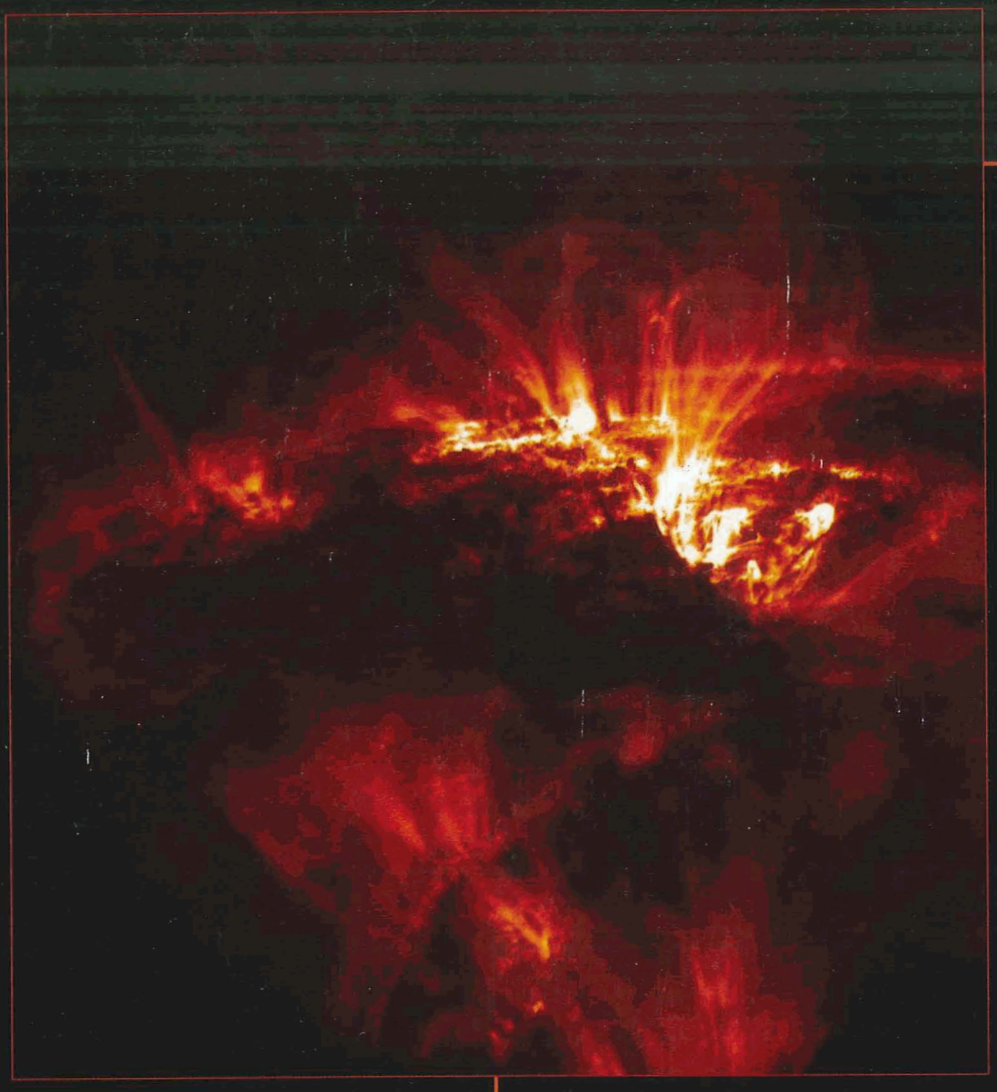
Source of Acquisition
NASA Washington, D. C.



National Aeronautics and Space Administration

Space Science Enterprise Strategy



Cover: Iron ions heated to a temperature of 1.3 million degrees illuminate filamentary magnetic structures in the Sun's atmosphere. This extreme ultraviolet snapshot obtained by the Transition Region And Coronal Explorer (TRACE) satellite in September 2000 also shows intricate bright patterns, called "moss," near the solar surface. **Above**: A visitor to the *Cosmic Questions* exhibition ponders the structure of the universe.

A Message from the Associate Administrator for Space Science



October 1, 2003

Dear Colleagues and Friends of Space Science:

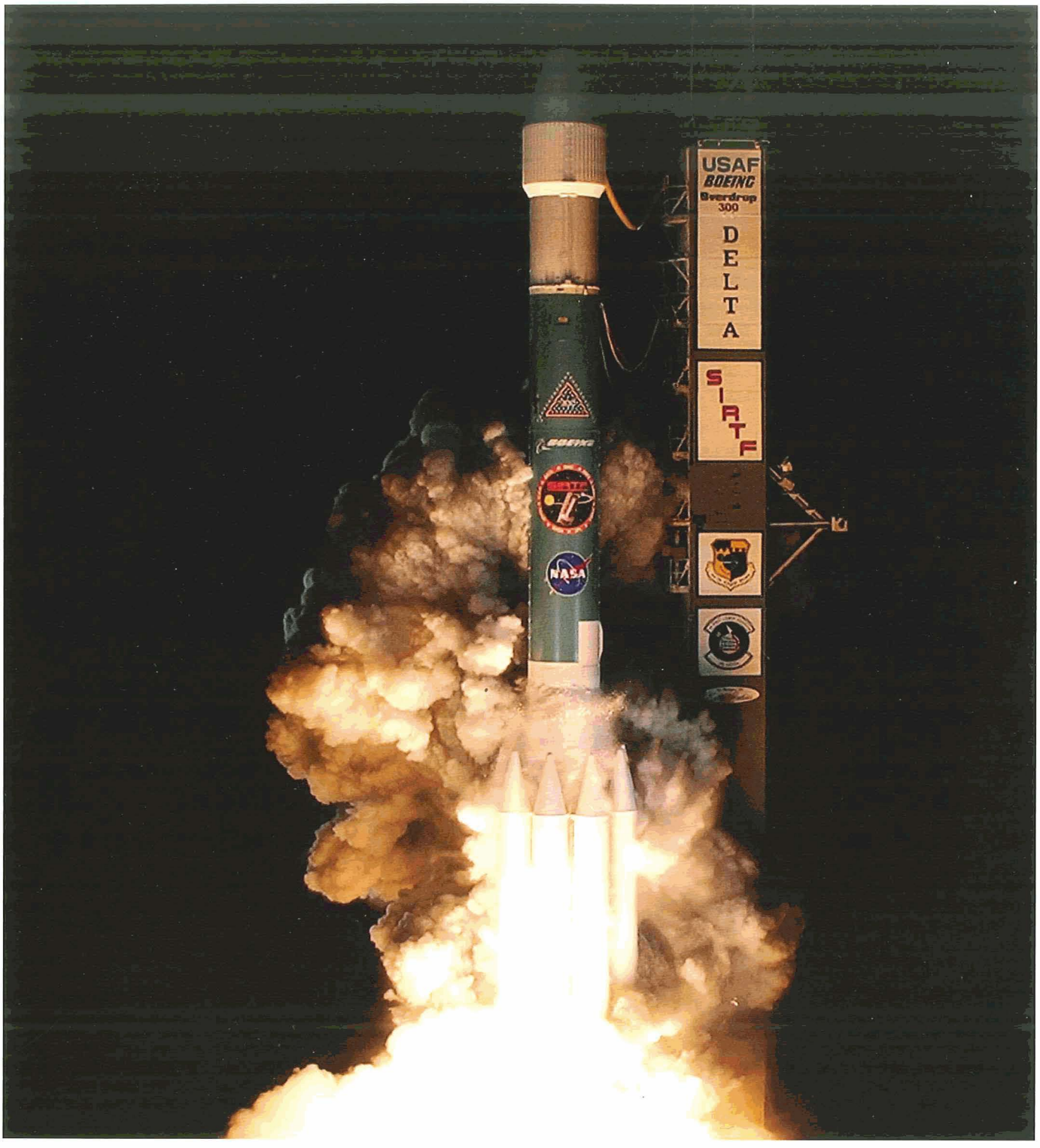
It is a pleasure to present the 2003 Space Science Enterprise Strategy. This Strategy represents the efforts of hundreds of scientists, staff, and educators, as well as collaboration with the other NASA Enterprises. It reveals the progress we have made, our plans for the near future, and our opportunity to support the Agency's Mission to "explore the universe and search for life."

Space science has made spectacular advances in the recent past, from the first baby pictures of the universe to the discovery of water ice on Mars. Each new discovery impels us to ask new questions or regard old ones in new ways. How did the universe begin? How did life arise? Are we alone? These questions continue to inspire all of us to keep exploring and searching. And, as we get closer to answers, we will continue to share our findings with the science community, educators, and the public as broadly and as rapidly as possible.

In our Strategy, you will find science objectives that define our quest for discovery. You will also find the framework of programs, such as flight missions and ground-based research, that will enable us to achieve these objectives. Our Strategy is founded on recommendations from the community, as well as lessons learned from past programs, and maps the stepping-stones to the future of space science.

The universe offers endless surprises and secrets; our vision of the future is limited only by our imagination. I hope you will join us on this fascinating journey.

Edward J. Weiler
Associate Administrator for Space Science



NASA's Space InfraRed Telescope Facility (SIRTF) is a new platform for exploring the universe using infrared light. It joins the Hubble Space Telescope and the Chandra X-Ray Observatory and is the final "Great Observatory." SIRTF is shown being lifted into space aboard a Boeing Delta II Heavy rocket from Cape Canaveral Air Force Station in Florida.

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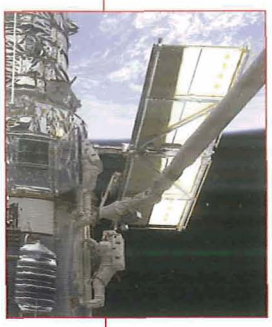
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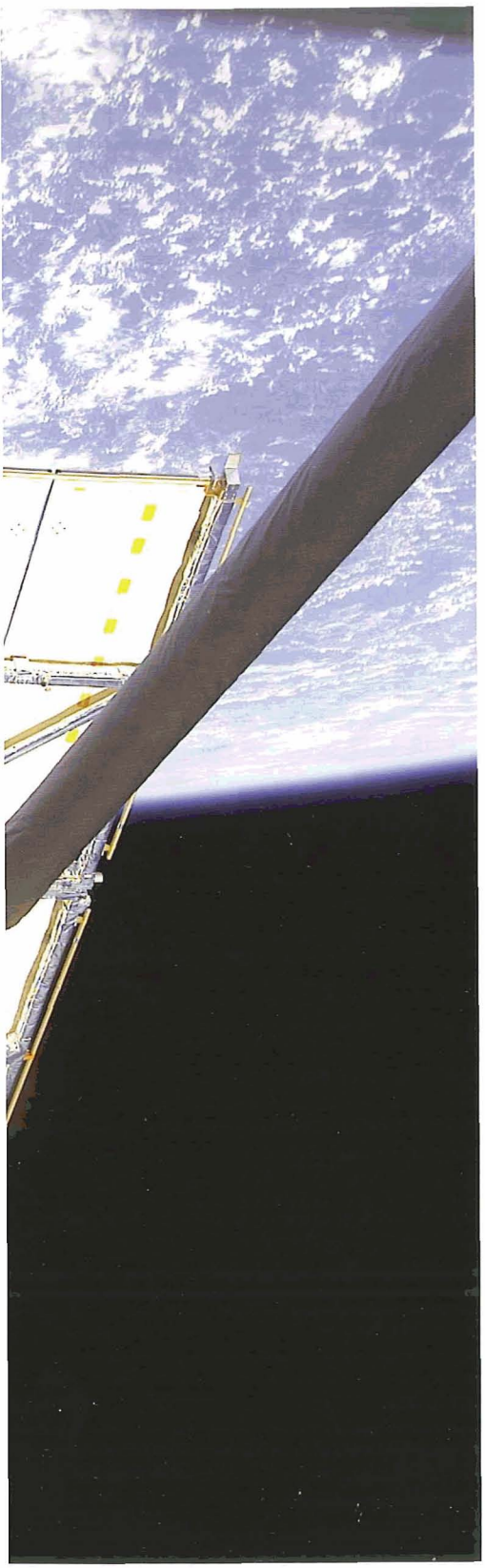
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1 Space Science and NASA's Vision and Mission


NASA



1 Space Science and NASA's Vision and Mission

1.1 Enabling the NASA Vision and Mission

The NASA Vision communicates our mandate in the 21st century simply but powerfully. The NASA Mission lays out a clear path to the future and provides a framework for developing goals that each part of NASA must achieve. NASA's Strategic Plan has seven strategic goals that enable the Enterprises to focus our planning, manage programs, and measure results. Each of the Agency's six Enterprises—Space Science, Earth Science, Biological and Physical Research, Aerospace Technology, Education, and Space Flight—uses the strategic goals to define and guide its programs. Table 1 lists the strategic goals and maps them to the Agency's Enterprises.

The NASA Vision—
To improve life here,
To extend life to there,
To find life beyond.

The NASA Mission—
To understand and protect our home planet,
To explore the universe and search for life,
To inspire the next generation of explorers
. . . as only NASA can.

Astronauts John M. Grunsfeld (top) and Richard M. Linnehan participate in a 6-hour, 48-minute spacewalk to install a new power control unit on the Hubble Space Telescope (HST). This Space Shuttle mission, STS-109, included spacewalks to install new solar arrays, the Advanced Camera for Surveys, and a cooling system to revive the Near Infrared Camera and Multi-Object Spectrograph (NICMOS).

1.2 Introduction to Space Science

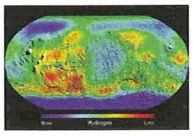
NASA's Space Science Enterprise has achieved remarkable results in our mission to explore the universe and inspire the next generation. In the 3 years since the last Space Science Strategic Plan was published, we have



looked below the Sun's surface;



traced the flow of energy from solar eruptions to Earth's atmosphere;



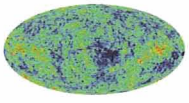
discovered abundant water ice on Mars;



found evidence of sedimentary processes on Mars;



detected an atmosphere on a planet outside our solar system;



made the first detailed full-sky map of the oldest light in the universe;



discovered that dark energy is accelerating the expansion of the universe;



discovered that supermassive black holes pervade the universe; and



tripled the scope of NASA's space science education and public outreach program.

The pace of discoveries will quicken in the years to come as new technologies allow us to explore the profound mysteries of life, space, time, and the workings of the universe. Our programs for the next 5 years build upon these recent results in the pursuit of answers to fundamental questions. We will search for signs of life elsewhere as we strive to understand all that the term "life" may encompass. We will look for the origins of our universe, including its beginning, its structure, and the formation of our cosmic neighborhood of planets, stars, and galaxies. We will learn about our nearest star, the Sun, to understand its effects on our lives and on the evolution of the solar system. And we will invest in the research and technology needed to achieve these objectives.

Conveying scientific results to the public is as important as the scientific discoveries themselves. Every program in the Space Science Enterprise will maintain its commitment to education and public outreach. We will use the unique features of our science to contribute exciting new material to national science curricula and to inspire both the young and old, but particularly the next generation, which represents humanity's future.

This 5-year Strategy communicates our objectives and our methods to achieve them. All of our flight programs, research programs, education and public outreach efforts, and collaborations are defined by and measured against the objectives laid out here and in the NASA 2003 Strategic Plan. In short, this is a guide to what we intend to do and why.

The following sections show the traceability of the space science objectives from the overarching NASA Vision, Mission, and strategic goals. They describe the processes we use to achieve the objectives and elaborate on our science themes and program elements. The content of our education effort and its tools are also described, as are technology requirements and development processes. We describe our partnerships and our unique resource requirements, including human and capital resources, and we conclude with a vision of the future of space science and discovery.

