will benefit greatly from an expanded program of precursory ground-based observations.

• *Big Bang Observer*. Early universe cosmology and phenomenology of quantum gravity, string theory, and brane world models; models of coalescing white dwarf and neutron star binaries and populations in the 0.1 to 1 Hz range.

• *Black Hole Imager*. Comprehensive simulation of black hole environments, including electromagnetic field interactions with flows and the spacetime metric, and radiative transfer over many decades of dynamic range.

Pathways to Life Theory Needs

The Pathways to Life Observatories encompass several approaches, and the associated objective is both challenging and broad. The theory areas defined below represent a portion of the theory challenges for the Pathways to Life Program:

• *JWST*. Calculations of the formation of the first stars; multi-dimensional magneto/radiation/hydrodynamical simulation of the formation, evolution, and spectra of stars and protostellar disks; models of the magnetic interstellar medium and the origin of the initial mass function of stars; studies of reionization; simulations of galaxy formation, large-scale structure, and Lyman-alpha clouds; models of the chemical and "metallicity" evolution of the universe and the history of star formation; studies of the formation of planetary systems; models of the zodiacal dust around nearby stars; MHD simulations of bipolar outflows.

• *Spitzer*, *SOFIA*, *SAFIR*. Simulations of particle and gas disks around protostars; chemical models of molecular clouds and protostellar disks; detailed spectral, kinetic, evolutionary, and growth models of debris disks; models of chondrule and planetesimal growth; spectral models of protoplanetary disks and brown dwarfs; studies of what distinguishes a giant planet from a brown dwarf; models of ultra-luminous infrared galaxies; studies of the formation of the Kuiper belt and Oort cloud; studies of star formation at high redshifts; models of chemical enrichment at the earliest epochs; simulations of the assembly of rocky planets from debris disks; models of the spectra of high-z and dust-enshrouded galaxies; calculations of the fine structure lines of molecules in protostellar and protoplanetary nebulae; spectral models of the molecular tracers of the multi-dimensional collapse of molecular cloud cores to stars; simulations of bipolar outflows from protostars.

• *Large UV/Optical Mission, EUXO.* Models of the IGM on small scales; high-precision calculations of big-bang nucleosynthesis, in particluar the D/H ratio; detailed models of AGN and AGN disks; models of star formation at high redshift and in various galaxy types; models of the role of supernovae and winds in galaxy formation; simulations of absorption features through the early warm- and hot-ISM/IGM; studies of the early structures of the universe and galaxy-galaxy interactions; simulations of the possible roles of supermassive black holes in galaxy formation and evolution.

Supporting Ground-Based Research and Analysis

Universe Exploration missions also require specialized supporting ground-based programs. As in the case of theory, these studies should start early in the program since they will influence the optimization of the mission design parameters. In the case of the Einstein Probes, a broad effort is needed since even the mission concept will be competed. Here, again, the BEFS program supports a modest experimental effort.

The Inflation Probe, if it is based on microwave background anisotropy polarization, will require new generations of polarization-sensitive detectors, excellent control of systematic effects and a thorough understanding of astrophysical foregrounds. Ground-based Cosmic Microwave Background polarization experiments will be essential preparation for this candidate Inflation Probe, both for testing of new technology, investigation of observing strategies and systematics, and for providing data to test new analysis techniques. (These needs are laid out in detail in the soon-to-be-released Report of the Task Force for Cosmic Microwave Background Research, which will act as the CMB technology roadmap document for the foreseeable future.) Detector technology for COBE, MAP and Planck was a direct product of ground-based and sub-orbital programs. In the same way, a strong ground-based program is an essential precursor to the Inflation Probe.

Whatever technique is adopted, the Dark Energy Probe will require ground-based data of unusual uniformity, quality and completeness. If Type Ia supernovae are employed, space studies must be supported by detailed and precise ground-based spectra and photometry of a large, uniformly selected sample of relatively nearby supernovae. This is required both as a calibrating set for the high-redshift Hubble diagram, and as a statistical control sample to study the systematic correlations of supernova properties--- the generalization of the one-parameter fits to light curve shape currently being used. Similar foundational studies are needed for other candidate techniques for the Dark Energy Probe. Programs supporting ground-based studies of this type are already underway with funding from the National Science Foundation.

Mission Priorities

The highest priority missions are the Beyond Einstein Great Observatories LISA and Constellation-X. These were both highly ranked by the National Academy of Sciences Decadal Survey and their science has also been highly ranked in several other reports. The science questions these missions address will provide crucial information necessary to make key decisions by the middle of phase 2, in order to prioritize and begin the Visions Missions at the start of phase 3. The next priority is the competed line of Probes to address focused science questions, central to the Beyond Einstein program. These competed missions will begin with the Joint Dark Energy Mission, and then continue at 3 to 4 yr intervals with the Black Hole Finder Probe and the Inflation Probe (with the mission order determined by technology readiness).

Mission Summary for Universe Exploration

Strategic Observatories providing breakthrough capabilities

- GLAST (Phase 1): Jets from black holes and dark matter decay signatures
- Pathways to Life: JWST (Phase 1): First galaxies and stars
- Beyond Einstein: LISA (Phase 1): Gravitational waves from many sources, how space and time behave around black holes and constrain dark energy
- Beyond Einstein: Constellation-X (Phase 2): Observe matter falling into black holes & address the mysteries of dark matter and dark energy

Competed Missions that address focused science questions through scientist-led investigations with a range of sizes, up to a strict cost cap of $600M

- Explorers: Missions linked to Universe Exploration strategic goals (all phases)
- Einstein Probe: Joint Dark Energy Mission (JDEM) (first prioritized probe) (Phase 2)
- Einstein Probe: Black Hole Finder Probe (BHFP) (Phase 2)
- Einstein Probe: Inflation Probe (IP) (Phase 2)
- Pathways to Life (Probe): What is the nature of the Cosmic Web?

Vision Missions that result from long term objectives (late Phase 2, Phase 3)

- Beyond Einstein: Big Bang Observer (BBO)
- Beyond Einstein: Black Hole Imager (BHI)
- Pathways to Life Observatories

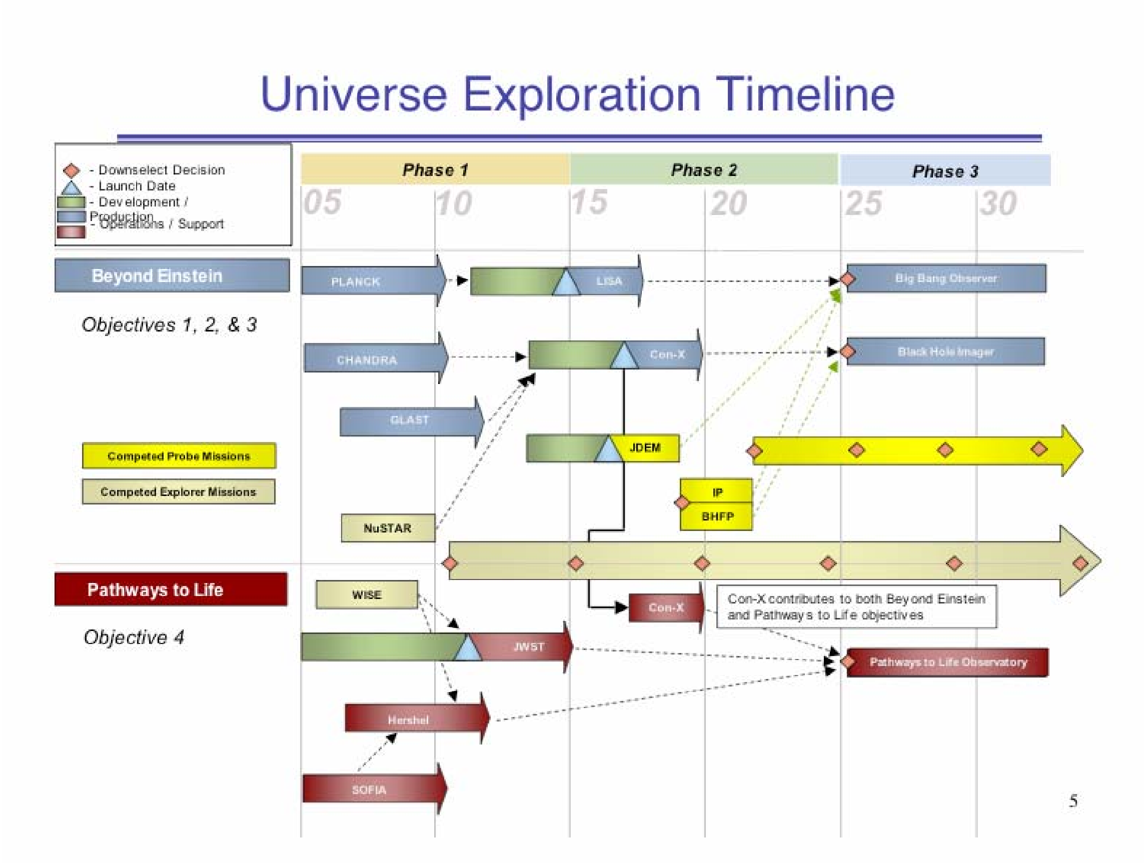

Figure 1 Roadmap timeline for Universe Exploration.

4. **Milestones and Options, with decision points and criteria**

OBJECTIVE 1: Find out what powered the Big Bang.

LISA, and its ground-based counterparts at higher frequencies such as LIGO, will for the first time measure directly the gravitational wave activity of the universe. We anticipate surprises. For example, LISA might unexpectedly detect a cosmic gravitational wave background originating from the early moments of the Big Bang. These first observations of the gravitational wave sky, combined with results from Planck and the Inflation Probe, will provide information on the priority of the Big Bang Observer and guide its final design.

OBJECTIVE 2: Observe how black holes manipulate space, time and matter.