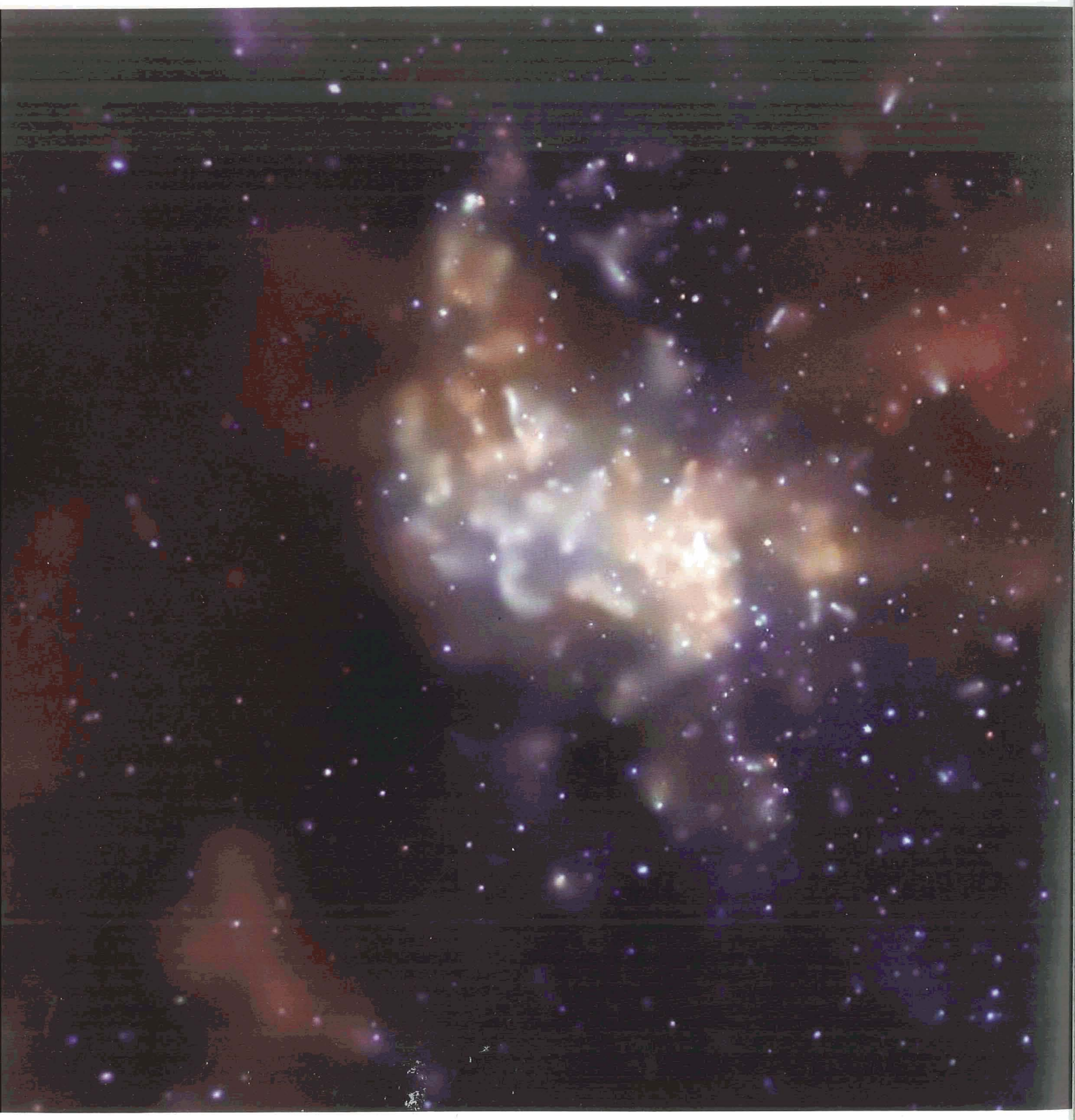
Mission Area	Agency Strategic Goal	NASA Enterprise
Understand and protect our home planet.	1. Understand the Earth system and apply Earth system science to improve prediction of climate, weather, and natural hazards.	Earth Science, **Space Science**, Space Flight
	2. Enable a safer, more secure, efficient, and environmentally friendly air transportation system.	Aerospace Technology
	3. Create a more secure world and improve the quality of life by investing in technologies and collaborating with other agencies, industry, and academia.	Biological and Physical Research, Space Flight, Aerospace Technology, Earth Science
Explore the universe and search for life.	4. Explore the fundamental principles of physics, chemistry, and biology through research in the unique natural laboratory of space.	Biological and Physical Research, Space Flight
	5. Explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.	**Space Science**, Space Flight
Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics.	6. Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics.	**Space Science**, Earth Science, Biological and Physical Research, Aerospace Technology, Education, and Space Flight
	7. Engage the public in shaping and sharing the experience of exploration and discovery.	

Table 1.—Among NASA's strategic goals, the Space Science Enterprise is entrusted with primary responsibility for goal 5: "To explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere." We also support the first goal and the education and public outreach goals (6 and 7).





2 Role of the Space Science Enterprise





2 Role of the Space Science Enterprise

The Space Science Enterprise is at the heart of exploration and discovery. It carries out NASA's space science research through a portfolio of programs and projects that provide opportunities for research, data analysis, and the development of new flight missions.

NASA's goals are very broadly stated. To enable the Enterprises to plan, manage, and measure progress, the Agency's goals are further subdivided into objectives. The process of developing space science objectives, as listed in table 2, is the foundation of our relationship with and commitment to the space science community.

The consolidated Enterprise objectives represent a consensus on priorities. They guide the selection of investigations and other programmatic decisions.

Scientists at universities and other external institutions guide the formulation and articulation of the Enterprise objectives. The National Research Council (NRC) performs independent studies of the status of scientific knowledge in key areas and provides recommendations for future investigations. Based in part on the NRC inputs, the Enterprise's Space Science Advisory Committee and its discipline subcommittees identify high-priority science objectives and suggest a program of flight missions to address the objectives.

The Enterprise analyzes these inputs—considering also such factors as technology readiness and

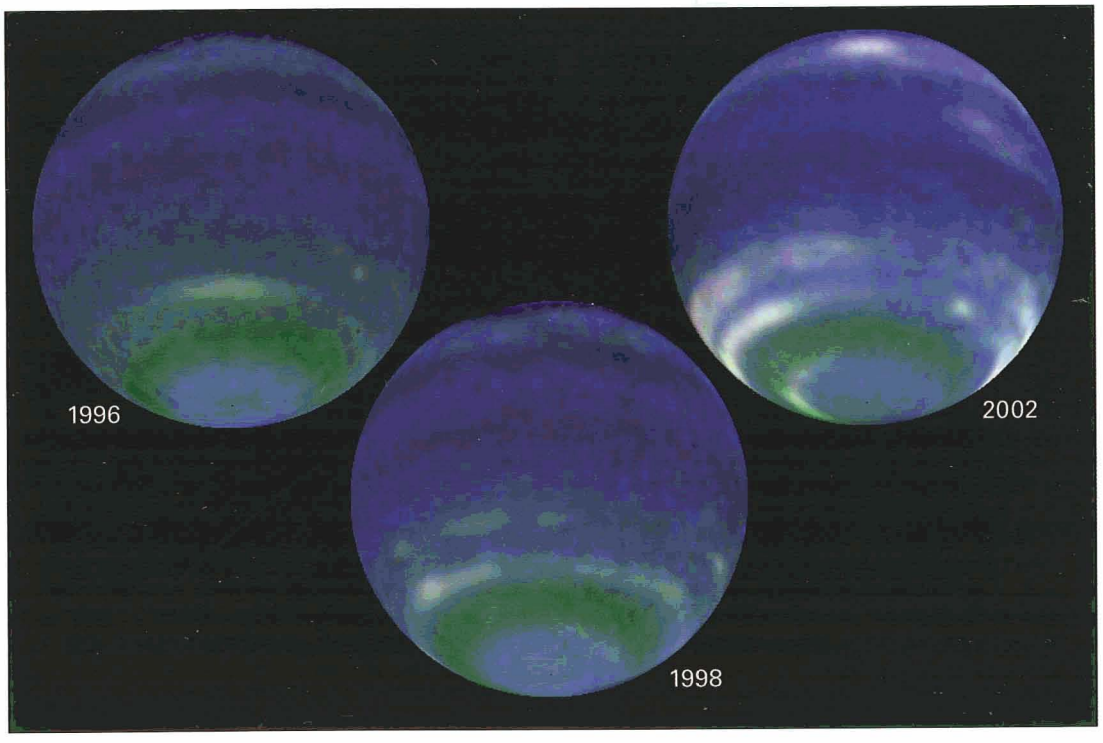
Sagittarius A* is the supermassive black hole at our galaxy's center. The red regions in this Chandra X-Ray Observatory image are huge lobes of 20-million-degree-Celsius gas that extend over dozens of light-years. (Credit: NASA/CXC/MIT/F.K. Baganoff et al.)



resource projections—and formulates an integrated program of flight missions, scientific research, and technology development. The consolidated Enterprise objectives represent a consensus on priorities. They guide the selection of investigations and other programmatic decisions, contribute to the NASA Strategic Plan and performance assessments, and support program and budget advocacy.

The programs and activities implemented to meet Enterprise objectives are funded through one of five space science themes: Solar System Exploration, Mars Exploration, Sun-Earth Connection, Astronomical Search for Origins, and Structure and Evolution of the Universe. These themes provide the structure for budget planning, program management, and performance reporting. For the purpose of clarifying program activities, the Enterprise further divides the strategic science objectives into research focus areas. These are summarized within the science theme discussions, and the full structure is provided in Appendix 3.

Education and public outreach are so important to NASA's overall Mission that a separate set of strategic goals has been established for them. Every Space Science Enterprise program contributes actively and directly to the Agency's education goals. Management and funding of these activities are distributed throughout the themes.

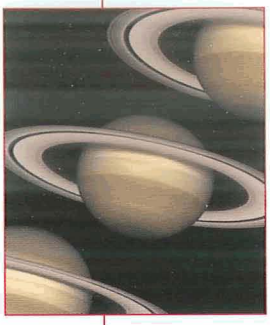


Neptune's brightness, as shown in these Hubble images, has increased significantly since 1996, perhaps due to seasonal changes caused by variation in solar heating. Because Neptune takes 165 years to orbit the Sun, springtime in the southern hemisphere will last for several decades. (Credit: NASA/HST/L. Sromovsky/P. Fry)

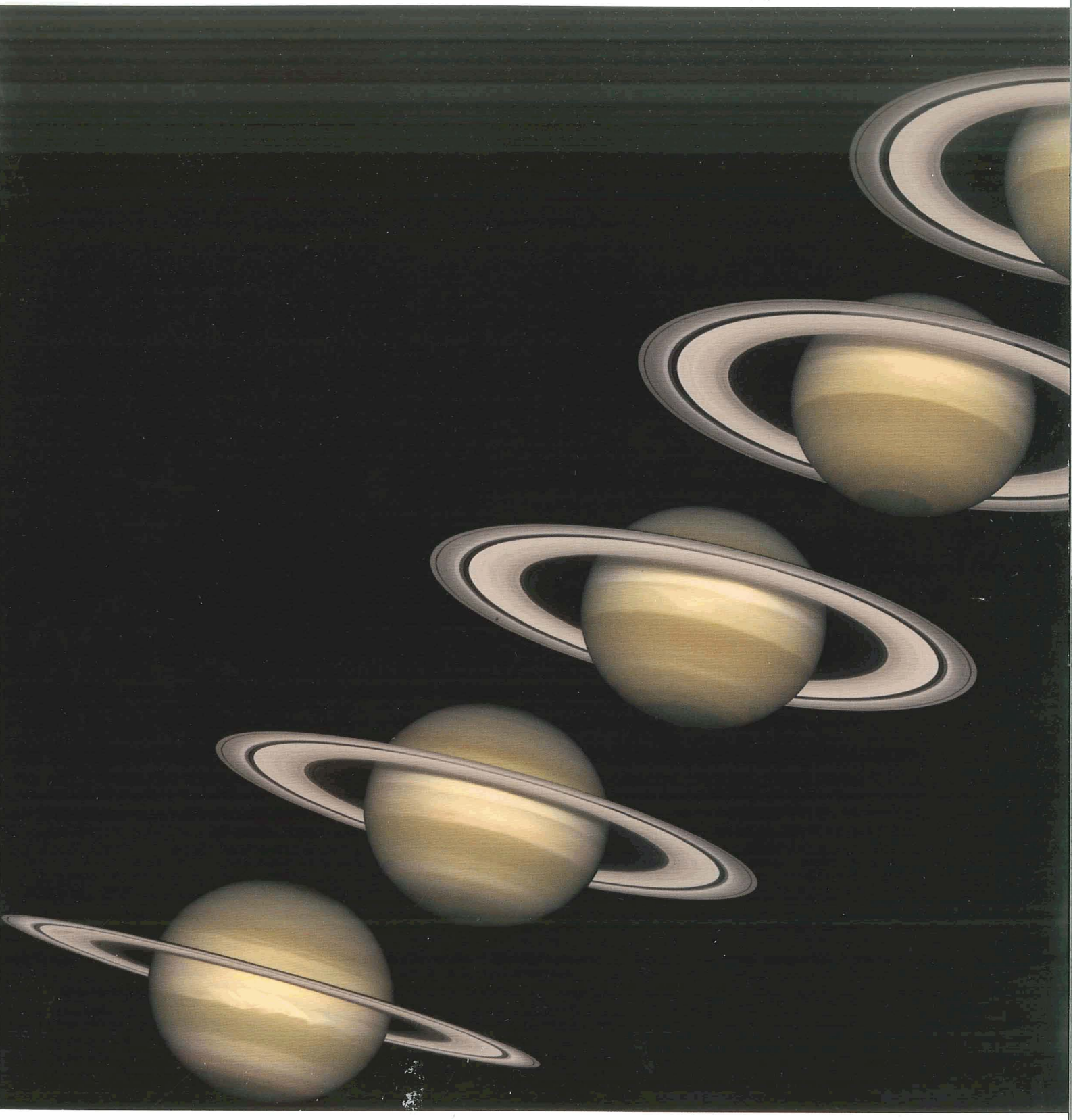
Agency Strategic Goal	Agency Strategic Objective	Space Science Theme
1. Understand the Earth system and apply Earth system science to improve prediction of climate, weather, and natural hazards.	1.3 Understand the origins and societal impacts of variability in the Sun-Earth connection. 1.4 Catalog and understand potential impact hazards to Earth from space.	Sun-Earth Connection Solar System Exploration
5. Explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.	5.1 Learn how the solar system originated and evolved to its current diverse state. 5.2 Understand how life begins and evolves and determine the characteristics of the solar system that led to the origin of life.	Solar System Exploration
	5.3 Understand the current state and evolution of the atmosphere, surface, and interior of Mars. 5.4 Determine if life exists or has ever existed on Mars. 5.5 Develop an understanding of Mars in support of possible future human exploration.	Mars Exploration
	5.6 Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments. 5.7 Understand the fundamental physical processes of space plasma systems.	Sun-Earth Connection
	5.8 Learn how galaxies, stars, and planetary systems form and evolve. 5.9 Understand the diversity of worlds beyond our solar system and search for those that might harbor life.	Astronomical Search for Origins
	5.10 Discover what powered the Big Bang and the nature of the mysterious dark energy that is pulling the universe apart. 5.11 Learn what happens to space, time, and matter at the edge of a black hole. 5.12 Understand the development of structure and the cycles of matter and energy in the evolving universe.	Structure and Evolution of the Universe
6. Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics.		All themes
7. Engage the public in shaping and sharing the experience of exploration and discovery.		All themes

Table 2.—Each strategic objective for which the Enterprise is responsible is managed within a science theme. This ensures direct traceability of the programs to Agency goals.





3 Achieving Space Science Objectives





3 Achieving Space Science Objectives

The Space Science Enterprise achieves its objectives through flight missions and ground-based scientific research and data analysis. The interplay between flight missions and supporting research is the source of vitality for the whole program.

All space science activities are managed within the themes using standard processes that impose fairness and consistency across the Enterprise. This section describes these processes and the programs that enable us to achieve our objectives.