If the things we call black holes are not actually the black holes of relativity, we may be so mystified by the results of LISA and Constellation-X that orbits and spectra alone may not be enough to understand them. In other cases the motions observed by Constellation-X may be so complicated (due to shock waves, ejected jets, instabilities) that more information is needed. These observations may point to fundamental flaws with General Relativity that change the priority of the next phase missions such that a direct image of a

Black Hole becomes the highest priority. The vision mission Black Hole Imager will address these problems by directly imaging the moving matter and its radial motion right down to the edge of the event horizon.

OBJECTIVE 3: Uncover the nature of the mysterious dark energy pulling the universe apart.

The combination of Constellation-X, LISA and the Joint Dark Energy Mission (JDEM) provide independent measurements of the acceleration of the universe. The most exciting result would be if the different techniques disagree. This would point to a fundamental problem with our view of the universe and would require a major reassessment of the priorities for the missions that follow in phase 3.

OBJECTIVE 4: Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

The creation of the conditions for life to emerge on the Earth is the result of a combination of events that start with the formation of the first elements, and ends with the emergence of the first life forms. The exact sequence of events and the ingredients necessary to produce a "Planet Earth" are not known. It may be that the correct sequence is highly improbable, a rare event; or it may be commonly found in our Galaxy. JWST, Constellation-X, and GLAST will investigate the various pathways that are necessary to set the scene for life. These missions might discover that the favorable conditions found in our own solar system are relatively rare, for example, that the relative inactivity of our Sun is rare and that this is essential for the emergence of life. Such a discovery will change the priority of the Pathways to Life Observatories so as to better define where to seek out habitable planets. The observations made by HST, Chandra, GLAST, JWST, Constellation-X, and LISA may find unusual objects. These may be new types of galaxies in the early universe, or massive nearby stars with unusual properties. These observations will determine the priority for the wavelength and capabilities of the first Pathway to Life Observatories, which currently encompass several possible approaches.

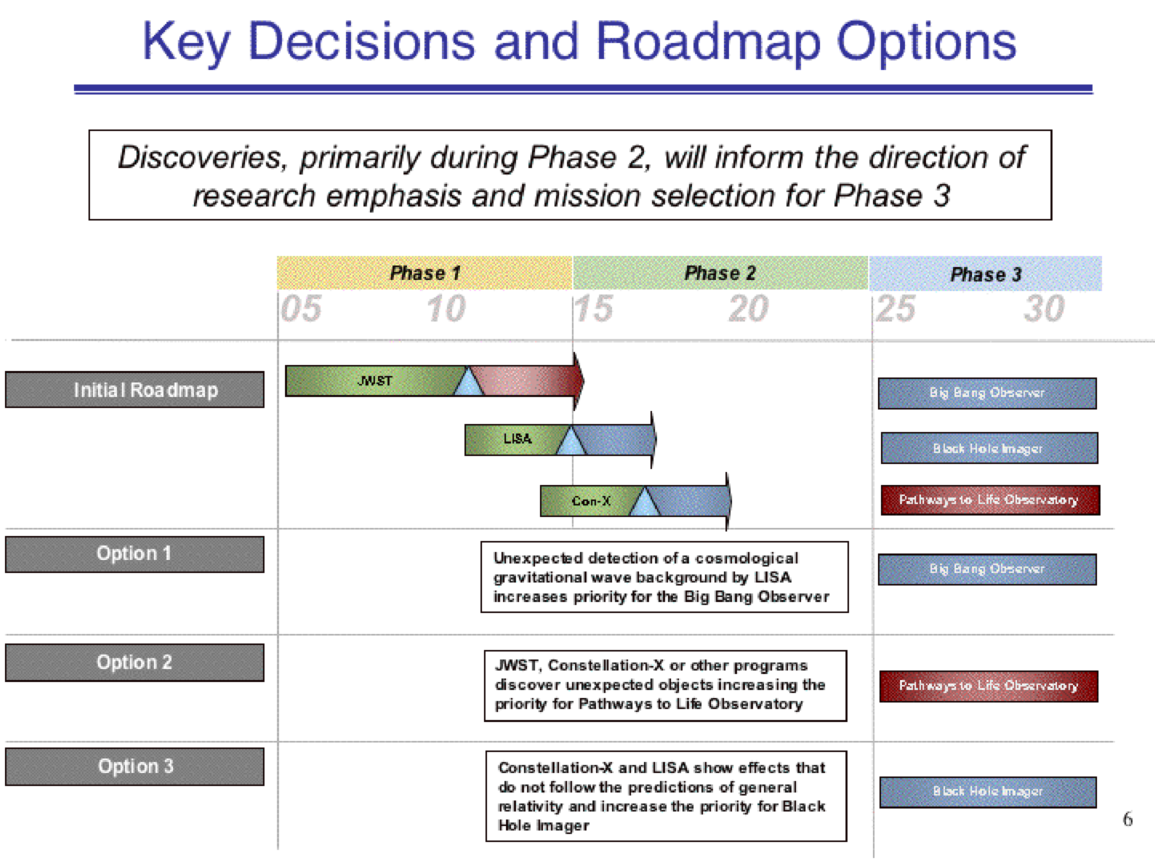

Figure 2 Milestones and Options.

5. Inter-roadmap Dependencies

Any decomposition of NASA's overall science goals into a finite set of strategic objectives will necessarily have linkages, or dependencies, between the individual strategic roadmaps. The Universe Exploration Roadmap (Strategic Roadmap 8) has linkages of several types to other roadmaps, ranging from weakly coupled "opportunistic" linkages to strongly coupled "synergistic" linkages.

Our strongest link by far is with Strategic Roadmap 4 (Search for Earth-like Planets). Sharing its home in the same Universe Division as our roadmap, several Universe Division missions address science goals of both roadmaps, and are of major importance in the achievement of both roadmaps' goals. These missions include JWST, SAFIR, SOFIA, and the Pathways-to-Life Observatories. In addition, the science goals of SR 8 flow naturally into those of SR4; SR 8 is devoted to understanding the origin, evolution, structure and destiny of the Universe, in which the stage is set for the emergence of life. SR 4 continues with this theme by searching for Earth-like planets which could harbor life as we know it. Finally, many of the technologies are shared as well: Light-weight and large optics, detectors, electronics, even novel materials (such as may be provided by nanotechnology) are technologies that enhance the capabilities for both roadmaps.

Strategic Roadmaps 1 (Robotic and Human Lunar Exploration) and 2 (Robotic and

Human Exploration of Mars) present an opportunity for furthering Beyond Einstein science. Specifically, the placement of laser ranging transponders on either the Moon or on Mars would allow much more sensitive solar system tests of Einstein's General Relativity than have been currently achieved. Similarly, radar timing studies with outer planetary probes (Strategic Roadmap 3, "Solar System Exploration") in the manner of Cassini would also enable more sensitive tests of the weak-field regime of Einstein's gravity.

SR 5 (Exploration Transportation) may impact SR 8 by providing launch capability for larger payloads, in particular for larger optics. A weaker synergistic link exists with SR 10, (Sun-Solar System Connection). Both roadmaps require improved understanding of astrophysical magnetic fields and plasmas, and stellar physics.

There are also substantial and important connections with Strategic Goal 12: (Identify and pursue opportunities to educate students and the public and to expand the nation's base of technical skills and capabilities). These education and public outreach activities are built into all of the Universe Division's science missions. Moreover, the scientific topics of the origin and fate of the universe, and black holes, are natural interests of the public and students so the Strategic Goals in Roadmap 8 are of particular importance to Roadmap 12.

SR8 also requires development of technologies that are called out in several capability roadmaps, specifically, CR4 (Advanced Telescopes and Observatories), CR10 (Autonomous Systems, Robotics and Computing Systems), CR12 (Scientific Instruments and Sensors), CR14 (Advanced Modeling, Simulation and Analysis), and CR15 (Nanotechnology and Advanced Concepts). Details are presented in the next section.

6.0 Required Capabilities

NASA missions require technologies usually well beyond the commercial state-of-the art in order to explore the universe with unprecedented clarity and sensitivity. The Hubble primary mirror is so smooth that if the mirror were expanded to the size of the Pacific Ocean, the highest waves would be five centimeters high. The Spitzer Space Telescope operates at temperatures just a few degrees above absolute zero, and this cold operating temperature gives it the sensitivity to detect infant stars buried in clouds of obscuring dust, thousands of light years away. X-rays glancing off Chandra's extremely smooth grazing incidence mirrors are focused so accurately that they could hit the bull's-eye of a dartboard placed six kilometers away. The high reflectivity and sharp images of these superb optics have allowed Chandra to identify, one-by-one, the accreting black holes at cosmic distances that collectively make up the diffuse X-ray background.

Future Universe Missions require even more demanding technologies. The James Webb Space Telescope (JWST) will carry a mirror with a collecting area nearly ten times larger than Hubble's, and will unfold on the way to its distant orbit. The light gathering power of this gigantic mirror will enable JWST to detect the first galaxies and quasars. Con-X will operate new-technology array detectors, cooled to just one-twentieth of a degree above absolute zero, in order to track X-ray-emitting plasma falling into the event horizon of a black hole. The LISA mission will sense the relative positions of its components, measuring changes in their five million kilometer separations with phenomenal accuracy — to within a small fraction of an atomic diameter – in order to detect the ghostly signal of a passing gravitational wave as it ripples the space-time between them.

"Vision" Missions such as Big Bang Observer (BBO), Black Hole Imager (BHI), and the Pathways to Life Observatories push the development of new technologies to achieve their extraordinary science goals. BBO will seek to observe relic gravitational waves that are a key signature of inflation at a level that is orders of magnitude fainter than LISA. BHI will perform X-ray imaging of the structure of a black hole's accretion disk at the microarcsecond level. The technologies such missions require are only now just being conceived. The various Pathways to Life Observatories require large, precise, lightweight optics and high-sensitivity sensors across a wide range in wavelength.