3.1 Program Elements

Although space science investigations cover very diverse topics, from cosmology to space plasmas to life in extreme environments, the Enterprise applies a uniform approach to selecting and implementing the individual flight projects in every theme. Supporting research and analysis cover an enormous breadth of topics, as do technology development and demonstration activities, but they too are managed, to the extent possible, in a consistent way. Education and public outreach, which are important mandates for the space science program, seek efficiencies by adopting common strategies and organizational approaches across the Enterprise.

3.1.1 Flight Missions

The National Aeronautics and Space Act of 1958 established NASA as a mission agency that sponsors and conducts flight missions to obtain data in furtherance of its objectives. In the Space Science Enterprise, flight missions range from suborbital projects—including balloons, sound-

From lower left to upper right, Saturn moves from the autumnal equinox in the Northern Hemisphere to its winter solstice. These Hubble images, taken over 4 years, are a preview of what Cassini will see in 2004.



ing rockets, and airplanes—to interplanetary probes and flagship observatories.

All investigations and missions selected and flown must respond to Agency goals and strategic objectives. In some cases, the Enterprise specifies mission science objectives and requirements based on the strategic planning process. Instrument investigations to meet these requirements are then solicited from the scientific community. In other cases, often called "community-based" missions, Principal Investigators (PIs) from the scientific community form teams to propose entire missions, from basic science requirements through mission operations and science data analysis after launch. These teams often include universities, industry, outside laboratories, NASA Centers, and foreign partners.

The Space Science Enterprise combines consecutive missions that address a cluster of science objectives into "mission lines." Within these mission lines, we fly successive missions as science priorities dictate and as resources and technology permit. Among the mission lines are the Discovery Program, which comprises Solar System Exploration and Origins missions; Mars Scout, which includes regular opportunities for innovative research in support of Mars objectives; New Frontiers, a new line for planetary exploration; Solar Terrestrial Probes; the Living With a Star (LWS) line; and the Explorer Program (see box).

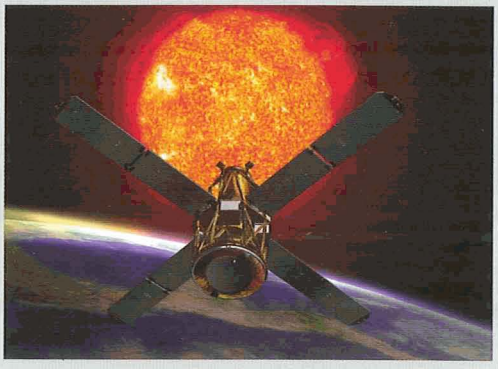
The Enterprise encourages broad participation in all of its flight missions by the academic community and outside industry. Foreign partners are also welcome to participate on a cooperative, no-exchange-of-funds basis. Open and competitive merit selection is fundamental to all aspects of Space Science Enterprise programs. That is, opportunities are open to all proposers, within fixed rules, via public announcement, and selections are based primarily on scientific and technical merit as evaluated by independent peer review. Another fundamental aspect of our programs is that instrument development and mission implementation are managed according to fixed performance requirements and cost caps. Finally, extension of a mission's operation beyond its funded baseline is determined by means of a competitive selection based on past and prospective scientific productivity of the mission compared to that of other ongoing missions.

Mission Lines: Explorers

NASA's Explorer Program is an example of the mission lines that are vital to realizing the Enterprise's science objectives. Explorer missions are space physics and astronomy missions intended to study the Sun, to examine the space environment of Earth and other planets, and to observe the universe beyond the solar system.

The Explorer Program offers frequent opportunities to carry out small- and medium-sized community-based missions (SMEX and MIDEX) that can be developed and launched in a short (approximately four-year) timeframe. These focused missions can address important science that complements the science of strategic missions. They also allow quick response to new scientific and technical developments.

The Mission of Opportunity option of the Explorer Program enables valuable collaborations with other agencies, both national and international. Explorer missions and Missions of Opportunity are selected for science value through competitive peer review. Each Explorer solicitation elicits more high-quality experiments than can be implemented. Peer review, implementation of creative ideas, and rapid reaction to new discoveries are essential elements for obtaining high science value in all space science mission lines.



Artist's concept of the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) Explorer observing the Sun.

3.1.2 Scientific Research and Analysis

Each science theme sponsors research programs that provide opportunities to develop new ideas, concepts, and methods, as well as to analyze and interpret data from space science missions. Research programs are crucial to the space science

community because ideas developed here often form the basis for new mission concepts. The NRC strongly supports these programs in a number of its reports and science discipline surveys. Strong university involvement in the programs provides the additional benefit of training graduate students and the leaders of future space missions; veterans of the programs often become major instrument builders and PIs of flight missions.

These programs consist of four key elements: Research and Analysis, Data Analysis, Suborbital Programs, and Science Data and Computing Technology. Participants are selected through a broadly advertised, open, competitive process. Proposals are solicited, usually annually, through NASA Research Announcements (NRAs) developed by the discipline scientist responsible for the particular program element.

Research and Analysis (R&A) provides the foundation for the formulation of new scientific questions and strategies. It supports research tasks across the entire breadth of the space sciences, including all aspects of cosmology; stellar and galactic astronomy and astrophysics; astrobiology and cosmochemistry; the origins and evolution of planetary systems; the atmospheres, geology, and chemistry of the solar system's planets (other than Earth); solar physics, heliospheric physics; and the physics of the ionospheres, thermospheres, and magnetospheres of Earth and the other planets.

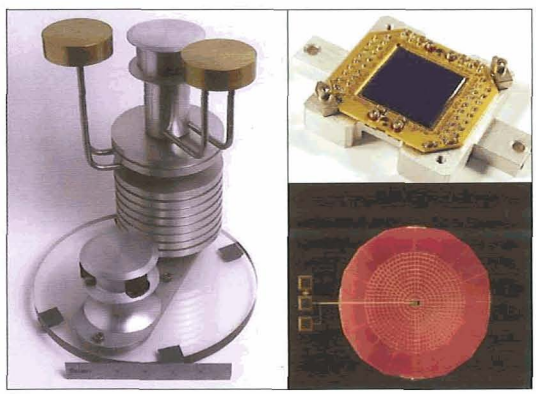
These tasks incorporate the full range of scientific techniques, including development of new detectors and instruments, corroborative ground-based observations, laboratory measurements, suborbital rocket and balloon payload experiments, supporting technologies, modeling, and basic theory. In all cases, we base our support of research tasks on their relevance to space science objectives, as well as to past, current, and planned NASA missions and programs.

Advanced detector and instrument system concepts are developed under sponsorship from space science R&A programs. For example, detector concepts for the Hubble Space Telescope, the Chandra X-Ray Observatory, the Solar and Heliospheric Observatory (SOHO), and the Space Infrared Telescope Facility (SIRTF) were developed largely within the R&A program. Likewise, future generations of instruments slated for possible use on Explorer, Discovery, and other strategic missions are currently under development within the R&A program.

Ground-based programs are particularly valuable in preparing for new missions, testing new technologies, investigating new observing strategies, and providing data to test new analysis techniques. They also provide data to correlate with complementary space-based measurements.

Laboratory measurements can provide the essential link between observations and scientific conclusions. For example, the Laboratory Astrophysics program supports a tremendous breadth of topics, from the coldest regions deep in molecular clouds to the extraordinary environments around supermassive black holes. R&A programs support laboratory and theoretical studies of atomic and molecular properties and plasma physics that are central to our understanding of important aspects of solar system plasmas. Techniques are also being developed for curating and analyzing returned samples of cometary dust and eventually of Mars's surface.

Supporting technologies such as lightweight mirrors, optical coatings, gratings, and solar blind filters are developed through R&A programs to the level of laboratory demonstration models. Because the advance of measurement capabilities informs our



Component development of high-performance detectors and cryocoolers lays the foundation for the next generation of astronomical observatories.



priorities for starting and launching future space missions, supporting technologies have a direct influence on future mission planning.

The modeling and theory work in the R&A program defines research directions, predicts observable phenomena, and enables the analysis and interpretation of data returned by NASA's space science missions to exploit them fully and achieve strategic objectives. The prediction of observable and measurable phenomena drives future missions, spacecraft, and payload design requirements.

The R&A programs can have a broad reach, affecting diverse science objectives and themes. As observed by the NRC report *Life in the Universe*, the Astrobiology Program (see box) has linkages to Solar System Exploration, Astronomical Search for Origins, and the Mars Exploration Program.

Astrobiology

Life on Earth exists under extreme conditions, in the heat and acidity of volcanoes and in the cold darkness of the deepest seabed. Could life exist in the icy oceans of Jupiter's moons or in the atmosphere of an extra-solar planet? This question captures the essence of the exciting and emerging discipline of astrobiology.

NASA's Astrobiology R&A programs have been at the forefront of an effort to break down barriers and promote vigorous research at the boundaries between traditional scientific disciplines. Astrobiology spans a wide range of investigations, including understanding the nature and distribution of habitable environments in the universe; exploring for past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our solar system; understanding how life emerges from cosmic and planetary precursors; understanding how past life on Earth interacted with its changing planetary and solar system environment; understanding the evolutionary mechanisms and environmental limits of life; understanding the principles that will shape the future of life, both on Earth and beyond; and determining how to recognize signatures of life on other worlds and on early Earth.

Astrobiology is multidisciplinary in its content and interdisciplinary in its execution. Four openly competed, complementary R&A programs provide the intellectual foundation and mechanisms to prepare for and guide future space exploration opportunities.

- The exobiology/evolutionary biology program focuses individual investigator research on the origins and evolution of life, using Earth as a benchmark against which the potential for life in the galaxy is to be measured.
- The NASA Astrobiology Institute, an institute without walls, enables concentrated science collaboration by expert teams located across the U.S. and the world to answer fundamental questions in astrobiology.
- An instrument program encourages development, from concept to laboratory-bench-level, of astrobiology-specific instruments capable of operating in space and extraterrestrial environments.
- A program of science-driven robotic explorations of extreme environments expands our understanding of life on Earth and improves our capacity for semi-autonomous operations when exploring other planetary bodies.

As a fundamental principle, astrobiology programs promote planetary stewardship through an emphasis on protection against forward and backward biological contamination and recognition of ethical issues associated with exploration. In addition, broad public interest in the science of astrobiology offers an important opportunity to educate and inspire the next generation of scientists, technologists, and informed citizens. Thus, there is a strong emphasis on education and public outreach in the astrobiology programs.



Cyanobacteria and purple sulfur bacteria from a microbial mat. Their study may reveal the nature of Earth's earliest ecosystems and potential biosignatures that could exist on other planets.

Data Analysis supports the analysis of scientific data returned by space science missions with the goal of maximizing the scientific return from NASA's investment in spacecraft and other data-collection sources. The Data Analysis program is fundamental to achieving space science objectives because it funds data analysis during and after a spacecraft's lifespan. Funding also supports long-term data archiving and database services.

Data Analysis supports interpretive research of mission data that leads to discoveries and predicts new directions for future scientific investigations. Work in this program is performed by mission instrument teams and interdisciplinary scientists who are competitively selected to participate on an individual mission for its lifetime. Support for investigations beyond a mission's baseline operation is determined through a competitive senior review process. In addition, there are periodic open and competitive solicitations for Guest Investigators to analyze data from these missions.

Suborbital Research Carriers—high-altitude balloons and sounding rockets—operate at the brink of space and are used for scientific research and to develop flight experiments. The goal of NASA's suborbital balloon and sounding rocket operations is to provide low-cost, frequent access to space. Here, scientific problems can be addressed in a wide range of scientific disciplines; new technology and techniques can be flight-tested relatively inexpensively; and students can be trained on timescales commensurate with their graduate studies. Detectors and instruments developed in the R&A programs are frequently tested under real-life conditions in the sounding rocket and balloon programs before they are selected to fly on much more expensive spacecraft. Sounding rocket and balloon investigations are especially suited to the university research environment. They are characterized by diversity in the number and types of scientific investigations they support. In a single year, typically over 200 scientists from more than 60 different institutions are involved in balloon and sounding rocket missions. These suborbital missions are the first payload flights for a large number of new experimental scientists, so they help form the foundation of the NASA space science orbital missions.



Balloon ready for launch on a long-duration flight from Alice Springs, Australia, to Brazil.



High school students conduct final preflight assembly of the suborbital student experiment module at Wallops Flight Facility.

The payloads are funded through the R&A program, independently of the flight operations. In addition, the Explorer Program allows long-duration balloon missions to be proposed as Missions of Opportunity. Although NASA provides reliability and quality-assurance oversight, the PI is completely responsible for each mission's success.

Balloon flights provide a cost-effective way to make scientific observations in the near-space environment, where the atmospheric pressure is a small fraction of that at sea level. Balloons frequently offer the only viable flight opportunity for large or heavy instruments or cost-constrained experiments. They provide the primary flight-test and calibration opportunities for space-based astronomy and physics missions.



Sounding rockets are uniquely suited to studying variations in the terrestrial atmosphere at a range of altitudes. They are also used to study Earth's magnetosphere and near-space environment; incoming energetic particles and solar radiation, including the production of the aurora; and radiation from the Sun, stars, and other celestial objects. Like balloons, sounding rockets are used to flight test and calibrate instruments and experiments being developed for future orbital missions.

The NASA Wallops Flight Facility is home to both sounding rocket and balloon projects.

Science Data and Computing Technology provides Enterprisewide, multidisciplinary support in the areas of science data management, scientific computing and communications, and applied information systems research and technology. Vast amounts of data are returned from space science missions. Without adequate storage and retrieval, the data, the fruit of years of labor, would be wasted. The Space Science Enterprise has a strong tradition of user-driven data systems that include systematic processing and archiving of data that are ultimately placed in open archives accessible to both scientists and amateur astronomers alike. The future Enterprise science data and information systems environment will continue to exploit advances in information technology to provide efficient access to widely distributed data sets, along with the ability to integrate data from multiple missions into a larger context.

Coordinated and interoperable data archives will evolve into virtual observatories that will enable exploration and data mining of the multitude of astronomical data from disparate observatories, from ground-based radio telescopes to space-based X-ray and gamma-ray platforms—the entire universe in all its electromagnetic glory at one's fingertips. Theoretical modeling and numerical simulations, as well as the assimilation of observational data into the models, will be enabled within the virtual-observatory environment. Examples of virtual-observatory collaborations include the Virtual Solar Observatory and the National Virtual Observatory (NVO) initiative to integrate most of the Nation's astronomical data.

The design and implementation of these virtual observatories will follow the proven formula of the Space Science Enterprise: they will be driven by the requirements of future missions and the needs of the user communities to realize the Enterprise's science objectives. This framework will build upon current successful, discipline-specific capabilities, including the Planetary Data System, the astrophysics wavelength-oriented science archive research centers, the Solar Data Analysis Center, and the multidiscipline National Space Science Data Center (NSSDC). Opportunities to coordinate with related activities in other Federal agencies and international partners will be encouraged.

Science Data Management supports Enterprisewide policies and standards to enhance compatibility and sharing across discipline science efforts. This effort promotes a more coherent and coordinated data environment to improve quality, accessibility, and usability of NASA's space data for scientists, educators, and the general public. This program element sponsors the NSSDC as part of the overall federation of Space Science Enterprise data capabilities mentioned above.

Scientific Computing and Communications support the application of high-performance computing and communications technologies to meet space science needs. The marriage of advancing detector technology and high-performance computational capability will continue to enable breakthroughs in our understanding of the cosmos. Current efforts in large-scale computation include designing "numerical laboratories" to model physical processes and effects impossible to study in the laboratory, such as the behavior of matter around a black hole. We will continue to close the gaps between theory, simulations, and observations to expand our understanding and, ultimately, predictive capabilities. Examples of computationally intensive endeavors include gravitational wave source modeling and the Living With a Star program, which is aimed at understanding space weather.

Applied Information Systems Research and Technology use new developments in computer science and information technology to enrich space science missions and research programs. Advanced software tools, algorithms, and computational

methods are selected through open, peer-reviewed solicitations and promote strong collaborations among the space science community, the computer science community, data systems engineers and technologists, and academic and private-sector technology innovators. Tools and capabilities developed under the program are broadly disseminated through the space science data and computing infrastructure and may be infused directly into missions.