6.1 Technology Implementation

To succeed in such an ambitious program of outstanding science, aggressive technology development is required. Developing these new technologies brings new missions and science to NASA, and new economic benefits for the country. Focused and efficient management of this technology development, with leadership of experienced and capable scientists and engineers in academia and industry, will reduce mission risk and cost. This technology program is an investment in NASA's future, and must be managed in a similar way to that of an investment portfolio, with one eye on short-term needs and another on long-term goals. *Enabling technologies* provide identified capabilities that are essential for nearer-term missions. These technologies have demonstrated feasibility, but must require significant further development and testing before they can be flown reliably on a major mission. These technologies are key to securing the most immediate and reachable science goals in this roadmap, so their development must be given high priority. The future vision missions needs are met with investment in more *exploratory technologies*, those based on new concepts with high potential, which can create new capabilities that address previously inaccessible science goals or address existing goals much more powerfully or less expensively. Advanced technologies can greatly improve the performance and reduce the cost of a mission, but no matter how attractive they seem in principle, we must first validate the new technologies in a space environment well before committing to build a strategic mission.

Maintaining a steady development program to bring forward both enabling and exploratory technologies to maturity is vital for the success of the Universe Exploration Roadmap. The Research & Analysis (R&A) technology incubation program takes the most innovative exploratory technologies through the initial development and testing phase. The R&A program also serves as a useful bridge by providing platforms such as balloons and sounding rockets for gaining confidence in new technologies before they are flown in space. The latter phases of guiding an enabling technology to full space readiness are traditionally carried out in the context of a specific mission, under the auspices of mission project funding. However, a systematic program supporting the early and mid-phases of enabling technology development has often been absent in the past. Such a program must support the development of technologies for missions in this roadmap that do not yet have their own funding lines; so once these missions are selected they can take advantage of the most powerful and appropriate technological tools. It also enables better decisions on mission timing: A new mission starts once the most appropriate technologies are mature enough to be incorporated.

6.2 Strategic Technologies

The Universe science missions described in this Roadmap require advances in four main strategic technology areas: *Optical Systems* — the optics, such as grazing and normal incidence, precision, high stability structures, and the wavefront sensing and control needed to focus electromagnetic radiation with superb accuracy and minimum mass; *Detector Systems* — the devices that convert electromagnetic or gravitational radiation to countable units; *Cryogenic Coolers and Thermal Control* — the methods for cooling telescopes and detectors so that they achieve very low noise and correspondingly high sensitivity and the capability to maintain extremely stable thermal environments; and *Distributed and Advanced Spacecraft Systems* – the critical technology required to support the science payloads including precision attitude control systems and the ability to fly spacecraft in coupled formations, measuring and maintaining their relative positions to extraordinary precision. Table 1 summarizes the technology needs for Universe missions.

For many of the Universe Exploration Probes and Vision Missions there exists multiple implementation approaches with different technology needs that can be used to achieve the desired science. For example, determining the nature of dark energy can be done through optical/infrared measurements or through X-ray measurements, with appropriately different technology needs. In many cases critical technology development progress and performance may be a factor in deciding the approach. So in the following discussion technology needs of multiple implementation approaches (where they exist) have been considered.

The increasing technical complexity and scope of major space science missions should also encourage NASA to explore new approaches for partnering in technology development with academic institutions and with U.S. industry. Besides supporting NASA missions this new technology partnership will help stimulate and advance U.S. technology leadership.

6.2.1 Optical Systems

Advanced telescopes are a critical capability to the Universe Exploration science goals for imaging the horizons of black holes, and galaxies near the edge of the universe, and exploring pathways to life. These telescopes must be larger and have better angular resolution than ever before. This requires that the optical systems be more stable than ever before, with unprecedented wavefront sensing and control, disturbance (mechanical and thermal) stability and control, and pointing and tracking stability. For example the lightweight, grazing incidence X-ray optics required for Constellation-X requires an increase in the effective area-to-mass ratio of X-ray mirrors by a factor of 10 over previous missions.

Lightweight, affordable, *optical systems* are an enabling capability for all future large-aperture space telescopes. They are systems of optical elements, substrates and support structures. Associated capabilities include wavefront sensing and control to compensate for unwanted surface irregularities, metrology, deployment and assembly of large telescope structures in space, and manufacturing and test processes. Key metrics for these systems are the mirror size, the mirror surface figure error or resolution for X-ray mirrors, the areal density, areal cost, and the performance requirements for the wavefront control, metrology and stability needed to meet science requirements.

The greatest technical challenge for optics is the ability to make large-aperture low-areal density mirrors of sufficient surface figure precision and mechanical stiffness. Current observatories are mass and volume limited by the launch vehicle, in turn limiting their maximum aperture. Developing a capability to produce lower areal density mirrors coupled with efficient launch packaging concepts will enable future large aperture observatories. Furthermore, lightweight optics must be very stiff and thermally stable to retain the required optical figure and line-of-sight pointing. The greatest programmatic challenge is to rapidly manufacture affordable mirrors. Reducing the areal-cost of mirrors enables missions to afford larger apertures within the constraint of launch mass/volume limits.

Constellation-X and other future X-ray telescopes such as the Early Universe X-ray Observer (EUXO) or the Black Hole Imager (BHI) require large-aperture precision-quality grazing incidence mirrors. The technology required to produce these mirrors is revolutionary compared to Chandra optics. Technology investment is needed to manufacture 1- to 2-meter class mirrors with two orders of magnitude (100X) reduction in both areal density and areal cost. This will require developing new materials and new fabrication processes, and the mechanical support, alignment and stability of such optics are an additional significant challenge. Both these X-ray mirrors and the normal incidence mirrors for future ultraviolet and visible wavelength missions such as Large Ultraviolet-Visible Observatory (LUVO) also require extremely smooth, extremely stable, ambient temperature mirrors — particularly as telescope apertures increase.

Future infrared/far-infrared/sub-millimeter and millimeter wavelength missions such as JWST, Single Aperture Far-Infrared Telescope (SAFIR), Far Infrared/ Submillimeter Interferometer (FIRSI), and one of the implementation approaches for the Inflation Probe (IP), require large-aperture modest-quality mirrors operating at temperatures from 4 to 40K. Current state of the art cryogenic mirrors can satisfy most of the technical requirements for such missions, but their areal cost is too great. The most important enabling capability is to reduce the areal cost of cryogenic mirrors by an order of magnitude. Approaches to achieve this goal include replication, nanolaminates, near-net shaping and advanced polishing techniques.

6.2.2 Detector Systems

Virtually all NASA Universe Exploration missions require detectors with exquisite sensitivity, extraordinary spectral resolution, spectacular imaging capabilities, and sometimes all of these. In addition, the Universe Exploration Strategic Roadmap cuts across the electromagnetic spectrum from the submillimeter to the gamma ray. Large-area, low-power gamma-ray and hard X-ray detector systems are required for Constellation-X, the Black Hole Finder Probe, Black Hole Imager and the Nuclear Astrophysics Compton Telescope. Multiplexed microcalorimeter and bolometer arrays are needed by Constellation-X, EUXO and the Black Hole Imager in order to meet the energy resolution and sensitivity requirements in the soft X-ray band. These are also required by one of the candidate Inflation Probe architectures to realize large-format high sensitivity mm polarimeters. The development of the Constellation-X and Inflation Probe detector arrays dovetails into the large-format, ultrahigh-sensitivity arrays also needed for SAFIR. Very large format (billion-pixel or greater) optical/infrared focal planes are needed for JDEM and LUVO, which also need high quantum efficiency, solar blind photon counting UV arrays.

The detector systems investment program should nurture the natural synergy between X-ray and far-infrared/millimeter-wave core detector technologies. For example, both wavelength regimes are rapidly developing transition-edge superconducting (TES) sensors and superconducting quantum interference device (SQUID) multiplexers. Newer technologies such as Kinetic Inductance Detectors (KIDs) or magnetic microcalorimeters hold substantial promise.

LISA and the Big Bang Observatory require gravitational reference sensors to perform drag-free flight. The sensors must minimize disturbance to the freely falling proof masses in addition to monitoring and controlling the position of the proof masses relative to the spacecraft. Precision micro-thrusters are required to maintain spacecraft attitude and position relative to the proof masses. Stabilized laser technology is required to monitor the position of the proof masses relative to the proof masses in the distant spacecraft.

6.2.3 Cryogenic Coolers and Thermal Control

Cryogenic coolers are required for Universe Exploration instruments and telescopes to produce much of the desired science. The advanced calorimeter and bolometer detectors that enable Constellation-X and other missions require cooling to 0.05 degree above absolute zero. Passive cooling techniques enable the Spitzer telescope to fully exploit the natural space environment, requiring no power, stored cryogens, or moving parts. Passive cooling allows space missions to achieve temperatures several tens of degrees above absolute zero, sufficient for near/mid-infrared telescopes such as JWST, and serves as a valuable first temperature stage towards reaching lower temperatures. But future applications, such as cooling very large telescopes as well as the detector system for some of the architectures for the Inflation Probe, SAFIR, and FIRSI require new technology. Active cooling technologies offer the potential of high efficiency and high reliability cooling to 4-6 K. New sub-Kelvin coolers, operating from this base temperature, will reach the ultra-low temperatures required for calorimeter and bolometer focal planes, providing more heat lift, continuous operation, and high temperature stability. Adiabatic Demagnetization Refrigerators (ADRs), ^{3}He sorption coolers, and open-cycle dilution refrigerator precursor technologies show many of the attributes needed to meet these requirements. In addition, cryogenic and non-cryogenic missions will require advances in thermal stability and control technology (heat pipes and other heat transport systems) that exceed current state of the art performance by an order of magnitude or more.

6.2.4 Distributed and Advanced Spacecraft Systems

Distributed Spacecraft Systems
In order to achieve the science goals described in this roadmap, NASA will require a precision formation flying capability (for LISA, BHI, BBO, FIRSI, and others). Carrying out this type of spacecraft coordination requires technologies such as extremely stable gyros, disturbance (thermal/mechanical) control, clock synchronization systems, precise star trackers, laser ranging systems between spacecraft, and micro-Newton thrusters to perform minute adjustments. In addition, spacecraft control algorithms need to be developed for continuous monitoring, formation flying, reconfiguration and reorientation and autonomous recovery. LISA will provide the initial demonstration of advanced formation-flying techniques by measuring the relative displacements of inertial test masses contained in each spacecraft separated by millions of kilometers to picometer accuracy.

These mission ensembles are a set of more than one spacecraft whose dynamics are coupled through a cooperative sensing and control architecture. This enables many satellites sometimes separated by millions of miles to act as one giant observatory. A key challenge is the need to build multiple spacecraft, requiring a reduction of development and test costs for replicated spacecraft to enable competitive formation flying systems. Current formation flying systems rely upon propulsion to maneuver and maintain formation, thereby limiting mission lifetime and contaminating their environment (deposition on optical surfaces, plume impingement, thermal emission). Propellant-less formation flight should be investigated, including the use of natural orbits, tethers, natural fields (magnetic, solar pressure), as well as potential fields generated by the spacecraft themselves (electro-magnetic, electrostatic).

Advanced Spacecraft Systems
Universe Exploration missions require improvement over the current state of the art in a number of fundamental spacecraft elements, i.e., more accurate and more stable gyros, star trackers and other attitude control sensors and algorithms. Also critically important are electronics and processors with better radiation tolerance and lower cost; lower cost, more efficient power systems; larger launch vehicle fairings; and launch load alleviation systems. Investments in these areas should not be neglected.

Industrial and Academic Capacities, Agency Human Capital and Infrastructure

As Universe Missions become more complex and technologically demanding, strong cooperation among NASA, universities, national labs, and industry is essential to meeting critical science objectives within cost and schedule constraints. For example, bolometer and microcalorimeter technologies for Con-X are developed through a collaboration including Goddard Space Flight Center (GSFC), the University of Wisconsin, Smithsonian Astrophysical Observatory (SAO), and National Institute of Standards and Technology (NIST). While NASA manages LISA, major technological components come from Stanford, the University of Colorado, the Jet Propulsion Laboratory, and Busek Technologies Corporation. Because the technologies for astronomy are driven by science objectives, scientists must be involved at all phases of development, working with the technologists who make these capabilities possible. In some areas, experimental scientists *are* the technologists, pushing the boundaries of performance to meet their scientific goals. Whenever NASA's technology goals align with commercial interests, NASA can leverage capabilities in industry to the fullest extent possible. On the other hand, whenever NASA is the sole customer, NASA must vigorously support research and development at universities, government research centers, and industrial research laboratories to realize its goals. NASA must also identify new ways to aggressively team with industry in areas of technology development, new facilities and test capabilities, and workforce development.

The availability of human capital, infrastructure, and institutional support at any or all of these types of institutions can make or break a NASA mission. At universities, the training of the next generation of instrumentalists for space missions is a key capability that must be encouraged and maintained. NASA contributes to this through funding R&A, sub-orbital payloads, and P.I.-led competed missions such as Explorers and Probes. Aerospace corporations provide the infrastructure for launch vehicles, management of large space hardware programs, spacecraft and instrument construction, and test facilities. Where industry cannot supply such facilities, NASA often develops unique infrastructures of its own: for example, the Marshall Space Flight Center X-ray Calibration Facility, which was used to calibrate the Chandra X-ray instruments and may be used for Con-X as well. A NASA facility will also be used for JWST testing. The development of microfabrication capabilities at NIST and NASA/GSFC were key to making prototype microcalorimeter arrays.

There are, however, significant concerns about the ability to maintain some of these capabilities for future Universe Exploration missions. The R&A and Explorer programs, while very cost effective in solving technology problems at an early stage of development, are under intense financial pressure in the current NASA budget environment. For many missions there are only a few suppliers of key detector, optics or filter technology. These are often small concerns which, if they cannot attract a steady stream of business, will lose key personnel or even go out of business. The Universe Division and Science Mission Directorate should undertake a comprehensive review of these issues to ensure that mission critical capabilities are preserved in the vendor community. In addition, it is essential that the most efficient methods be invoked to ensure mission reliability, so that excessively burdensome review processes do not significantly drive up mission costs.

Unique Requirements

Investments in infrastructure that enable researchers to communicate, organize and share information are crucial to ensure the widest participation in the research effort. These assets include NASA's Deep Space Network (DSN), TDRSS, and other supporting orbital and ground networks, data archival and distribution networks, and high-speed ground links.

It is anticipated that the rates and volume of scientific data in the future missions, especially those involving wide-field imaging and orbits at L2 and beyond, will far exceed existing downlink and storage capabilities. An upgraded DSN and wider bandwidth space communication systems will be vital. The large data volumes may be accommodated in part by distributing data sets and analysis. However, the software tools as well as the connectivity for such data systems will require new approaches and architectures for synthesizing these data streams (e.g., National Virtual Observatory (NVO). Continual investment in information technology tools will be required to address the spatial, temporal, and spectral data needed to understand the cosmos. Furthermore, information technology investments to
support on-board control strategies of more capable spacecraft will be essential as we move to an era of constellation or formation flying.

Critical Technology Needs for Univere Exploration Science	Strategic Missions		Probes			Vision Missions							
Mission						Beyond Einstein		Pathways to Life Observatories					
Technology Area & Sub-Areas	LISA	Con-X	JDEM	IP	BHFP	BHI	BBO	NACT	LUVO	SAFIR	EUXO	FIRSI	UVOI
Optical Systems													
Light Weight Grazing Incidence Mirror Systems		Enabling			Enabling	Enabling					Exploratory		
Light Weight Normal Incidence Mirror Systems			Enabling				Enabling		Exploratory				Enabling
Light Weight Cryogenic Mirror Systems				Enabling						Exploratory		Exploratory	
Wavefront Sensing and Control and Interferometry			Enabling						Enabling			Exploratory	Exploratory
Precision Structure Disturbance Sensing and Control						Exploratory			Exploratory	Enabling	Exploratory	Exploratory	Exploratory
Detector Systems													
γ-Ray and Hard X-ray Detector Systems		Enabling			Enabling	Exploratory		Enabling			Enabling		
X-ray Detector Systems (calorimeters, CCDs, etc)		Enabling				Exploratory					Exploratory		
UV, Optical, Near-IR Detector Systems, including Large Focal Plane Technology			Exploratory						Exploratory				Enabling
Mid- and Far-IR Detector Systems				Exploratory						Exploratory		Exploratory	
Gravitational Wave Detector Systems	Enabling						Exploratory						
Cryogenic Coolers and Thermal Control													
Passive Thermal Systems for Cooling and/or Control (sunshades, radiators, etc)	Enabling		Enabling				Enabling		Enabling	Enabling		Enabling	
Low Power, Low Vibration, Active Instrument Cooling Systems		Enabling	Enabling	Exploratory				Exploratory		Enabling	Exploratory	Enabling	
Low Power, Low Vibration, Active Telescope Cooling Systems				Exploratory						Exploratory		Exploratory	
High Precision Thermal Sensing and Active Control (> 0.01 K stability)						Exploratory			Exploratory	Exploratory		Exploratory	
Distributed & Advanced Spacecraft Systems													
Micro-Newton Thrusters	Enabling					Enabling	Enabling						Enabling
Propellant-less Formation Flight						Exploratory	Exploratory					Exploratory	Exploratory
Precision Formation Flying Algorithms						Exploratory	Exploratory				Exploratory	Exploratory	Exploratory
Precision Formation Flying Metrology and Navigation Sensors & Systems						Exploratory	Exploratory				Exploratory	Exploratory	Exploratory
Precision Attitude Control Sensors & Systems (sensors, gyros, momentum wheels, etc)	Enabling	Enabling	Enabling			Enabling	Enabling		Enhancing	Enhancing	Enhancing	Enhancing	Enhancing

Key	
Enabling Technology	Technology Currently at TRL 3-6
Exploratory Technology	Technology Currently at TRL 1-3

Table 1 Capabilities needed to reach roadmap science goals.

APPENDICES

A. National Policy Framework

The Universe Roadmap is a framework for Exploration on the grandest scale. It lays out a scientific and technological agenda to discover the origin, structure, evolution, and destiny of space and time, matter and energy, atoms and molecules, the stars and galaxies that animate and enrich the cosmos, and ultimately life itself. It leverages NASA's considerable experience to achieve what only NASA can. It is a response to NASA's Mission statement "…To explore the Universe and Search for Life" and "…To Inspire the Next Generation of Explorers." If fully implemented, it would realize a critical component of the Space Exploration Vision, as described in the "President's Commission on Implementation of United States Space Exploration Policy." This Vision calls for the exploration of the beginnings of the universe, planetary systems, and life. This roadmap advocates a scientific agenda that would reveal the origin, structure, evolution, and fate of the elements, the stars, the galaxies, and the cosmic web that comprise the known Cosmos. The Vision also challenges NASA to conduct a comprehensive program to explore the origin, evolution, and destiny of the universe. Space astronomy has been a powerful development driver of American high technology, and is a credible source of national pride.

The NASA Strategic Roadmapping process does not operate in isolation. It has benefited from guidance provided by a number of other national advisory committees that have been commissioned in recent years to chart the future of multi-agency research in astronomy, astrophysics, cosmology, and planetary science. Of particular importance is the decadal survey in astronomy and astrophysics conducted by the National Academy of Sciences (NAS), which resulted in the report "Astronomy and Astrophysics in the New Millenium." Many of the missions identified in this Universe Roadmap were highly ranked in that report. The NAS also subsequently commissioned "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century," which recommended a multi-agency coordinated program of research at the frontiers between physics and astronomy. The Beyond Einstein program included here has been formulated largely along the lines recommended by that study. Finally, in 2004, the Office of Science and Technology Policy (OSTP) issued the report "A 21st Century Frontier for Discovery: The Physics of the Universe, A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy," which responded to these NAS recommendations with a prioritized program of research on the physics of the universe. The NASA Universe Exploration roadmap is fully consistent with the OSTP recommendations.