3.1.3 Education and Public Outreach (E/PO)

Employees at NASA know that the mere mention of their jobs to friends, relatives and acquaintances evolves into a multitude of questions about life on Mars or the fate of matter around a black hole. Space science has a capacity to captivate the public unlike that of any other scientific discipline. By engaging the imaginations of teachers, students, and the general public, space science has demonstrated extraordinary potential for strengthening interest in science and improving the quality of science, technology, engineering, and mathematics education in America. By attracting bright individuals to advanced study in technical fields, space science also plays a significant role in ensuring a continuing cadre of trained scientists, technologists, and engineers to meet our society's needs in the 21st century.

The Space Science Enterprise has developed an extensive education and public outreach program that strongly supports the NASA mission to "inspire the next generation of explorers." Consistent with NASA priorities, the two main elements of our education and public outreach program are to "inspire and motivate students to pursue careers in science, technology, engineering, and mathematics" by supporting education in the Nation's schools and to "engage the public in shaping and sharing the experience of exploration and discovery" by supporting informal education and public outreach efforts. Our program emphasizes sharing the results of our missions and research programs with wide audiences and using space science discoveries as vehicles to improve teaching and learning at all levels. We place special emphasis on precollege education, diversity, and increasing the general public's understanding and appreciation of science, technology, engineering, and mathematics. This emphasis complements our traditional role in higher education, where we will continue to support professional education through research involvement. This involvement is a central element in fulfilling our responsibility to help create the scientific and engineering workforce of the future. We also provide opportunities for participation in the space science program to a diverse population, including opportunities for minorities and minority universities, which compete for and participate in space science missions, research, and education programs.

Since the previous Enterprise Strategic Plan's release in 2000, our education and public outreach efforts have reached a visible level of maturity. Funded education and public outreach programs are embedded in all of our missions and research programs; partnerships have been established with hundreds of local, regional, and national institutions and organizations; and thousands of education and public outreach events are taking place annually throughout the Nation.

Education and Public Outreach Implementation Approach

The Space Science Enterprise approach to supporting NASA's education and public outreach goals and objectives is based on our policy of incorporating education and public outreach as integral components of all of our activities, both flight missions and research programs. Contributing to education and outreach is the collective responsibility of all levels of Enterprise management and of all participants in the space science program. Space science mission personnel and researchers, in particular, are encouraged to become active participants in education and outreach activities. We focus on identifying and meeting the needs of educators and on emphasizing the unique contribution NASA space science can make to education and the public's understanding of science.

With limited resources, leverage is key to building a national program that contributes both to improving teaching and learning at the precollege level and to increasing the scientific literacy of the general public. The Enterprise achieves this leverage in precollege education by building on existing programs, institutions, and infrastructure and by coordinating activities and encouraging part-



A young explorer examines the Sun as it appears in *Voyage*, an accurate, one-ten-billionth scale model of the solar system on the National Capitol Mall.



In the cosmic kitchen, visitors to the *Cosmic Questions* exhibition learn that, in order to make apple pie, you must first make the universe. (Credit: Smithsonian Astrophysical Observatory/Kevin Burke)

nerships with other ongoing education efforts. We have also established alliances for informal education with science centers, museums, and planetariums, as well as producers of public radio and television programs. We are experimenting with new ways to bring the results of the space science program to teachers, students, and the public through partnerships with community organizations of many different types across the country. In all of these partnerships, we seek to provide space science content and expertise while relying on our partners to provide the educational expertise and context.

To improve the effectiveness of our education and public outreach program, we operate a national space science support network that helps the space science community become involved in education and outreach and ensures that products and programs developed locally become national resources. We make our educational products readily available to educators through an online education resource directory that is linked to other NASA and national databases of educational materials. We provide opportunities for participation in space science programs by an increasingly diverse population by emphasizing inclusiveness and developing special opportunities for minority students and educators, minority institutions, students with disabilities, and other targeted groups. The Braille book of Hubble images entitled *Touch the Universe*, for example, offers the visually impaired community, for the first time, access to these wonderful pictures that many of us take for granted. Finally, we seek expert feedback on quality and impact through a variety of evaluations by external groups.

Future Efforts

Our future education and public outreach efforts will build on these activities and accomplishments with an emphasis on improving their quality and impact and on extending their reach into new areas. Our efforts will include the following:

- Continue to contribute to the professional training of scientists by supporting research assistantships and postdoctoral opportunities offered through Space Science Enterprise research awards and through other NASA research and higher education programs

- Coordinate our education and public outreach program with other similar efforts undertaken throughout NASA in order to optimize our contribution to the Agency's overall education program

- Provide opportunities for students to work directly with NASA space science missions, facilities, and data; such opportunities are particularly important for pre-college students, where the experience of being involved in a NASA mission or research program inspires career choices and life-long interests

- Increase opportunities for diverse populations to participate in space science missions, research, and education and outreach programs; continue and expand our efforts to develop space science capabilities at minority institutions; develop and enhance partnerships with special interest organizations such as professional societies of minority scientists; develop working partnerships and coordinate with the diversity initiatives of scientific professional societies; extend the accessibility of space science E/PO programs and products to an increasingly broad population, including girls, residents of rural areas, and persons with disabilities

- Improve the coherence of NASA space science materials for educators by building a framework that will show the appropriate standards-aligned sequencing of space science topics throughout the K–12 years for

the materials being produced by individual missions

- Build on strong mutual interests between the Space Science Enterprise and the science center, museum, and planetarium communities by continuing to provide space science content, materials, and technical expertise to support the development of exhibitions and programs

- Enrich the science, mathematics, engineering, and technology education efforts of community groups such as the Girl Scouts, 4-H Clubs, and Boys and Girls Clubs through the introduction of space science

- Take advantage of the advanced-technology nature of the Space Science Enterprise's programs to develop new materials and new programs in technology education

- Provide coherent and sustained professional development to personnel engaged in NASA space science education and public outreach in order to increase the effectiveness of their work in education

- Extend and deepen previous work on education evaluation to understand more fully the impact of the Space Science E/PO effort, and continue to use the results of assessment and evaluation studies to improve the quality of Space Science E/PO programs

- Seek out and capitalize on special events and particularly promising opportunities in our scientific program to involve the public in the process of scientific discovery and to use space science to improve science, engineering, mathematics, and technology education at all levels; such opportunities arise naturally from within our missions and science programs, and they are discussed in the context of each research theme in the sections that follow

3.2 Science Themes

The Enterprise's broad research program comprises five themes: Solar System Exploration, Mars Exploration, Sun-Earth Connection, Astronomical Search for Origins, and Structure and Evolution of the Universe. Each theme aggregates related science objectives and activities, including flight missions and supporting research and technology development. The themes are, in turn, managed by one of the three Enterprise divisions. These line organizations are responsible for managing the Enterprise's budget resources. Overlap and cross-fertilization of scientific questions and research occurs between themes, stimulating scientific innovation.

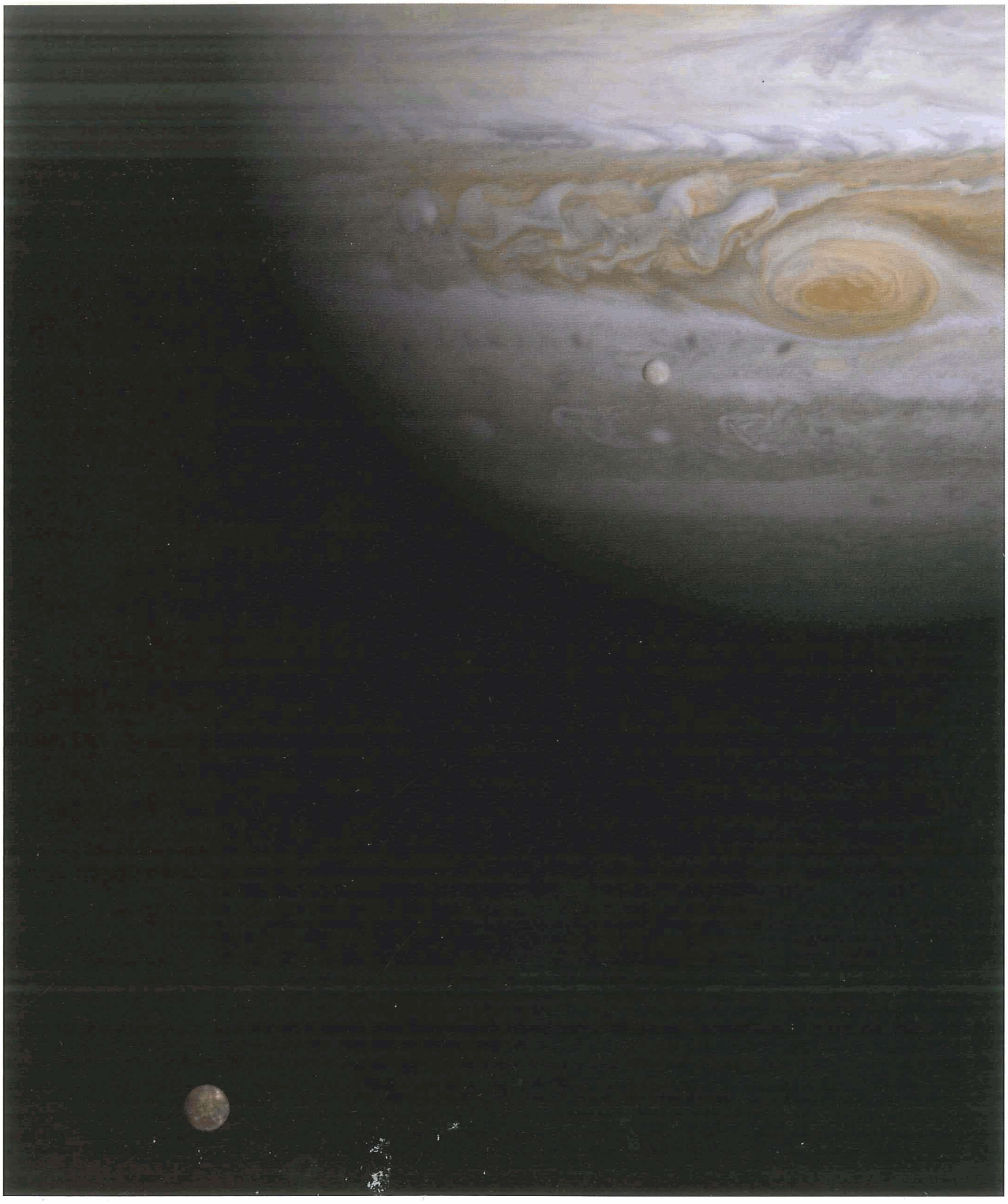
The following section discusses each theme's objectives, education and public outreach highlights, and key technology requirements. Missions and programs that are or will be in development over the period covered by this Strategy, 2003 through 2008, are named. Later candidate missions are also described. However, since scientific priorities evolve, this Strategy implies no ordering for missions that could begin development after 2009.

Further details on the objectives, research focus areas, and planned missions are available in five separate roadmaps: the Solar System Exploration Roadmap, the Sun-Earth Connection Roadmap, the Origins Roadmap, the Structure and Evolution of the Universe Roadmap, and the Astrobiology Roadmap. A summary of missions in all five themes is given in Appendix 2, and a table of the objectives and research focus areas can be found in Appendix 3.



Viewing sunspots through a small telescope outfitted with a special filter introduces students to the nearest star—our Sun. (Credit: Sun-Earth Connection Education Forum/Lou Mayo)





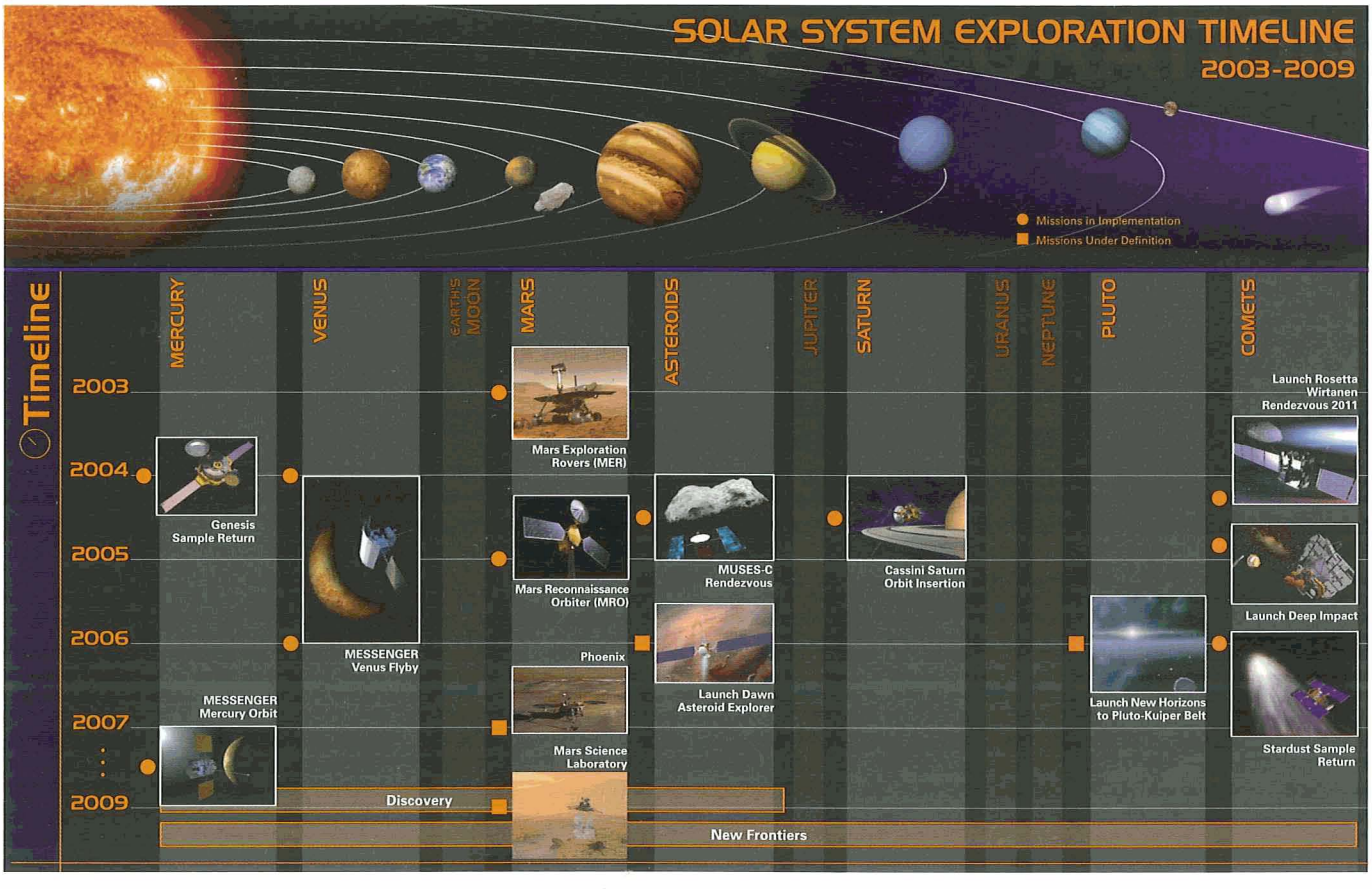
3.2.1 Solar System Exploration

Our solar system is a place of beauty and mystery, incredible diversity, extreme environments, and continuous change. It is also a laboratory that we can use to unlock mysteries of the origins of life and our place within the universe. The planets and the ancient icy bodies that reside far from the Sun are Rosetta stones that encode our own system's history and help us improve our understanding of the formation of other planetary systems and the prevalence of planets around other stars. Our Sun's planets have numerous moons with diverse characteristics, and each tells a story about the evolution of our solar system. As we discover more about these moons and about the origins of living systems, we may learn that life once arose or still exists on some of them.

Strategic objective 5.1.—Learn how the solar system originated and evolved into its current diverse state.

Within the first billion years of our solar system's history, the planets formed and life began to emerge on Earth and, perhaps, elsewhere. Many of the current characteristics of the solar system arose during this critical formative epoch. The tremendous changes that Earth and the other planets have undergone over the intervening eons, however,

Our Sun's planets have numerous moons with diverse characteristics. As we discover more about these moons and about the origins of living systems, we may learn that life once arose or still exists on some of them.



Above: A comprehensive portfolio of Solar System Exploration missions planned for this decade promises a series of dramatic discoveries.
Left: The Saturn-bound Cassini spacecraft captured this image of Jupiter with Europa and Callisto, two of its four largest moons.

Solar System Exploration Education and Public Outreach Highlights

The intrinsic excitement of exploration, coupled with the beauty and mystery of the planets, provides a compelling opportunity for direct participation by students and the public in our quest to understand the origin and evolution of the solar system and its potential to harbor life beyond Earth.

Public Outreach

Working through community-based organizations and in community settings leverages the immense public appeal of planetary exploration.



Three GSUSA leaders learn to infer the history of a mystery planet by observing crustal material samples.

For example, through a partnership with the Girl Scouts of the USA (GSUSA), science activities and materials based on solar system topics are provided for a variety of Girl Scout programs, including day and residential camps, a solar system patch program, training programs for Girl Scout leaders, and articles in the Girl Scouts' *LEADER* magazine. These efforts make solar system exploration accessible to nearly 3 million girls and 1 million adults who are members of the Girl Scouts of the USA.

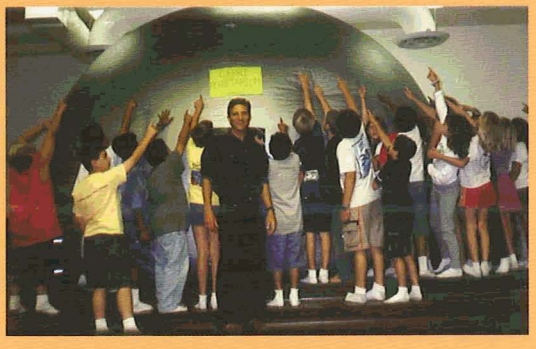
Another example of community outreach is the Solar System Ambassadors program. Solar System Ambassadors are volunteers from the general public who are given training in recent solar system discoveries and then commissioned to organize and conduct public events based on those topics. Through this program, more than 250 Ambassadors serving all 50 states routinely conduct public events in such settings as Rotary Clubs, small local museums and planetariums, shopping malls, and libraries.

Teachers and Students

NASA solar system exploration missions and scientists collaborate with educators to produce educational resources. To organize this material, science and mathematics search tools for educators have been developed. These "Standards Quilts" allow educators to search for resources according to the national science or math standards they address, the educational methods they use, and grade levels to which they are targeted.

Future Plans

Solar system missions planned for the next decade and beyond will spawn a wealth of education opportunities. Efforts to engage the public through community-based programs will be expanded, and methods for delivering new solar-system-based resources to educators will be improved. The Solar System Exploration theme will be a strong contributor to the NASA effort to build a space science framework that will provide coherence and context to the educational materials produced by individual missions. This framework will organize and package solar system materials along story lines that both follow the discoveries being made and coincide with national science education standards.



Solar System Ambassadors host a Monthly Star Party at a home for abused children in San Diego, CA. (Credit: Casa de Amparo)

have erased most of the physical records of this period. Our knowledge of it is only fragmentary.

Fortunately, vital clues are scattered throughout the solar system. The Moon's South Pole Aitken Basin may offer the oldest rocks accessible for detailed geochemical analysis. The surface and environment of Mercury may yield clues to conditions in the innermost parts of the solar nebula and to the processes that formed the inner planets. The interior structure and chemical composition of Jupiter may illuminate the processes that formed the giant planets, and the most distant objects in the solar system—the Pluto-Charon system and Kuiper Belt objects—may retain the best records of the materials present in the original solar nebula. Also, the Kuiper Belt, birthplace of the short-period comets, may have delivered water and other volatiles and organic materials to the inner planets. The MErcury Surface, Space ENvironment, GEo-chemistry, and Ranging (MESSENGER) mission, a Discovery mission currently in development, will conduct comprehensive geophysical and geochemical investigations of Mercury. Deep Impact, another Discovery mission, will investigate volatile and organic materials in the deep interior of the nucleus of a short-period comet. New Horizons, the first New Frontiers mission (see box), will address the highest priority science area of the NRC's 2002 decadal survey: Pluto and the Kuiper Belt. New Horizons will characterize the global geology and morphology of Pluto and Charon, map their surface compositions, and characterize the atmosphere of Pluto.

The underlying physical, chemical, geological, and biological processes of the bodies in our solar system interact in complex and surprising ways. For example, after the epoch of planet formation, the evolutionary paths followed by each of the inner planets led to dramatically different outcomes. Life flourished on Earth, while Mars became cold and dry and Venus was consumed by radical greenhouse warming. We will study this interplay of processes to understand how they shaped the solar system and potential habitats for life. Comprehensive comparative studies of the atmospheric chemistry, dynamics, and surface-atmosphere interactions on Mars and Venus will yield insight into the evolutionary paths these planets followed and their implications for Earth.



Comets may have transported water to Earth from the outer reaches of our solar system.

The exploration of our solar system will also tell us much about the formation of extrasolar planetary systems. Conversely, characteristics of extrasolar systems will also inform our understanding of our own home system—and may give us insight into how typical or unique our solar system might be.

Strategic objective 5.2.—Understand how life begins and evolves and determine the characteristics of the solar system that led to the origin of life.

The essential requirements for life as we know it are basic nutrients, organic material, liquid water, and a source of usable energy. The availability of all of these ingredients defines what is called a "habitable zone." Scientists once thought that the habitable zone of our solar system was limited, primarily by a need for the right amount of sunlight, to a fairly narrow region around Earth's distance from the Sun. On Earth, habitable environments were thought to be limited to regions on or near the surface, where our familiar temperature, pressure, and chemical conditions are found.

Discoveries made within the past few decades, however, have greatly enlarged our view of the range of conditions capable of supporting life on our own planet. Scientists have discovered microbial life-forms that survive, and even thrive, at high and low extremes of temperature and in extremes of acidity, salinity, alkalinity, and concentrations of heavy metals that were once considered lethal. These discoveries on Earth, coupled with a fuller understanding of the range of possible conditions on other planetary bodies, have significantly expanded our view of the number of environments within our solar system that might be, or might

once have been, conducive to life. We are rethinking the fundamentally habitable zones in our solar system based on this recent and ongoing research.

To understand how life can begin on a habitable planet, it is essential to know which organic compounds are available and how they interact with the planetary environment. Geochemical synthesis is a potentially important source of organic compounds and is a focus of research on this question. It is also important to establish the sources of prebiotic organic compounds and to understand their history in terms of processes that would take place on any newly formed planet. We will study Earth's geological and biological records to determine the historical relationship between Earth and its biosphere. NASA currently supports research in these areas via its Astrobiology Institute and other grants in the Astrobiology Program.

NASA's Galileo spacecraft found evidence of subsurface oceans on Callisto, Ganymede, and Europa, a finding that ranks among the major scientific discoveries of the space age.

New Frontiers, a New Mission Line for Exploration

New Frontiers is a mission line dedicated to ambitious solar system exploration. The principal objective of the New Frontiers program is to provide regularly scheduled opportunities for scientific investigations that fulfill the Solar System Exploration objectives. In keeping with Enterprise practices, these missions will be competitively selected through peer-reviewed proposals.

Following the recent publication by the National Research Council of the decadal solar system exploration survey, entitled *New Frontiers in the Solar System: An Integrated Exploration Strategy*, the Space Science Enterprise has identified five medium-class missions for immediate consideration for these first opportunities within the New Frontiers program. These investigations are as follows:

(1) Kuiper Belt/Pluto
(2) Venus in situ explorer
(3) Lunar South Pole Aitken Basin sample-return mission
(4) Jupiter polar orbiter with probes
(5) Comet surface sample-return mission



The icy bodies of the Kuiper Belt may preserve pristine samples of the primordial material from which the planets formed.

Research suggests that when Earth formed, the inner solar nebula was too hot to retain the large quantities of water and organic materials seen in the current Earth environment. Instead, organics, water, and volatile materials probably condensed in the outer reaches of the solar nebula, where low temperatures favored their retention in comets. Laboratory simulations have recently demonstrated that relevant molecules can be synthesized in interstellar ices in a nascent solar system. Analyses of meteorites, interplanetary dust particles, and comets have shown that many chemical compounds essential to life processes are present in these bodies, supporting the hypothesis that these materials were delivered to Earth and the other forming inner planets by comet and asteroid impacts. We expect to find that the planetary system we know today is strongly linked to these early mechanisms for transportation of volatiles and organics.

To achieve this objective, we will focus on an inventory of the nature, history, and distribution of organics and volatiles in the solar system. The processes and products of long-term organic evolution on Titan may have important parallels to the origin of life on Earth. The Huygens probe, a cooperative project with the European Space Agency (ESA), is now en route to Saturn aboard NASA's Cassini spacecraft and will characterize the murky and mysterious atmosphere of Saturn's moon Titan. In addition, a potential New Frontiers comet-surface sample-return mission would bring back a sample of organic material for detailed analysis.

NASA is also developing plans for an ambitious mission to orbit three planet-sized moons of

Jupiter—Callisto, Ganymede, and Europa—that may harbor vast oceans beneath their icy surfaces. NASA's Galileo spacecraft found evidence of these subsurface oceans, a finding that ranks among the major scientific discoveries of the space age. This mission, called the Jupiter Icy Moons Orbiter (JIMO), would orbit each of these moons for extensive investigations of their makeup, their history, and their potential for sustaining life. JIMO would determine whether the moons do indeed have subsurface oceans, map organic compounds and other chemicals of biological interest, and determine the thicknesses of ice layers with an emphasis on locating potential future landing sites. JIMO would also investigate the origin and evolution of these moons by determining their interior structures, surface features, and surface compositions. Information on the moons' geology, geochemistry, and geophysics may reveal their evolutionary histories, as well as illuminate our understanding of the origin and evolution of Earth. JIMO would determine the radiation environments around the moons and the rates at which the moons are weathered by material hitting their surfaces. Callisto, Ganymede, and Europa all orbit within the powerful magnetic field that surrounds Jupiter and display varying effects from the natural radiation, charged particles and dust. Understanding this environment has implications for understanding whether life could have arisen on these distant moons.

A JIMO Science Definition Team has been chartered to define detailed science objectives and requirements that take the greatest advantage of technological advances. At a minimum, JIMO would meet all of the Europa Geophysical Orbiter objectives called out in the NRC's decadal survey and, most likely, far exceed them.

The JIMO mission would also raise NASA's capability for space exploration to a revolutionary new level by pioneering the use of electric propulsion powered by a nuclear fission reactor being developed under Project Prometheus (see box on next page). This technology would not only make possible a realistic mission for orbiting three of the moons of Jupiter, one after the other, but would also open the rest of the solar system, and perhaps beyond, to detailed exploration in later missions.

Strategic objective 1.4.—Catalog and understand potential impact hazards to Earth from space.

The effects of cosmic impacts on Earth were realized in the early 1980s, when the extinction of the dinosaurs was first associated with the impact of an asteroid at least 10 kilometers in diameter. More recently, it has been estimated that impacts by asteroids as small as 1 kilometer in diameter could cause regional devastation and major climate perturbations. Furthermore, the direct effects of impacts by bodies as small as 100 meters could cause major damage on more local scales. In 1908, the impact of a body about that size leveled 2,000 square kilometers of forest near the Tunguska River in Siberia. A similar impact on a modern city would take an enormous toll in lives and property. To assess the level of danger posed by such an occurrence, we plan to determine the inventory and dynamics of bodies that could pose an impact hazard to Earth. In addition, we will determine the physical characteristics of comets and asteroids relevant to any threat they may pose to Earth.

More recently, it has been estimated that impacts by asteroids as small as 1 kilometer in diameter could cause regional devastation and major climate perturbations.

Dawn, a Discovery mission about to enter implementation, will conduct extensive geochemical and geophysical investigations of the Main-Belt asteroids Ceres and Vesta. Vesta has been identified as the source of the basaltic achondrite class of meteorites that impact Earth. The overwhelming majority of Near-Earth Objects (NEOs) come from the Main Belt, so physical characterization of Ceres and Vesta is important for understanding the type of threat that NEOs pose.

The NEO Observation Program supports several teams of ground-based astronomers working toward a congressionally mandated goal to discover, by 2008, at least 90 percent of the asteroids whose diameters are larger than 1 kilometer and whose orbits closely approach Earth, and to determine their orbits with sufficient accuracy to predict whether any of them pose a threat to



Earth. Researchers are on course to meet this goal, and, so far, none of the objects studied has been found to pose a foreseeable threat to Earth. We are also studying the feasibility and cost of extending the NEO search to much smaller, more numerous, and fainter objects that may be capable of causing regional destruction.

Key Technology Requirements for Solar System Exploration

Solar system exploration is a challenging endeavor. It requires us to send robotic vehicles across vast distances; furnish them with electrical power for propulsion, data acquisition, and communication; place them in orbit around or onto the surfaces of bodies about which we may know relatively little; ensure that they survive and function in hostile environments; acquire and transmit data from these throughout their lifetimes; and sometimes bring the vehicles themselves safely back to Earth with samples.



It is imperative to understand the dynamics and physical structure of near-earth asteroids, such as Eros (seen in this image from the Near-Earth Asteroid Rendezvous (NEAR) satellite), that might pose serious impact threats to Earth.

The future Solar System Exploration missions described in this Strategy will demand progress in power and propulsion systems, telecommunications, entry/descent/landing, mobility, autonomy, and science instrumentation. For example, Project Prometheus (see box on facing page) is a response to the demand for high-performance, long-lived power supplies for extended missions that will carry advanced science instrumentation, high-power communications capabilities, and advanced electric propulsion. Increasingly, future missions will also demand spacecraft systems that tolerate severe environments.

Sample-return missions will require enhanced handling and curation techniques and facilities. Also, to prevent contaminating other planets, new methods of microbe identification and spacecraft sterilization must be developed. For the latter, the solution is likely to be a combination of sterilization-tolerant spacecraft systems and more effective sterilization methods.

Project Prometheus, the Nuclear Systems Program

Project Prometheus, the Nuclear Systems Program, will develop the means to substantially increase the power available to spacecraft, thereby revolutionizing our capability to explore the solar system. Increased power for spacecraft means not only traveling farther or faster, but also exploring more efficiently with enormously greater scientific return. High levels of sustained power would permit a new era of solar system missions designed for agility, longevity, flexibility, and comprehensive scientific exploration.

Project Prometheus focuses on research and development of nuclear electric power and propulsion systems, specifically radioisotope-based systems that make use of the heat produced by the natural decay of a radioisotope fuel and reactor-based systems that make use of the heat produced by nuclear fission.

The Radioisotope Power Systems program focuses on improvements to the existing radioisotope thermoelectric generator (RTG) design and on development of the Stirling Radioisotope Generator. The Multi-Mission RTG will be developed to work in space and on planetary bodies with atmospheres, such as Mars. The Stirling Radioisotope Generator offers the potential for a more than threefold increase in RTG efficiency.

The Nuclear Power and Propulsion program will focus on research and development of a fission reactor designed to operate in space, advanced heat-to-power conversion technologies, and power management and distribution technologies. These technologies will enable a new paradigm for mission flexibility and duration, as well as power for science instruments.

Project Prometheus will include substantial involvement by the U.S. Department of Energy (DOE), which will be responsible for the nuclear systems development. NASA will define the science requirements that in turn will direct the systems requirements and mission design, resulting in technology development requirements to be met by DOE. NASA Headquarters will directly manage the overall program with substantial participation by NASA Centers such as Glenn Research Center, Marshall Space Flight Center, and the Jet Propulsion Laboratory. A substantial portion of Project Prometheus research and development activities will be competitively awarded.