As the arena of space has become increasingly vital in the scientific investigations of various research communities, the programmatic goals of other Federal funding agencies, such as the NSF and DOE, intersect with those of the Universe Division within NASA. The Gamma-Ray Large Area Telescope (GLAST) is being developed in partnership with the DOE, and a similar arrangement has been envisioned for the Joint Dark Energy Mission (JDEM), which will be the first of the Einstein Probes. Given these collaborations, it is essential that the strategic planning efforts at NASA be coordinated with those at these other agencies. The membership of the Universe Exploration Startegic Roadmap committee has been constructed to enable this coordination: Senior NSF and DOE personnel have been included, as well as a representative of the Astronomy and Astrophysics Advisory Committee and High Energy Physics Advisory Panel.

The intense multi-agency interest in the topics discussed here reflect the expectation that the *discoveries likely to emerge from the Beyond Einstein and Pathways to Life missions will fundamentally change our understanding of our place in the universe.* The implications could be as profound and paradigm-breaking as those that resulted from the revolutions due to Copernicus, Galileo, Newton, and Einstein. The Universe Exploration Program will ignite the public imagination, while fulfilling its obligation to inspire the students of the future who will carry out its programs of discovery. It will play a major role in helping to maintain the U.S. presence at the forefront of fundamental research in the physical sciences.

External Constituencies

Space-based astronomical research is not an isolated discipline, but rather has important and direct links to other research areas and to other constituent groups. Research fields in fundamental physics (in particular particle physics, nuclear physics, cosmology and gravitational physics) are asking questions which in many cases can only be answered by space missions using the universe as a laboratory. Two specific examples — understanding the nature of dark energy and of the quantum gravity of the early universe — could well have enormous repercussions on our picture of particle physics, but, as yet, there is no currently known way to directly probe these issues using ground-based accelerators and laboratories. Another research field that links to the Universe Exploration theme is biology. With the search for habitable solar systems and with the increasingly detailed understanding of the chemical and environmental makeup of the universe, astronomers are providing important clues towards unraveling the mystery of the origin of life. Indeed, the field of astrobiology has emerged as an exciting discipline both at NASA and at research institutions across the country.

There are other important constituencies that go beyond the broader scientific research community. Educators and students at K-12 schools and universities make heavy use of the results from astronomical research in classrooms and in extracurricular activities (for example, museum visits). Information gathered from NASA web sites serves, in many cases, as the primary scientific archive for students of all ages. Another key constituency is represented by our industrial and commercial partners. These groups work with researchers at universities and NASA centers to design and carry out space missions and to develop forefront technologies for future missions. Finally, the general public, as our ultimate customer, is a crucial external constituency. Results from NASA space missions, as covered by popular media, have the demonstrated ability to inspire citizens of all ages, and they engender good will in support of the overall vision and goals of the agency.

B. **Unique Education and Outreach Opportunities**

The Universe Exploration missions and related activities are key to achieving NASA's strategic objective #13:

> "Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation."

The Universe Roadmap Committee affirms the importance of aiding the nation's efforts in science, technology, engineering, and mathematics (STEM) education—both in higher education and at the pre-college level. Maintaining and nurturing an adequate workforce is especially critical in view of the long lead-time for missions and the increasing restrictions on foreign nationals at NASA's corporate partners. A strong public engagement effort is also key to achieving sustained public support for NASA's space effort.

Demand is high, need is great

The public's interest in Universe Exploration is evident from the great popularity of museum exhibits, planetarium shows, and television shows in the Universe Exploration theme. For example, recent and forthcoming television documentaries on black holes have already garnered millions of viewers. More than a million people have visited the *Cosmic Questions* traveling exhibition. *Inside Einstein's Universe*, a collaborative effort of missions in Universe Exploration, has attracted the active participation of 114 science museums nationally. Research on our cosmic origins has led to extensive coverage in major newspapers such as *The New York Times* and *The Washington Post*.

In the nation's schools, black holes remain one of the two most asked-about topics in astronomy. More importantly, the topics of Universe Exploration are firmly rooted in the *National Science Education Standards* (issued by the National Academy of Sciences), which together with the AAAS' *Benchmarks for Science Literacy* form the basis for most frameworks for education at the state level. The national standards mandate an understanding of the Big Bang and the life cycles of stars, while the benchmarks cite black holes as "an excellent" way to explore the nature of science.

The Universe Exploration missions have an important role: Recent surveys confirm that, despite the standards, students and teachers are generally unfamiliar with the universe beyond the solar system. In a recent assessment of 7,000 students in 37 states, *most* students had trouble with such basic concepts as where the stars are in relation to the solar system and the space shuttle, or with concepts such as the nature of gravity. This situation is unlikely to improve without NASA's presence in the classroom.

Universe Exploration missions offer unique opportunities

NASA's goal to "Explore. Discover. Understand." is well-served by the Universe Exploration Program. Missions such as Constellation-X, LISA, the Black Hole Finder Probe and, ultimately, the Black Hole Imager, will take the public on a great voyage of exploration culminating at the very edge of a black hole. Like any great exploration, the ultimate goal is preceded by scouting and reconnaissance — making sense of the ultimate target. Similarly, LISA, the Inflation Probe, and the Big Bang Observer will engage the public in a form of time travel, exploring the universe's distant past back to its origins, and the Joint Dark Energy Mission will help predict the universe's eventual destiny. In addition, missions exploring the "ecology" of our universe will paint an extraordinary story of why our physical universe appears to be so hospitable to life, setting the stage for the search for life beyond Earth. Finally, one of the great stories of our time is the emerging revolution in fundamental physics, a story that will likely blossom in the public's attention shortly after the world's most powerful collider goes on line at CERN in 2007. Many of the missions presented here—especially LISA, JDEM, the Inflation Probe, Planck and GLAST—are likely to play key roles in testing the new physics and will be an important part of the narrative. These great stories of exploration, discovery, and understanding are an indispensable vehicle for engaging the public's interest.

Furthermore, the Universe Exploration missions offer unprecedented opportunities in the classroom for helping students and teachers with such fundamental STEM concepts as the structure of the universe, gravity, the interaction of light and matter, and the formation of elements. These are not mere facts, but rather core concepts that leverage future learning in STEM. For example, the Universe Exploration missions offer an unmatched opportunity for students to learn about (and to visualize) all regions of the electromagnetic spectrum, a concept that is fundamental to every branch of science. Missions such as LISA, which push the bounds of technology, will also provide unmatched learning opportunities for technology education.

Elements of the Public Engagement Plan

Identifying the Needs of Stakeholders. Basic to our approach is to research and identify the needs of our audiences and stakeholders. The Universe public engagement programs seek to harness NASA's unique resources to help address the needs of three major audiences:

> *Formal education*. These are classroom teachers (K-12 and college level), curriculum developers, textbook publishers, and other educators who are tasked with teaching the national science education standards and who need compelling examples, activities, and scientific visualizations, as well as professional development to make optimum use of these materials. Formal education can include the use of real research data and learning tools such as online telescopes.
>
> *Informal education*. These organizations include science museums, planetariums, and other institutions of informal learning which bring the public along on the exploration of space, and which require compelling stories to tell as well as the

raw resources such as scientific visualizations and artifacts with which to construct these stories. Informal learning also takes place in after-school programs, and with organizations such as the Girl Scouts, amateur astronomers' clubs, and national parks, which engage the public with demonstrations, activities, and other educational resources.

General public. Young and old alike participate in the excitement of NASA's space exploration through news, radio and television programs and Web access to information.

Focus on High-Priority Areas.

Several areas have been identified for which NASA's educational assets can make a particularly important contribution. Among these are:

- Professional development for pre-service and in-service teachers and college instructors.
- Flexible learning tools and experiences that support the learning of scientific inquiry, fundamental concepts in STEM (science, technology, engineering and math), and / or language arts.
- National partnerships with informal education organizations.
- Scientific visualizations, including multimedia and interactive experiences.
- Distance and e-learning.

Guiding Principles.

Universe public engagement programs incorporate several principles that will guide all future work:

Coherence. Achieve a coherent and coordinated set of programs and products that meet the needs of varied audiences and stakeholders, and that mesh seamlessly with NASA's other science themes and education initiatives.

Leverage. Expand public engagement on a large scale by creating sustainable national programs through effective and flexible partnerships with existing organizations.

Scientist participation. Maximize the impact of NASA's programs by fostering the participation of scientists and engineers.

Authentic experiences. Involve students and teachers in real research and expand access to real data.

Diversity. Engage underserved and underutilized groups in ways that genuinely meet mutual needs and interests and that contribute to the pipeline.

Training of students. Provide continuing support for STEM students in higher education, including programs providing research experiences for undergraduates.

Pathways to the Future for Public Engagement

Universe public engagement programs build on and extend an existing educational network of scientists, educators, brokers, and forums that is unprecedented in scope and reach. This network ensures that future efforts will be both cost-effective and highly leveraged.

One key component is the active participation of research scientists and engineers who provide visualizations, data, artifacts, public lectures, reviews for accuracy and, most important, serve as role models and mentors for the next generation of explorers. Another important element is the active involvement of education organizations nationwide, such as the Girl Scouts USA, the Night Sky Network of astronomy clubs, the Great Lakes Planetarium Association, and many more. Finally, the network is coordinated by a small number of education forums who work with mission scientists and mission educators to develop educational strategies and products—and by regional brokers, who partner with educational institutions and regional audiences to ascertain their needs.