In addition, a range of technologies and system designs beyond the specific technologies already under consideration will be explored for possible NASA and DOE investment over the next several years. NASA and DOE may also identify and recommend additional strategic technology investments to potentially enable future human exploration of the solar system.

Project Prometheus, like all Space Science programs, will support education and public outreach programs, with a strong emphasis on engineering and technology education.



The technology-pioneering JIMO spacecraft approaches Jupiter's moon Europa in this artist's rendering.

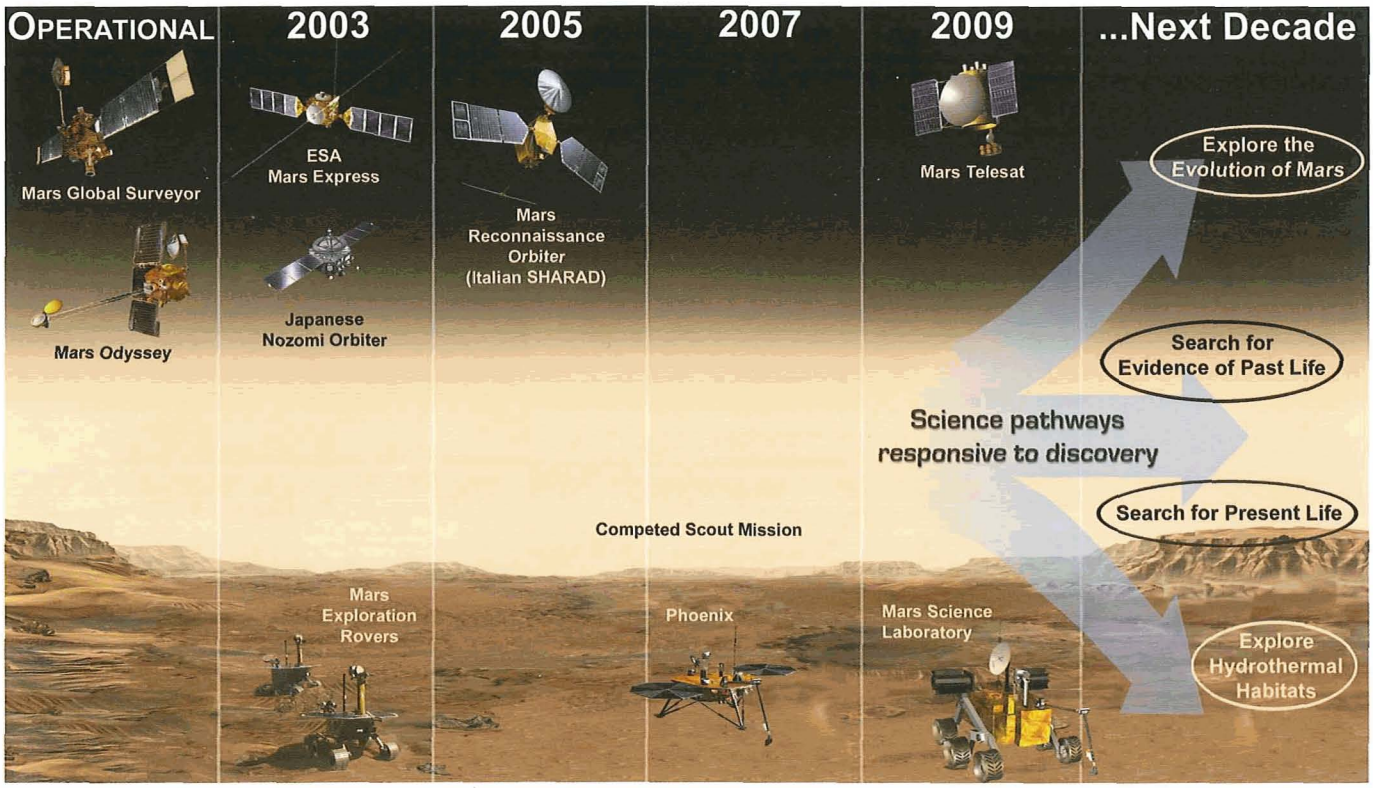




3.2.2 Mars Exploration

Mars holds a special place in the solar system by virtue of its similarities to Earth, its potential for having been a home for life, and its value as a "natural laboratory" for understanding the environmental and geological evolution of rocky planets. Mars is within our reach; of all the Sun's planets, we can most easily land on and probe this one. The flood of new discoveries about Mars—including the role and abundance of water, the character of global climate variability, and the tantalizing array of environmental niches that exist even today as potentially life-hospitable places—has inspired a comprehensive scientific campaign to understand the red planet. Overarching objectives focus on characterizing Mars, understanding its evolution and biological potential, and ultimately laying the groundwork for future human exploration that would extend our current campaign of robotic scientific exploration. We can apply an understanding of the biological potential of Mars to other high-priority solar system objects.

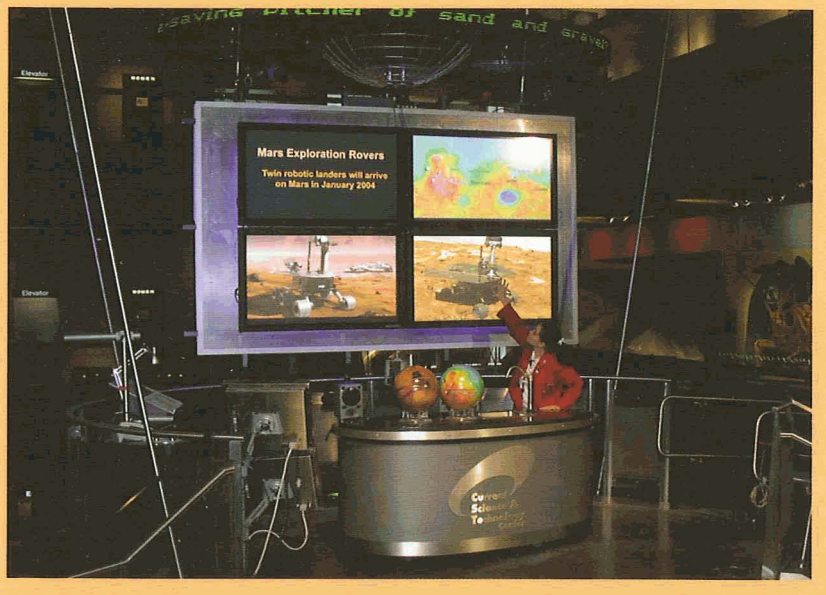
The flood of new discoveries about Mars has inspired a comprehensive scientific campaign to understand the red planet. NASA plans involve a methodical succession of orbiting and surface laboratories over this decade.



Above: NASA's Mars Exploration Program combines orbital reconnaissance and in situ surface measurements to understand and characterize the planet—a critical step in the search for habitable environments. **Left:** Gullies found along the walls of impact craters in the Newton Basin on Mars. Thousands of gully sites have now been identified, and there is new evidence that some of these sites may have been formed by the release of groundwater in geologically recent times. (Credit: NASA/JPL/Malin Space Science Systems)

Mars Education and Public Outreach Highlights

Mars education and public outreach is based on a two-part vision of "Sharing the Adventure"—creating opportunities for the public to participate directly and interactively in Mars Exploration—and "Making Mars a Real Place"—transforming Mars into something that is as psychologically real as someone's backyard. Two examples of activities based on this vision follow.



Through the Mars Visualization Alliance, visitors to science centers across the country share the excitement of exploring Mars. (Credit: Museum of Science, Boston)

Mars Visualization Alliance

NASA is working with an alliance of science centers, museums, and other informal education partners to disseminate collections of imagery for exhibition displays and real-time large-screen viewings during Mars Exploration Rover mission landings and subsequent Mars mission events.

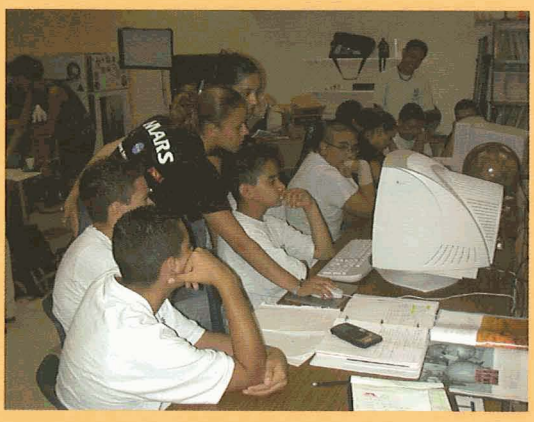
In order to accomplish this, NASA has formed a collaborative team of museum representatives with expertise in imaging and distance learning to help design and test a program aligned with their interests and needs. NASA is also forming partnerships with organizations representing large numbers of science centers to help identify needs and to provide publicity and organization for outreach campaigns.

The potential for outreach to the public through this alliance is huge, as pre-advertised events at museums around the country would engage the public as if they were participating directly in the mission.

Mars Student Imaging and Analysis

The Mars Student Imaging Project offers opportunities for students (grades 5–14) to participate in authentic science research using a camera on the Mars Odyssey orbiter. Student teams submit proposals to take pictures of specific regions of Mars and then have the opportunity to participate in acquiring the images, analyzing the data, and presenting their findings. To date, 52 teams of students in 15 states have participated; this number is expected to increase substantially in future years.

With the wealth of images and data expected from future missions such as the Mars Reconnaissance Orbiter, it may be possible to give thousands of future teams of students their own "square mile of Mars" to analyze. This would allow students to become as familiar with their piece of Mars as they are with their own backyards and, in many cases, to be the first people on Earth to "discover" that piece of Mars and analyze it in detail.



Mars Student Imaging Project alumni show a new group of students how to target the THermal EMission Imaging System (THEMIS) camera onboard the Mars Odyssey orbiter. (Credit: Arizona State University)

Strategic objective 5.3.—Understand the current state and evolution of the atmosphere, surface, and interior of Mars.

Understanding Mars's atmosphere, surface, and interior, and their interactions with one another, can tell us much about the environment in which life could have developed and subsequently been preserved. Characterizing these interactions also bears directly on the search for evidence of life on planets elsewhere in the universe.

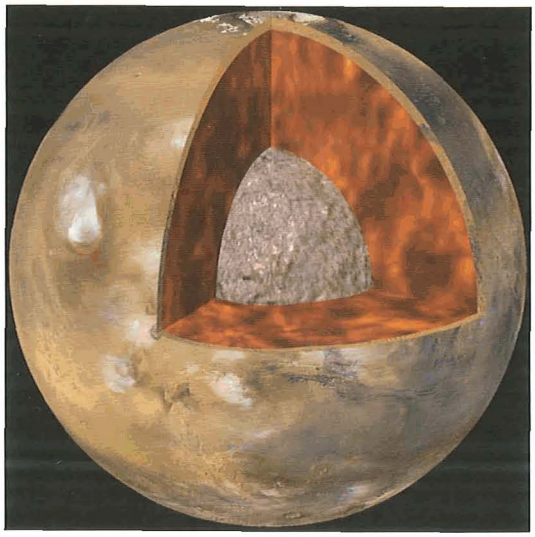
NASA plans involve a methodical succession of orbiting and surface laboratories over this decade to progressively refine our understanding of the planet. In the near term, the Mars Global Surveyor orbiter will continue to characterize the dust and temperature properties of the martian atmosphere, document surface landforms that show evidence of liquid-water erosion and climate change, and refine our knowledge of the interior by mapping Mars's magnetic field and gravity. The 2001 Mars Odyssey orbiter will map the elemental composition and infrared properties of the martian surface and document aspects of its water cycle. The two 2003 Mars Exploration Rovers, Spirit and Opportunity, will make surface observations of the chemistry, mineralogy, and mechanical properties at two locations where liquid water appears to have played a major role. Also launched in 2003, the NASA subsurface sounding radar on the European Space Agency (ESA) Mars Express orbiter will map the uppermost 1 to 5 kilometers of the martian crust in search of water-related layering and other fundamental subsurface structures.

Later in the decade, the 2005 Mars Reconnaissance Orbiter will characterize atmospheric processes over a full Mars year and provide the first definitive measurements of local mineralogy in the search for habitats. This orbiter will also observe surface layering to clarify how the surface has evolved in association with standing bodies of water or other water-related processes. In 2007, the Phoenix Mars Scout mission will land at ice-rich northern latitudes to measure climate, chemistry, and organics. Subsequently, the 2009 Mars Science Laboratory (MSL) will explore a vast terrain on Mars's surface for evidence of organic materials and other signatures of past or present life, including microscopic textures and associated chemistry. NASA has defined multiple pathways of scientific inquiry for the next decade. The pathway to be followed will depend on the discoveries made through the present one.

Strategic objective 5.4.—Determine if life exists or has ever existed on Mars.

The discovery of life, past or present, on Mars would be a defining moment for humankind. Evidence may come from the study of meteorites from Mars, as well as from exploration of Mars itself for biomarkers and other indicators of biological processes. NASA sponsors studies of Mars meteorites to detect the presence of chemical indicators of life or, at least, of hospitable indicators such as water. In addition, NASA sponsors development of new sensors that will be able to search for evidence of organic materials on the surface of Mars. There may be present-day environmental niches on Mars that are life-hospitable, as well as specific deposits that have favored preservation of organic materials. Chemical indicators of prebiotic activity are also key to the question of whether life ever arose on Mars.

Orbital reconnaissance by the Mars Global Surveyor, Mars Odyssey, and the Mars Recon-



Artist's rendering of the interior structure of Mars inferred from Viking, Pathfinder, and Mars Global Surveyor (MGS) data. The outer surface is a global image acquired by MGS. Future network missions may refine our knowledge of the martian interior, which is part of the puzzle of the habitability of Mars.





The Rio Tinto, an acid river in Spain. This iron-rich habitat supports diverse microbial life and may be analogous to potential habitats on other planets, like Mars.

naissance Orbiter will enable us to locate the highest priority surface sites relevant to the search for life by identifying evidence of past or present water or by locating telltale minerals indicative of ancient hospitable environments. The Mars Exploration Rovers and MSL will land on Mars and explore three sites for mineralogical and chemical evidence of the role of liquid water. The MSL will seek organic materials or related biosignatures in the accessible surface layer. The 2007 Phoenix Mars Scout mission will also contribute to the understanding of the habitability of Mars.

The discovery of life, past or present, on Mars would be a defining moment for humankind.

Strategic objective 5.5.—Develop an understanding of Mars in support of possible future human exploration.

Focused measurements of the martian environment will help us identify potential hazards to human explorers and will allow us to inventory martian resources of potential benefit to future human missions. Missions over the next decade will characterize the distribution of water—as ice or liquid—both from orbit and from in situ analysis of local materials; these missions will also provide understanding of the space radiation environment in the vicinity of Mars.

The Mars Global Surveyor and Odyssey orbiters have already improved estimates of the abundance of water within the uppermost surface layer, atmosphere, and icecaps of Mars. The 2005 Mars Reconnaissance Orbiter mission will use subsurface sounding radar to search as deep as hundreds of meters for evidence of aqueous processes. The 2003 Mars Exploration Rovers will measure the martian surface's mechanical properties, the magnetization of local materials, and the composition of specific rocks and soils. The 2009 MSL, another lander, will emphasize characterization of organic and related molecules, as well as toxicity of soils. The Odyssey orbiter is currently measuring the galactic cosmic radiation background from Mars's orbit, and it is likely that solar and cosmic radiation measurements will be conducted from the Mars surface later in the present decade. The 2009 MSL mission will access the shallow subsurface to measure the presence of water and oxidants as a function of depth. Thus, by early in the next decade, a relatively complete inventory of critical environmental parameters, local hazards, and potential resources will be available to support future human exploration.