The connectivity of this network of scientists, missions, and educational institutions allows NASA's educational assets to enjoy maximum reach and impact. When high-resolution images from the Chandra X-ray Observatory are quickly distributed to a large number of planetariums; when world-class scientists give public presentations about black holes; or when amateur astronomers hold hundreds of NASA-sponsored events around the country, it is clear that the network insures that programs achieve the broadest possible reach and impact.

Strategic leadership.

The Universe public engagement program is coordinated by a team at the Space Telescope Science Institute and the Harvard-Smithsonian Center for Astrophysics. The team helps provide continuity and direction for the education programs of missions and research scientists, and provides core services such as evaluation of products, entree to the education research literature, and coordination of effort. Future missions will be able to take advantage of existing partnerships and programs, and it is expected that new programs will relate to the overall goals, program areas, and customer needs identified in this roadmap.

C. **External Partnerships**

Other Federal Agencies. Understanding the origin, evolution, structure and destiny of the universe is an inherently interdisciplinary enterprise, and it is becoming increasingly clear that a broad-based multi-agency attack on the key problems is warranted. The National Academy of Sciences report "Connecting Quarks with the Cosmos" highlighted the need for inter-agency coordination of overlapping science areas. In response to this report, a Physics of the Universe Interagency Working Group (IWG) was formed by OSTP. This IWG reports to the National Science and Technology Council (NSTC) Committee on Science (COS). The IWG delivered a strategic plan to respond to the

"Connecting Quarks with the Cosmos" recommendations, identified priorities for immediate investments, and the appropriate agency roles and responsibilities. The IWG gave high priority to studies of dark energy and a future Joint Dark Energy Mission (JDEM) to be implemented by NASA, in partnership with DOE. This will build on the successful NASA/DOE partnership for the Gamma Ray Large Array Telescope (GLAST). The IWG also recommended a Task Force for Cosmic Microwave Background Research that has delivered a technology roadmap (including a candidate Inflation Probe based on CMB polarization measurements) that will inform not just NASA, but also the NSF and the DOE, so that the funding strategies of each agency may be combined into a comprehensive program of support to achieve the collective aims of these agencies. Interagency cooperation continues to be exemplified by the participation of NSF and DOE personnel in our roadmap efforts, with reciprocation on NASA's part.

International Partners. With the increasing complexity and cost of major space science missions, international partnerships provide a lower-cost-to-NASA option for carrying out its space missions. The European Space Agency (ESA) and several of the European national space institutes are major partners in LISA and JWST. Substantial ESA and Japanese (JAXA) participation in the Constellation-X mission also appears to be likely. There is also considerable international interest in the Einstein Probes for Dark Energy and Inflation, the Pathways to Life Missions and Big Bang Observer.

D. **Bibliography**

Key Agency Documents

- Universe Division Roadmap (to be completed 2005)
- Report of the President's Commission on Implementation of United States Space Exploration Policy: A Journey to Inspire, Innovate and Discover (2004)
- Space Science Enterprise Strategy (2003)
- Structure and Evolution of the Universe Roadmap, *Beyond Einstein: From the Big Bang to Black Holes* (2003)
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- *Assessment of NASA's Draft 2003 Space Science Enterprise Strategy*, Space Studies Board (2003)
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- *Interim Assessment of Research and Data Analysis in NASA's Office of Space Science*, Space Studies Board (2000)

E. **Inputs to Roadmap Committee**

This roadmap was prioritized on the basis of science priorities and programmatic considerations. The committee gave careful consideration to a wide variety of inputs from the public and the astronomy and physics communities during three open meetings. These inputs included direct presentations by Vision Missions Concept Study teams, white papers submitted in response to a call for community input by NASA's Advanced Planning and Integration Office, review of power point presentations prepared by Origins Probes Concept Study teams, and drafts of the Universe Division's Legacy Roadmap which itself incorporates substantial additional input from the community.

F. **Universe Exploration Strategic Roadmap Committee**

<u>Committee Members</u>
Anne Kinney, NASA Science Mission Directorate, *co-chair*
Nick White, Goddard Space Flight Center, *co-chair*
Kathryn Flanagan, Massachusetts Institute of Technology, *co-chair*
Chuck Bennett, Goddard Space Flight Center
Craig Hogan, University of Washington
Steven Kahn, Stanford University, Stanford Linear Accelerator Center
Rene Ong, University of California, Los Angeles
Sterl Phinney, California Institute of Technology
Ron Polidan, Northrop Grumman Space Technology
Michael Shull, University of Colorado
Robin Staffin, Department of Energy, Office of Science
Bob Stern, Lockheed Martin
Michael Turner, National Science Foundation, Mathematical and Physical Sciences Directorate
Jakob van Zyl, Jet Propulsion Laboratory

Michael Salamon, Mission Directorate Coordinator, *Designated Federal Official*
Rich Capps, Advanced Planning and Integration Office Coordinator (JPL)

<u>Ex Officio and Liaison</u>
Louis Barbier, Goddard Space Flight Center
Roy Gould, Harvard-SMithsonian Center for Astrophysics, Education Roadmap Committee Liaison
Steve Maran, American Astronomical Society, community and media liaison

<u>Staff</u>
Gary Blackwood, Systems Engineer, Jet Propulsion Laboratory

G. Acronyms

BBO	Big Bang Observer
BHFP	Black Hole Finder Probe
BHI	Black Hole Imager
CMB	Cosmic Microwave Background
COBE	Cosmic Background Explorer
Con-X	Constellation-X
DEP	Dark Energy Probe
ESA	European Space Agency
EUXO	Early Universe X-ray Observer
FIRSI	Far Infrared/ Submillimeter Interferometer
GLAST	Gamma Ray Large Area Telescope
GPB	Gravity Probe B
Herschel	ESA/NASA far infrared mission
HST	Hubble Space Telescope
IP	Inflation Probe
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
LIGO	Laser Interferometer Gravity Wave Observatory
LISA	Laser Interferometer Space Antenna
LUVO	Large Ultarviolet/Optical Telescope
NACT	Nuclear Astrophysics Compton Telescope
NuSTAR	Nuclear Spectroscope Telescope Array
P.I.	Principal Investigator
Planck	ESA/NASA cosmic microwave background mission
SAFIR	Single Aperture Far-InfaRed Telescope
SOFIA	Stratospheric Observatory For Infrared Astronomy
UVOI	UV/Optical Interferometer
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
XMM	X-ray Multimorror Mission

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
UNIVERSE EXPLORATION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Universe Exploration Strategic Roadmap Committee (the “Committee”), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on exploring our Universe to understand its origin, structure, evolution, and destiny. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation’s space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

Administrator   Date

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
EXPLORATION TRANSPORTATION SYSTEM
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Exploration Transportation System Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on developing a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
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ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

Administrator | Date

MEMBERSHIP ROSTER

Exploration Transportation System Strategic Roadmap Committee

Committee Members

Craig E. Steidle, Admiral USN (Ret), NASA Exploration Systems Mission Directorate, *co-chair*
James Kennedy, NASA Kennedy Space Center, *co-chair*
Charles Bolden, Jr., General USMC (Ret), TechTrans International, Inc., *co-chair*
John Campbell, NASA Goddard Space Flight Center/Wallops Flight Facility
Edward F. Crawley, Massachusetts Institute of Technology
Peter Diamandis, X-Prize Foundation
Delma Freeman, NASA (retired)
Wes Harris, Massachusetts Institute of Technology
Sydney Michael Hudson, Rolls Royce North American (retired)
Tamara Jernigan, Lawrence Livermore National Laboratory
Dave King, NASA Marshall Space Flight Center
Wayne Littles, NASA (retired)
Max Nikias, University of Southern California
Karen Poniatowski, NASA Space Operations Mission Directorate
Robert Sieck, NASA (retired)

Mark Borkowski, Directorate Coordinator
Dana Gould, Advanced Planning and Integration Office Coordinator (LaRC), *Designated Federal Official*

Ex Officio and Liaison

Lynn Cline, NASA Space Operations Mission Directorate
Doug Cooke,NASA Exploration Systems Mission Directorate
Lisa Guerra, NASA Exploration Systems Mission Directorate
Susan Hackwood, Executive Director of the California Council on Science and Technology, liaison with the Education Strategic Roadmap Committee
Colonel Jim Knauf, Secretary of the Air Force, Undersecretary of the Air Force for Launch, National Security Space liaison
Garry Lyles, NASA Exploration Systems Mission Directorate

Final December23, 2004
Updated March 28, 2005

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
NUCLEAR SYSTEMS
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Nuclear Systems Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on utilization of nuclear systems for the advancement of space science and exploration. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

Administrator Date

MEMBERSHIP ROSTER

Nuclear Systems Strategic Roadmap Committee

Committee Members
Craig E. Steidle, Admiral USN (Ret), NASA Exploration Systems Mission Directorate, *co-chair*
Chris J. Scolese, NASA Goddard Space Flight Center, *co-chair*
John F. Ahearne, Sigma Xi Center, Duke University, *co-chair*
Doug Allen, Schafer Corporation
Ken Anderson, NASA Goddard Space Flight Center
George Apostolakis, Massachusetts Institute of Technology
Dave Bartine, NASA Kennedy Space Center
Stephen Bowen, NASA Johnson Space Center
Theron Bradley, NASA (retired)
Andy Christensen, Northrop Grumman
Tom Gavin, Jet Propulsion Laboratory
Roger Kasperson, Clark University
Andy Klein, Oregon State
Gerald Kulcinski, University of Wisconsin
Jim Mosquera, Department of Energy
Ted Swanson, NASA Goddard Space Flight Center
Earl Wahlquist, Department of Energy
Ann Whitaker, NASA Marshall Space Flight Center

Perry Bankston, Advanced Planning and Integration Office Coordinator (JPL)
Victoria Friedensen, NASA Exploration Systems Mission Directorate, *Designated Federal Official*
Jason Jenkins, Directorate Coordinator

Ex Officio and Liaison
Dennis Berry, Department of Energy, Sandia National Laboratories
John-Luc Cambier, Air Force Research Laboratory, National Security Space liaison
Don Cobb, Department of Energy, Los Alamos National Laboratory
Bret Drake, NASA Exploration Systems Mission Directorate
Daniel Gauntner, NASA Glenn Research Center
Lisa Guerra, NASA Exploration Systems Mission Directorate
David Hill, Department of Energy, Oak Ridge National Laboratory
James Lake, Department of Energy, Idaho National Laboratory
Gary Martin, NASA Advanced Planning and Integration Office
Ajay Misra, NASA Science Mission Directorate
Joe Nainiger, NASA Glenn Research Center
Curt Niebur, Jet Propulsion Laboratory

Carl Pilcher, NASA Science Mission Directorate
Jeff Rosendhal, NASA (retired), liaison with the Education Strategic Roadmap Committee
Michael Stamatelatos, NASA Safety and Mission Assurance
Eugene Tattini, Jet Propulsion Laboratory
Ray Taylor, NASA Exploration Systems Mission Directorate
Mike Wollman, KAPL, Inc., a Lockheed Martin company

Final 12/22/04
Updated3/31/05

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
ROBOTIC AND HUMAN LUNAR EXPLORATION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Robotic and Human Lunar Exploration Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on undertaking robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

MEMBERSHIP ROSTER

Robotic and Human Lunar Exploration Strategic Roadmap Committee

Committee Members
Craig E. Steidle, Admiral USN (Ret), NASA Exploration Systems Mission Directorate, *co-chair*
William F. Readdy, NASA Space Operations Mission Directorate, *co-chair*
Jefferson D. Howell, Jr., General USMC (Ret), Johnson Space Center, *co-chair*
Thomas P. Stafford, General, USAF (Ret), *co-chair*
CAPT Bruce Abbott, United States Navy, National Reconnaissance Office
Michael Duke, Colorado School of Mines
Mike Hawes, NASA Space Operations Mission Directorate
James Head, Brown University
Milt Heflin, NASA Johnson Space Center
John Horack, NASA Marshall Space Flight Center
Howard McCurdy, American University
Thomas Morgan, NASA Science Mission Directorate
Firouz Naderi, Jet Propulsion Laboratory
Bradford Parkinson, Stanford University
Donald Pettit,NASA Johnson Space Center
R. Edwin Smylie, Grumman (retired)
Paul Spudis, Applied Physics Laboratory
Tom Tate, House of Representatives Committee on Science and Technology (retired)
Jeff Taylor, University of Hawaii
Brenda Ward, NASA Johnson Space Center

Scott Wilson, Mission Directorate Coordinator, *Designated Federal Official*
Frank Bauer, Advanced Planning and Integration Coordinator

Ex Officio and Liaison
Doug Cooke, NASA Exploration Systems Mission Directorate
Tom Cremins, NASA Space Operations Mission Directorate
Orlando Figueroa, NASA Science Mission Directorate
James Garvin, NASA Chief Scientist
Lisa Guerra, NASA Exploration Systems Mission Directorate
Tom Jasin, NASA Science Mission Directorate
Michael Lembeck, NASA Exploration Systems Mission Directorate
Wendell Mendell, NASA Johnson Space Center
Cassandra Runyon, College of Charleston, liaison with the Education Strategic Roadmap Committee
Charlie Stegemoeller, NASA Johnson Space Center
Richard Vondrak, NASA Goddard Space Flight Center

Jim Watzin, NASA Goddard Space Flight Center
Joe Wood, NASA Advanced Planning and Integration Office

Final December 17, 2004
Updated March 28, 2005

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
AERONAUTICAL TECHNOLOGIES
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Aeronautical Technologies Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on providing advanced aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

MEMBERSHIP ROSTER

Aeronautical Technologies Strategic Roadmap Committee

Committee Members
Terry Hertz, NASA Aeronautics Research Mission Directorate, *co-chair*
Jim Jamieson, The Boeing Company, *co-chair*
Nicholas Altiero, Tulane University
Frank Cappuccio, Lockheed Martin
Randall Friedl, Jet Propulsion Laboratory
Frank Frisbie, Northrop Grumman
Richard Golaszewski, GRA, Incorporated
William Lebegern, Metropolitan Washington Airport Authority
Nancy Levenson, Massachusetts Institute of Technology
John O'Brien, Air Line Pilots Association
Col Stuart Rodgers, Air Force Research Laboratory
Nick Sabatini, Federal Aviation Administration
Roger Wall, FedEx Corporation
Terry Weisshaar, Defense Advanced Research Projects Agency

Yuri Gawdiak, Mission Directorate Coordinator, *Designated Federal Official*
Vicki Regenie, Advanced Planning and Integration Office Coordinator (JPL)

Ex Officio and Liaison
Rich Christiansen, NASA Glenn Research Center
Tom Edwards, NASA Ames Research Center
Bob Meyer, NASA Dryden Flight Research Center
Jerry Newsom, NASA Langley Research Center
Mary Ann Thompson, Aerospace Foundation, liaison with the Education Strategic Roadmap Committee

Draft 2/4/05

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
EARTH SCIENCE AND APPLICATIONS FROM SPACE
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Earth Science and Applications from Space Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on research and technology development to advance Earth observation from space, improving scientific understanding, and demonstrating new technologies with the potential to improve future operational systems Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

MEMBERSHIP ROSTER

Earth Science and Applications from Space Strategic Roadmap Committee

Committee

Orlando Figueroa, NASA Science Mission Directorate, ***co-chair***
Diane Evans, Jet Propulsion Laboratory, ***co-chair***
Charles Kennel, Scripps Institution of Oceanography, ***co-chair***
Waleed Abdalati, Goddard Space Flight Center
Leopold Andreoli, Northrop Grumman Space Technology
Walter Brooks, Ames Research Center
Jack Dangermond, ESRI
William Gail, Vexcel Corporation
Colleen Hartman, National Oceanic and Atmospheric Administration
Christian Kummerow, Colorado State University
Joyce Penner, University of Michigan
Douglas Rotman, Lawrence Livermore National Laboratory
David Siegel, University of California, Santa Barbara
David Skole, Michigan State University
Sean Solomon, Carnegie Institution of Washington
Victor Zlotnicki, Jet Propulsion Laboratory

Gordon Johnston, Mission Directorate Coordinator, ***Designated Federal Official***
Azita Valinia, Advanced Planning and Systems Integration Coordinator

Ex Officio and Liaison

Roberta Johnson, University Corporation for Atmospheric Research, liaison with the Education Strategic Roadmap Committee

Final December 17, 2004
Updated March 28, 2005

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
SUN-SOLAR SYSTEM CONNECTION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Sun-Solar System Connection Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on exploring the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

Administrator

Date

MEMBERSHIP ROSTER

Sun-Solar System Connection
Strategic Roadmap Committee

Committee Members

Al Diaz, NASA Science Mission Directorate, co-chair
Franco Einaudi, NASA Goddard Space Flight Center, co-chair
Thomas E. Moore, NASA Goddard Space Flight Center, co-chair
Timothy Killeen, National Center for Atmospheric Research, co-chair
Scott Denning, Colorado State University
Jeffrey Forbes, University of Colorado
Stephen Fuselier, Lockheed Martin
William C. Gibson, Southwest Research Institute
Donald Hassler, Southwest Research Institute
Todd Hoeksema, Stanford University
Craig Kletzing, University of Iowa
Edward Lu, NASA Johnson Space Center
Victor Pizzo, National Oceanic and Atmospheric Administration
James Russell, Hampton University
James Slavin, NASA Goddard Space Flight Center
Michelle Thomsen, Los Alamos National Laboratory
Warren Wiscombe, NASA Goddard Space Flight Center

Barbara Giles, Mission Directorate Coordinator, *Designated Federal Official*
Azita Valinia, Advanced Planning and Integration Office Coordinator (GSFC)

Ex Officio and Liaison

Donald Anderson, NASA Science Mission Directorate
Alan Shaffer, Office of the Secretary of Defense, Network Information Integration, National Security Space liaison
Richard Fisher, NASA Science Mission Directorate
Rosamond Kinzler, American Museum of Natural History, liaison with Education Strategic Roadmap Committee
Michael Wargo, NASA Exploration Systems Mission Directorate
Mark Weyland, NASA Johnson Space Center

Final 12/22/04
Updated 3/14/05

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
ROBOTIC AND HUMAN EXPLORATION OF MARS
STRATEGIC ROADMAPPING COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Robotic and Human Exploration of Mars Strategic Roadmapping Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on Mars exploration, including robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration. The purview of the Committee also includes advice and recommendations on human expeditions to Mars after acquiring adequate knowledge about the planet using these robotic missions and after successfully demonstrating sustained human exploration missions to the Moon. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

MEMBERSHIP ROSTER

Robotic and Human Exploration of Mars Strategic Roadmap Committee

<u>Committee Members</u>

Alphonso Diaz, NASA Science Mission Directorate, *co-chair*
Charles Elachi, Jet Propulsion Laboratory, *co-chair*
A. Thomas Young, Lockheed Martin (retired), *co-chair*
Ray Arvidson, Washington University
Robert Braun, Georgia Institute of Technology
James Cameron, producer/writer/director
Aaron Cohen, Texas A & M University
Steven Dorfman, Hughes Electronics (retired)
Linda Godwin, NASA Johnson Space Center
Noel Hinners, Lockheed Martin (retired)
Kent Kresa, Northrop Grumman
Gentry Lee, Jet Propulsion Laboratory
Laurie Leshin, Arizona State University
Shannon Lucid, NASA Johnson Space Center
Paul Mahaffy, NASA Goddard Space Flight Center
Christopher McKay, NASA Ames Research Center
Sally Ride, University of California, San Diego
Lawrence Soderblom, U.S. Geological Survey
Steven Squyres, Cornell University
Margaret (Peggy) Whitson, NASA Johnson Space Center