Key Mars Exploration Technology Requirements

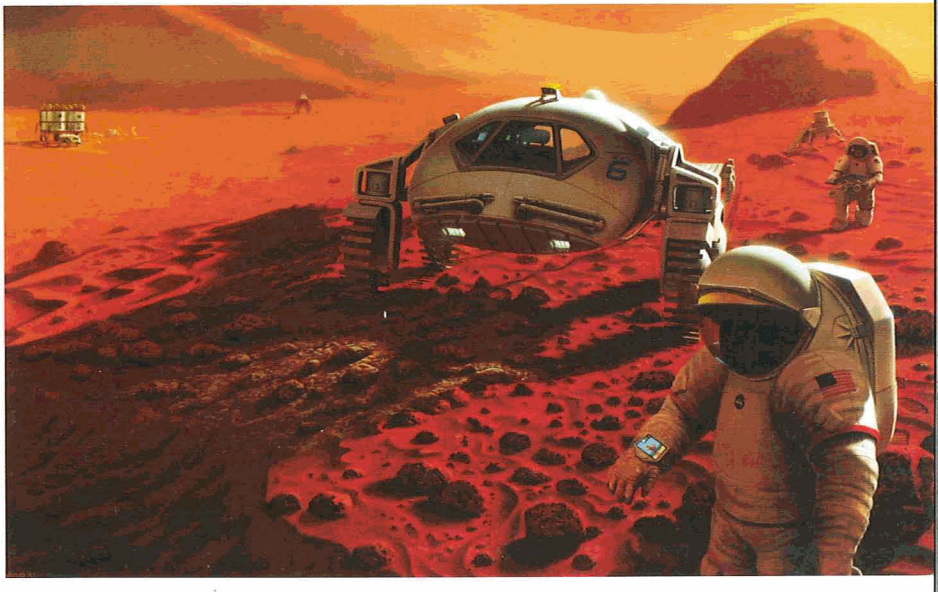
Comprehensive scientific exploration of Mars during the current decade and projected into the next requires technology investments and developments today. Given the technology maturity required to make substantial headway in the understanding of the habitability of Mars, near-term investment in the following capabilities is needed:

- High-precision, targeted access to the surface of Mars via improved entry, descent, and landing systems
- Active landing-hazard avoidance systems for precision landing even in more complex terrain
- Penetrator or other landing systems with high-g-tolerant instruments that provide

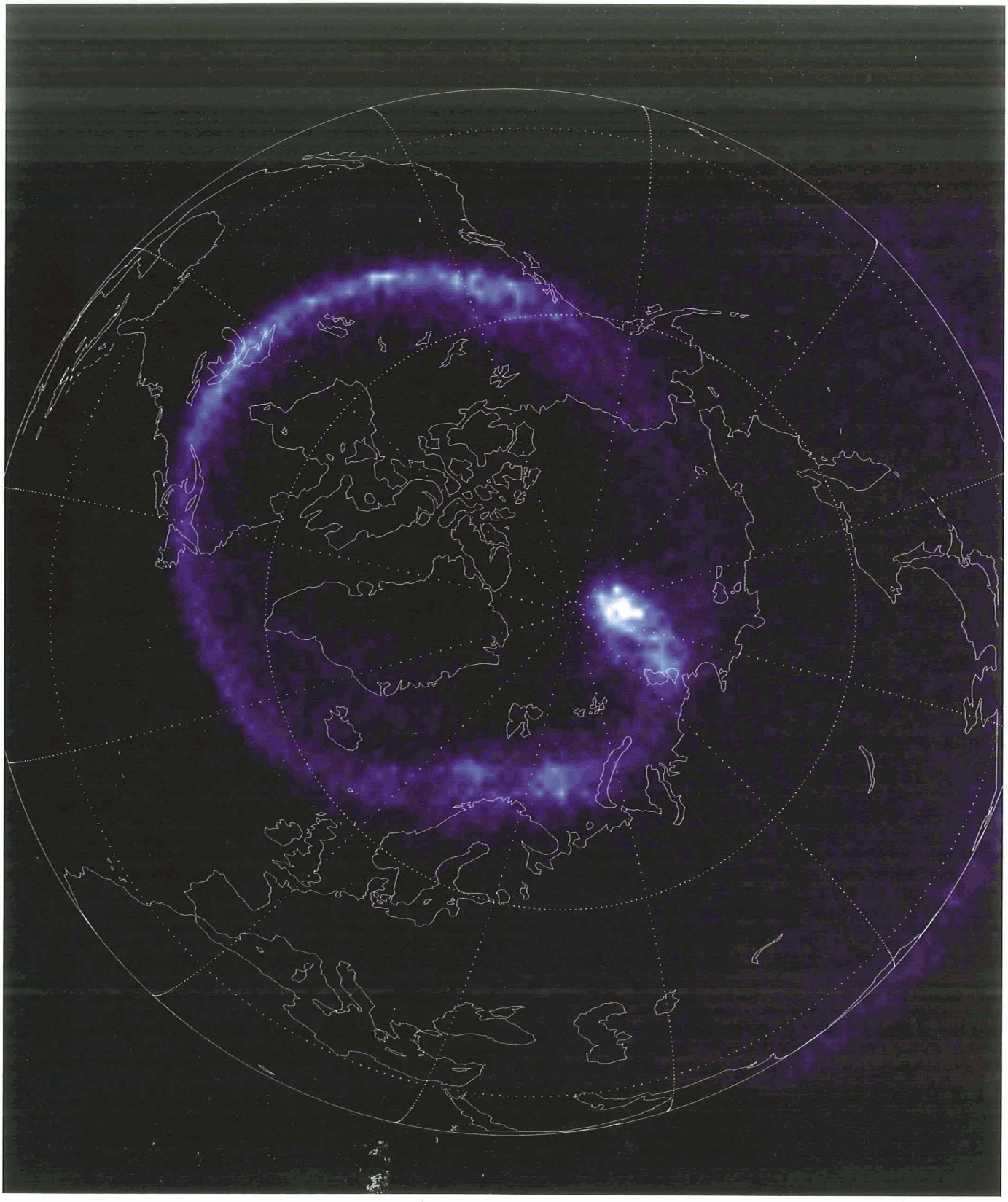
access to high-priority sites with terrain too complex for landing rovers

- Access to the shallow subsurface of Mars to depths in excess of 1 meter
- Enhanced lateral mobility systems that allow safe access to a greater breadth of materials for analysis on the surface
- Longer-lived surface power systems that provide for year-long surface operations at virtually all latitudes, independent of solar illumination
- Improved analytical instruments for precise measurements of key chemical indicators, presence of liquid water, and geophysical parameters on the surface
- Sample acquisition, preparation, distribution, and handling necessary for definitive surface-based analyses of a full range of materials (such as rock, soil, dust, ices, and gases)
- Ascent vehicle systems suitable for launch of martian samples to Mars orbit and other systems necessary to return samples to Earth
- Airborne platforms suitable for obtaining regional to local scale observations not possible from surface vehicles
- New classes of instruments that can operate below the ground or ice surface of Mars for direct observations of unique materials and environmental conditions
- Small, scientific stations on the martian surface suitable for a global planetary network for understanding the climate and interior of Mars
- Operational-environment tools to aid extended around-the-clock operations
- Biological planetary protection technologies

These capabilities and the technologies associated with them are directly linked to planned and potential missions to help us understand and characterize the martian system and its biological potential. In addition, the Mars Exploration Program will serve as a technology pathfinder for exploring other solar system bodies. For example, the 2009 Mars Science Laboratory requires unique capabilities for precision landing; sample acquisition, handling, and preparation; and long-range surface mobility . . . all high-priority technologies for the future.



Artist's rendering of one scenario for human-based scientific exploration of Mars involving pressurized roving vehicles to provide surface access to key astobiological sites. (Credit: Pat Rawlings)

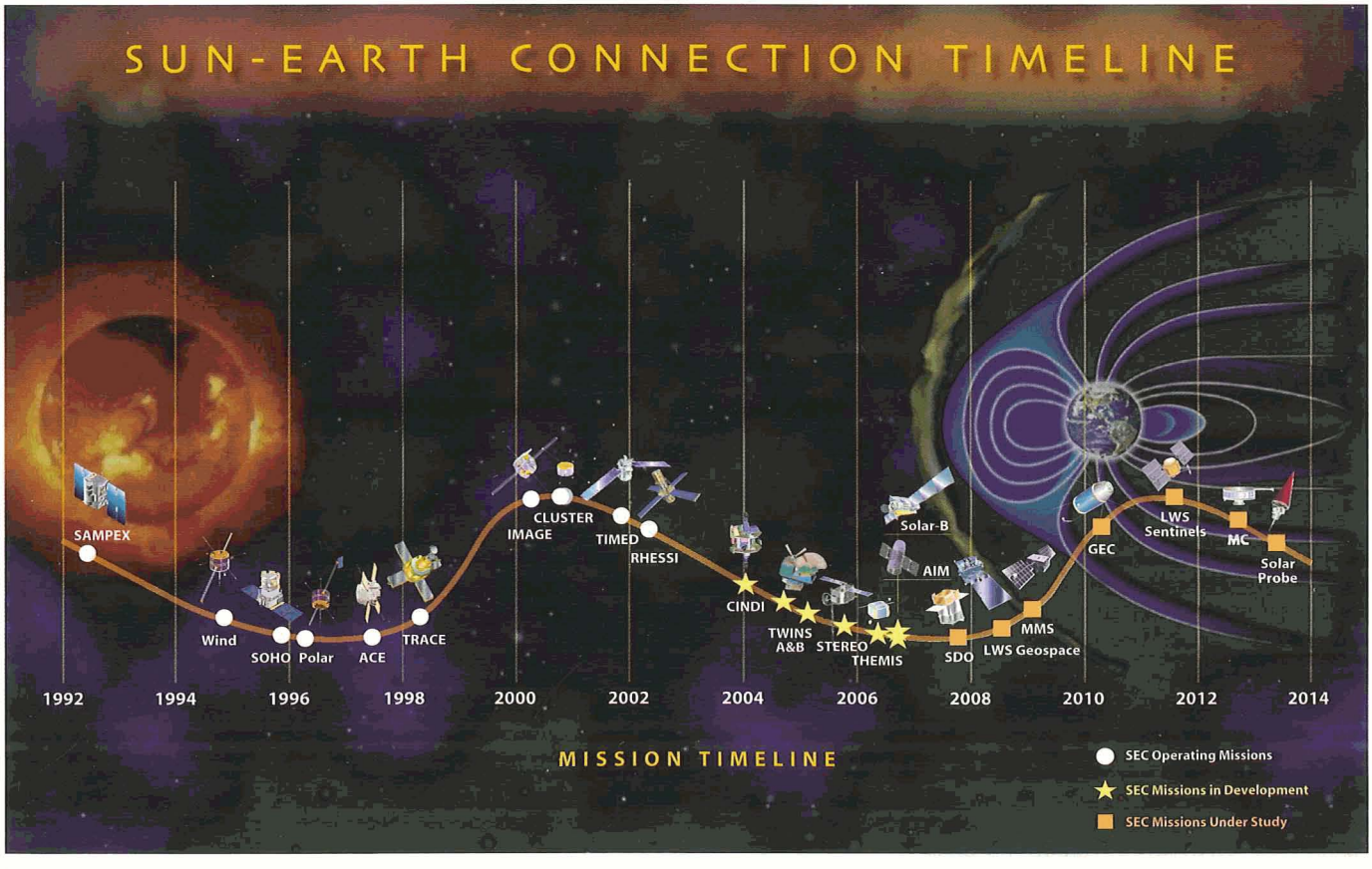


3.2.3 Sun-Earth Connection

Life on Earth prospers in a biosphere sustained by energy from the Sun. We are living with a star, constant in its energy output when averaged over millennia, yet highly variable on an 11-year cycle and, sometimes, from second to second. Our planet orbits within the inhospitable outer layers of this magnetically variable star's atmosphere. Fortunately, our Earth's atmosphere and magnetic field shield us from dangerous radiation and particles coming from the Sun and the galaxy beyond. Still, powerful flares and coronal mass ejections arriving at Earth can disrupt telecommunications and navigation, threaten astronauts, damage satellites, and disable electric power grids on Earth.

The region of space influenced by the Sun, called the heliosphere, extends beyond the planets and ends where the solar wind encounters the interstellar medium at our solar system's edge. We are just beginning to understand the physics of space weather, the diverse array of dynamic and interconnected phenomena that affect both life and society. Understanding space-weather effects

Knowledge of long-term variability of solar activity is important because of its effects on planetary atmospheres, the radiation and energetic particle environment, and planetary surfaces—and, therefore, the development of life.



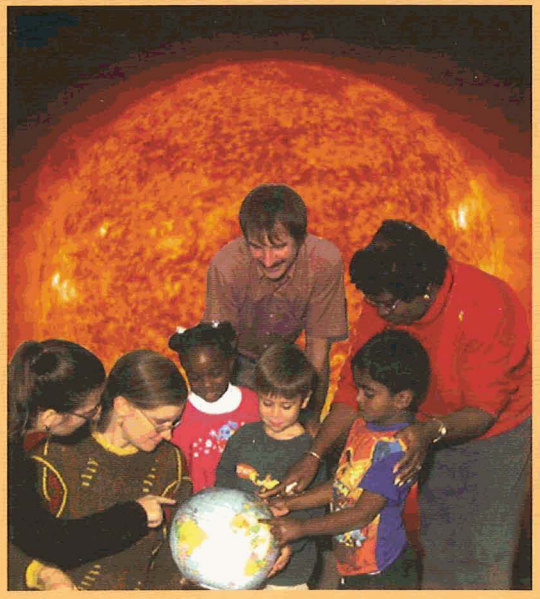
Above: Planned and existing Sun-Earth Connection missions will help us understand the Sun-Earth system, including space plasmas and Earth's magnetosphere. Planned launches for the missions are shown on the 11-year cycle of solar activity. **Left**: Earth's far-ultraviolet proton aurora, as viewed from above the North Pole by NASA's IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft. The bright emission near the right center of the image is produced by solar wind protons that are sent beaming into the upper atmosphere by the merging of the Sun's magnetic field with Earth's. (Credit: NASA/SWRI/UC Berkeley/S.B. Mende and the IMAGE Far-Ultraviolet Imaging team)

Sun-Earth Connection Education and Public Outreach Highlights

The Sun-Earth Connection (SEC) theme investigates phenomena that directly impact people's lives but are not often in people's conscious thoughts. The SEC theme therefore uses high-visibility public events coupled with classroom activities to draw attention to the Sun and its impacts on life on Earth.

Public Outreach

National Sun-Earth Days celebrate the Sun, the space around Earth (geospace), and how all of it affects life on our planet. They feature programs and activities at NASA Centers; special television broadcasts and Webcasts; and associated local events held in classrooms, museums, shopping malls, planetariums, and auditoriums around the world. In recent years, Sun-Earth Days have been supplemented with a special focus on the images, cultural parallels, and activities that Native Americans have used to share Sun-Earth science through several generations. Typically, tens of thousands of people attend the special Sun-Earth Days events, while the broadcasts and Webcasts reach millions of additional individuals.



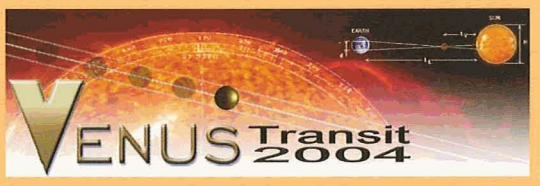
Sun-Earth Days focus attention on the Sun and its impact on life on Earth. (Credit: Sun-Earth Connection Education Forum/Troy Cline)

Teachers and Students

Activity guides prepared for Sun-Earth Day events allow teachers to bring such events into their classrooms. Other SEC guides for teachers, such as those published as part of the Lawrence Hall of Science's Great Explorations in Math and Science (GEMS) series, allow teachers to address SEC themes in the context of their normal curriculum. For example, *Real Reasons for the Seasons* addresses key misconceptions about seasons and the scale and interaction of the Sun-Earth system. The *Living With a Star* guide engages students in studying the effects of the active Sun and solar energy on humans and society.