Michael Meyer, Directorate Coordinator, *Designated Federal Official*
Judith Robey, Advanced Planning and Integration Office Coordinator

<u>Ex Officio and Liaison</u>

Douglas Cooke, NASA Exploration Systems Mission Directorate
Orlando Figueroa, NASA Science Mission Directorate
James Garvin, NASA Chief Scientist
William Gerstenmaier, NASA Johnson Space Center
Michael Hawes, NASA Space Operations Mission Directorate
Daniel McCleese, Jet Propulsion Laboratory
Douglas McCuistion, NASA Science Mission Directorate
Firouz Naderi, Jet Propulsion Laboratory
Michelle Viotti, Jet Propulsion Laboratory, liaison with the Education Strategic Roadmap Committee Liaison
Joseph Wood, NASA Advanced Planning and Systems Integration Office

December 23, 2004
Updated February 4, 2005

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
SEARCH FOR EARTH-LIKE PLANETS
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Search for Earth-like Planets Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on searching for Earth-like planets and habitable environments around other stars using advanced telescopes. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

MEMBERSHIP ROSTER

Search for Earth-like Planets
Strategic Roadmap Committee

Committee Members
Ghassem Asrar, NASA Science Mission Directorate, *co-chair*
Adam Burrows, University of Arizona, *co-chair*
David Spergel, Princeton University, *co-chair*
Jerry Chodil, Ball Aerospace (retired)
Tom Greene, NASA Ames Research Center
Maureen Heath, Northrop Grumman Space Technology
John Mather, NASA Goddard Space Flight Center
Victoria Meadows, Jet Propulsion Laboratory
Geoff Marcy, University of California
Frank Martin, Lockheed Martin (retired)
Neil Tyson, American Museum of Natural History
Alycia Weinberger, Observatories of the Carnegie Institution of Washington

Eric P. Smith, Directorate Coordinator, *Designated Federal Official*
Rich Capps, Advanced Planning and Integration Office Coordinator (JPL)

Ex Officio and Liaison
Charles Beichman, Jet Propulsion Laboratory
Mike Devirian, Jet Propulsion Laboratory
Edna Devore, SETI, liaison with the Education Strategic Roadmap Committee
Anne Kinney, NASA Science Mission Directorate
Col Steve Petersen, National Reconnaissance Office, National Security Space liaison

Final 12/6/04
Updated 3/29/05

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
UNIVERSE EXPLORATION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Universe Exploration Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on exploring our Universe to understand its origin, structure, evolution, and destiny. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

MEMBERSHIP ROSTER

Universe Exploration Strategic Roadmap Committee

<u>Committee Members</u>

Anne Kinney, NASA Science Mission Directorate, *co-chair*
Nick White, NASA Goddard Space Flight Center, *co-chair*
Kathy Flanagan, Massachusetts Institute of Technology, *co-chair*
Chuck Bennett, NASA Goddard Space Flight Center
Craig Hogan, University of Washington
Steve Kahn, Stanford University, Stanford Linear Accelerator Center
Rene Ong, University of California, Los Angeles
Sterl Phinney, California Institute of Technology
Ron Polidan, Northrop Grumman Space Technology
Michael Shull, University of Colorado
Bob Stern, Lockheed Martin
Michael Turner, National Science Foundation
Jakob van Zyl, Jet Propulsion Laboratory

Michael Salamon, Mission Directorate Coordinator, *Designated Federal Official*
Rich Capps, Advanced Planning and Integration Office Coordinator (JPL)

<u>Ex Officio and Liaison</u>

Louis Barbier, NASA Goddard Space Flight Center
Roy Gould, Harvard Center for Astrophysics, liaison with the Education Roadmap Committee
Steve Maran, American Astronomical Society
Colonel Steve Petersen, National Reconnaissance Office, National Security Space liaison

Final 12/17/04
Updated 2/3/05

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
SPACE SHUTTLE
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Space Shuttle Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on returning the Space Shuttle to flight, completing assembly of the International Space Station, and safely transitioning from the Space Shuttle to a new exploration transportation system. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

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Administrator

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Date

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
INTERNATIONAL SPACE STATION
STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA International Space Station Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on completing assembly of the International Space Station and focusing research on supporting space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 15-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 15-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 15 months are estimated to be $400,000 including 0.7 work years of staff support.

DURATION

The Committee shall terminate 15 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

__________________________ ____________________

Administrator Date

MEMBERSHIP ROSTER

International Space Station
Strategic Roadmap Committee

<u>Committee Members</u>
Mark Uhran, NASA Space Operations Mission Directorate, ***co-chair***
Robert Cabana, NASA Johnson Space Center, ***co-chair***
Thomas C. Betterton, Admiral USN (Ret), Naval Postgraduate School, ***co-chair***
John-David Bartoe, NASA Johnson Space Center
William Bastedo, Booz Allen Hamilton
Jon Bryson, Aerospace Corporation (retired)
Nick Kanas, University of California at San Francisco
Terri Lomax, NASA Exploration Systems Mission Directorate
Ronald Merrell, Virginia Commonwealth University
Charles Oman, Massachusetts Institute of Technology
Jeffrey Sutton, National Space Biomedical Research Institute
Charles Walker, Boeing Aerospace Corporation

Michele Gates, Directorate Coordinator
Stacey Edgington, Advanced Planning and Integration Office Coordinator, *Designated Federal Official*

<u>Ex Officio and Liaison</u>
Michael Lembeck, NASA Exploration Systems Mission Directorate
Edward Lu, NASA Johnson Space Center
Marlene MacLeish, Morehouse School of Medicine, liaison with
Education Strategic Roadmap Committee
Richard Williams, NASA Chief Medical Officer

Final January 24, 2005
Updated February17, 2005

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CHARTER OF THE
EDUCATION STRATEGIC ROADMAP COMMITTEE

ESTABLISHMENT AND AUTHORITY

The NASA Administrator hereby establishes the NASA Education Strategic Roadmap Committee (the "Committee"), having determined that it is in the public interest in connection with the performance of Agency duties under the law, and with the concurrence of the General Services Administration, pursuant to the Federal Advisory Committee Act (FACA), 5 U.S.C. App. §§ 1 et seq.

PURPOSE AND DUTIES

1. The Committee will draw on the expertise of its members and other sources to provide advice and recommendations to NASA on using NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the nation's scientific and technological capabilities. Recommendations to be provided by the Committee will help guide Agency program prioritization, budget formulation, facilities and human capital planning, and technology investment.
2. The Committee shall function solely as an advisory body and will comply fully with the provisions of the FACA.
3. The Committee reports to the Associate Deputy Administrator for Systems Integration (ADA-SI) and to the Administrator.

MEMBERSHIP

1. The Committee co-chair(s) will be appointed by the Administrator. The remaining Committee members will be appointed by the ADA-SI. Membership will be selected to assure a balanced representation of expertise and points of view within the government, academia, and private industry in scientific and technological areas relevant to the Nation's space policy.
2. Members will be appointed for a 21-month term, renewable at the discretion of the ADA-SI. However, members serve at the discretion of the ADA-SI.

SUBCOMMITTEES AND TASK FORCES

Subcommittees and/or task forces may be established to conduct special studies requiring an effort of limited duration. Such subcommittees and/or task forces will report their findings and recommendations to the Committee. However, if the committee is terminated, all subcommittees and/or task forces will terminate.

ADMINISTRATIVE PROVISIONS

1. The Committee will meet approximately three to four times during a 21-month period. Meetings will be open to the public unless it is determined that the meeting, or a portion of the meeting, will be closed in accordance with the Government in the Sunshine Act, or that the meeting is not covered by FACA.
2. The Executive Secretary of the Committee will be appointed by the ADA-SI and will serve as the Designated Federal Official.
3. The Advanced Planning and Integration Office will provide staff support and operating funds for the Committee and is responsible for reporting requirements of section 6(b) of the FACA.
4. The operating costs for its expected duration of 21 months are estimated to be $500,000 including 1.0 work years of staff support.

DURATION

The Committee shall terminate 21 months from the date of this charter unless terminated before that date or subsequently renewed by the NASA Administrator.

Administrator

Date

MEMBERSHIP ROSTER

Education Roadmap Committee

Committee

Adena Williams Loston, NASA Chief Education Officer, *co-chair*
Julian Earls, NASA Glenn Research Center, *co-chair*
France A. Córdova, University of California, Riverside, *co-chair*
Edna DeVore, SETI Institute
Roy Gould, Harvard Center for Astrophysics
Susan Hackwood, California Council on Science and Technology
Heidi Hammel, Space Science Institute
Roberta Johnson, University Corporation for Atmospheric Research
Wayne C. Johnson, Hewlett-Packard
Douglas R. King, St. Louis Science Center
Rosamond Kinzler, American Museum of History
Lt. Col. Timothy Lea, National Security Space
Marlene MacLeish, Morehouse University
Jeff Rosendhal, NASA (retired)
Cassandra Runyon, College of Charleston
Mary Anne Thompson, Aerospace Education Foundation
Michelle Viotti, Jet Propulsion Laboratory

Shelley Canright, Directorate Coordinator, *Designated Federal Official*
Ashley Stockinger, Advanced Planning and Integration Office Coordinator

Ex Officio and Liaison

Bill Anderson, NASA Education Division
Larry Bilbrough, NASA Education Division
Katie Blanding, NASA Education Division
Larry Cooper, NASA Education Division
Jason Freeman, NASA Education Division
Angie Johnson, NASA Education Division
Mayra Montrose, NASA Exploration Systems Division
Nitin Naik, NASA Assistant Chief Technology Officer
Melissa Riesco, NASA Office of Human Capital Management
Carla Rosenberg, NASA Education Division
James Stofan, NASA Education Division
Ming-Ying Wei, NASA Education Division

Staff

(as identified)