Future Plans

Future major events, such as the 2004 transit of Venus across the face of the Sun or the 2006 total solar eclipse, will continue to be used to focus attention on SEC topics. The impact of SEC science on classroom education will be increased by developing curriculum materials connected to national education standards and SEC themes such as solar variability, magnetic fields, and voyages to the Sun and to the edge of the solar system and beyond.



A rare transit of Venus will provide education opportunities on subjects ranging from the size of our own solar system to the scale of the entire universe. (Credit: Sun-Earth Connection Education Forum/Troy Cline)

becomes more important as the Government and private sectors increasingly rely on space- and ground-based systems subject to the influences of the space environment.

The Sun also provides the most accessible laboratory to study the structure and evolution of stars and stellar systems. Knowledge of long-term variability of solar activity is important because of its effects on planetary atmospheres, the radiation and energetic particle environment, and planetary surfaces—and, therefore, the development of life. The elements of this stellar-planetary system are highly interlinked. Continued progress in understanding them will require theory, modeling, and data analysis that cross traditional discipline boundaries.

The aim of the Sun-Earth Connection (SEC) theme is to understand the Sun, heliosphere, and planetary environments as a single, connected system. The SEC science objectives and strategic missions, presented here and detailed in the 2003 SEC Roadmap, are closely aligned with the challenges and priorities in the NRC's *The Sun to Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics.* This Strategy addresses all of this survey's recommended NASA-related programs, including the vitality program, with the exception of the lowest-ranked of the small programs.

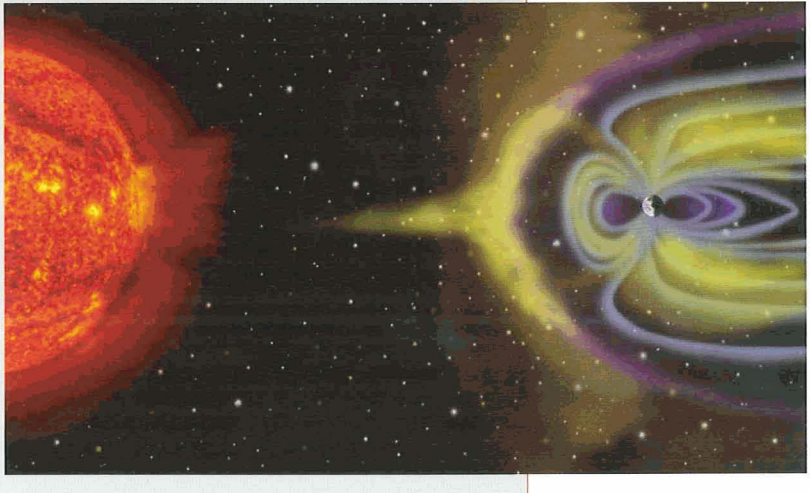
The SEC strategic missions reside in the Solar Terrestrial Probes (STP) or Living With a Star (LWS) mission lines. The STP missions address fundamental science questions about the physics of plasmas and the flow of mass and energy in the solar system. By contrast, the LWS missions are designed to develop specific knowledge and understanding of those aspects of the connected Sun-Earth system that directly affect life and society.

A Milestone in Exploring the Sun-Earth Connection

We now have instruments in place to trace the flow of energy every step of the way from the Sun to our home planet. April 2002 marked a time of violent solar disturbances, including flares and coronal mass ejections (CMEs). Energetic particles are accelerated in the flares and CME-driven interplanetary shocks. For the first time, scientists were able to link these particles with measurements made upstream from Earth—just before the particles reached Earth's upper atmosphere—and watch as they altered the atmosphere's chemical composition. Scientists subsequently observed the interaction with Earth's magnetosphere—generating electric fields, accelerating atomic particles, and heating the upper atmosphere. These atmospheric fireworks cause brilliant auroras also known as the northern lights.

This linked chain of observations required a combination of measurements from SEC and partner-agency satellites, including one new STP mission, six Explorer satellites, one NASA/ESA mission, and several satellites in extended missions.

With the suite of near- and mid-term missions described in this Strategy, NASA will be able to probe the origin of the solar wind; explore the causes of solar activity; track the propagation and evolution of solar ejections through interplanetary space; and explore the consequences of solar activity for magnetospheric storm development and resultant effects on the radiation belts, ionosphere, and upper atmosphere on Earth. The detailed physical processes that enable the transfer of energy across Earth's magnetic barrier and through the geospace system will be probed, and the implications for human society will be clarified.



This artist's rendering shows a solar mass ejection's collision with Earth's magnetic shield (not to scale).

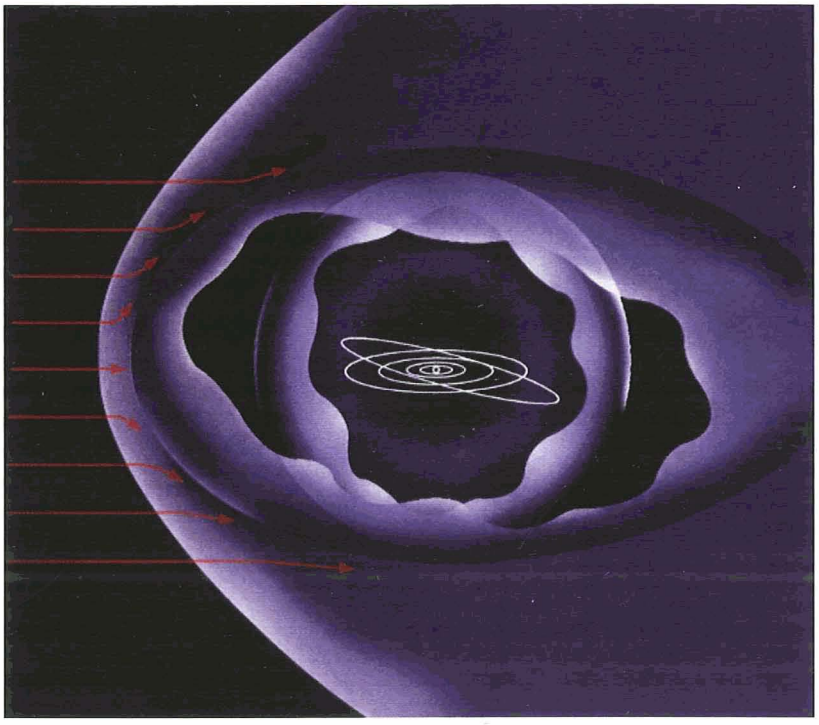


Other flight programs, including the Explorer and suborbital programs, supplement these strategic mission lines. Both of these programs provide opportunities for sharply focused investigations to address the strategic objectives and newly emerging science questions. In addition, SEC pursues opportunities for collaborative missions with other themes and agencies, including foreign space agencies.

Strategic objective 5.6.—Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

At one end of the causal chain, we have questions about the structure and dynamics of the Sun, its corona and solar wind, and the origins of magnetic changes in the Sun. At the opposite end, we need to determine how the variable heliosphere interacts with the interstellar medium at the heliopause, the outer boundary of the solar system. Between the Sun and the heliopause orbit Earth and all the other planets. Understanding how their diverse magnetospheres and atmospheres respond to both internal and external influences will help explain the behavior of our own planet. This broadest theme objective includes research focus areas addressed by both STP and LWS missions.

Understanding how the other planets' diverse magnetospheres and atmospheres respond to both internal and external influences will help explain the behavior of our own planet.

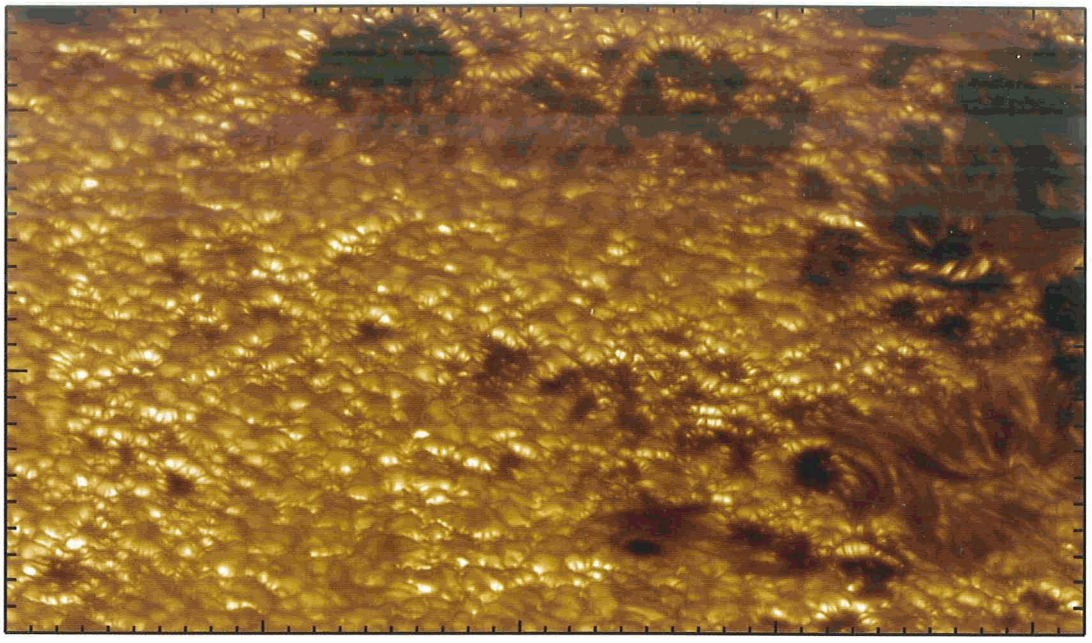


The heliosphere carved out by the solar wind. Generated by the Sun, the gusty solar wind flows outward past the planets at a million miles per hour and eventually stops when it can no longer push aside the interstellar medium.

Two relevant STP missions are already in development. Solar-B, a Japanese-led mission with significant NASA participation, will reveal how the Sun's photosphere is magnetically coupled with the corona and will track the life cycle of small magnetic regions at the solar surface with high-resolution solar telescopes. The Solar TErrestrial RElations Observatory (STEREO) will, for the first time, determine how coronal mass ejections begin and how they propagate toward Earth. STEREO's two spacecraft in solar orbit will move gradually ahead of and behind the Earth to provide stereoscopic views of evolving features in the solar atmosphere, giving us a 3-D view never seen before.

Geospace Electrodynamic Connections (GEC) is a subsequent STP mission to investigate how Earth's ionosphere-thermosphere system responds to the variations in the overlying magnetosphere. It features a string of spacecraft, in a very low-perigee orbit, measuring local conditions.

Currently under study as a potential new mission, Solar Probe would make the first voyage to a star, plunging to within 2 million miles of the Sun's surface. This ambitious mission would fly through the solar atmosphere to answer fundamental questions that can be answered in no other way. Solar Probe would determine the acceleration processes and source regions of fast and slow solar-wind streams. The mission would also locate the source and trace the flow of energy that heats the corona to over 3 million degrees, much hotter than the Sun's surface. This journey to the Sun poses special technological challenges because of the extreme and unexplored environment. Solar Probe received highest priority in the National Research Council's decadal survey of solar and space physics research.



This image of a solar active region, taken with the Swedish 1-meter telescope in La Palma, Spain, highlights the three-dimensional nature of the photosphere and enables us to better understand the dynamics of sunspots and solar active regions. The structures in the dark sunspots in the upper central area of the image show distinct elevation above the dark "floor" of the sunspot. The tickmarks are 1,000 kilometers apart. (Credit: LMSAL/Scharmer/Lofdahl)

Later STP mission concepts include a constellation of several dozen nanosatellites in Earth's magnetotail to understand the regulation of energy in the magnetosphere; a probe to measure the polar regions of the Sun and the heliosphere from high solar latitude; a two-spacecraft mission to determine how small-scale waves in Earth's upper atmosphere interact with its lower atmosphere; a stereoscopic magnetospheric imager to reveal the dynamic global structure of Earth's plasmasphere, ring current, radiation belts, and auroral regions; and a deep-space probe to image the boundaries of the heliosphere remotely by detecting interstellar neutral atoms and radiation.

Strategic objective 5.7.—Understand the fundamental physical processes of space plasma systems.

This objective spans many astrophysical problems and relies primarily on STP missions. One focus area is to discover how solar magnetic fields are created and evolve and how they produce heat and high-energy particles. Mechanisms for creating, destroying, and reconnecting magnetic fields are key to many Sun-Earth Connection problems—solar activity, geomagnetic activity, the heliospheric boundary, and most forms of particle acceleration. The other space plasma research focus area involves understanding how and why processes that occur on very small scales generally affect large-scale global dynamics. This interaction across multiple scale lengths is important for understanding instabilities and turbulence in all space plasmas. The solar system offers the opportunity to test our scientific understanding of these processes in diverse plasma environments.

In the near term, the Magnetospheric Multi-Scale STP mission (MMS) will measure reconnection, turbulence, and particle acceleration at small and intermediate scales using a small cluster of spacecraft to explore key magnetosphere regions. Also in the near term, potential collaboration on the ESA's BepiColombo mission to Mercury may enable detailed exploration of a planetary magnetosphere that lacks an ionosphere.

Future exploration may focus on Jupiter's auroral regions. Imaging and in situ data from such a mission, perhaps developed jointly with the Solar

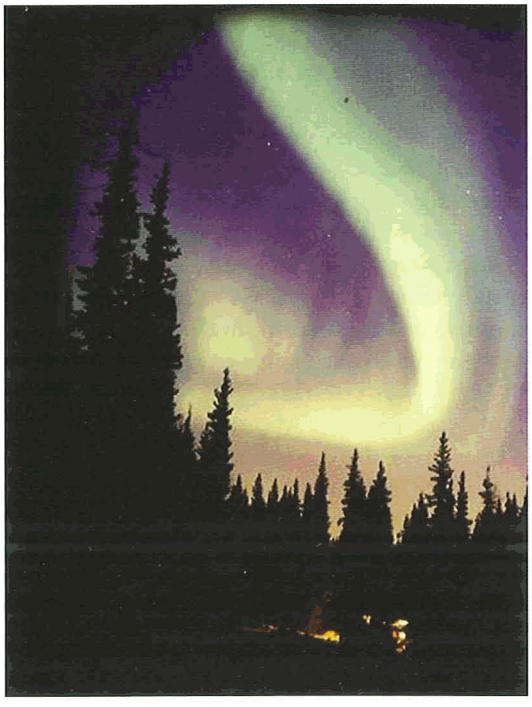


System Exploration theme, would show magnetospheric processes operating under vastly different conditions from those on Earth. Another future mission may focus on magnetic reconnection and microscale processes in the solar atmosphere using both high-resolution spectroscopy and imaging.

Strategic objective 1.3.—Understand the origins and societal impacts of variability in the Sun-Earth connection.

This objective has the most immediate relevance to society and relies primarily on LWS missions. Two research focus areas investigate space-weather variations on the scales of hours and days. The first relates to disturbances that travel from Sun to Earth, such as radiation and immense clouds of magnetized material that can damage telecommunication satellites, knock out ground-based power grids, and affect the health of astronauts. This effort involves monitoring the Sun and developing the capability to forecast solar activity and predict the evolution of structures as they move through the heliosphere. The second focus area is the development of the capability to specify, and ultimately predict, changes to Earth's radiation environment, ionosphere, and upper atmosphere. On longer time scales, human society has a real need to understand the role of solar variability in global changes in Earth's atmosphere and space climate. These three areas are addressed in three ways: by the LWS Targeted Research and Technology program, which will also speed the transition of space-weather understanding to routine use; by the LWS Space Environment Testbeds program, which will help us learn how to mitigate the effects of solar variability on spacecraft; and by the investigations supported by flight missions.

On longer time scales, human society has a real need to understand the role of solar variability in global changes in Earth's atmosphere and space climate.



Aurora caused by particles accelerated near Earth. Auroral displays are an enthralling manifestation of the interactions of Earth with a nearby variable star, the Sun.

In the near term, the LWS Solar Dynamics Observatory (SDO) will observe the solar interior and atmosphere continuously from geosynchronous orbit to determine the causes of solar variability. Its imagers will provide global views with four times the resolution of those currently available. Coordinated observations from the two pairs of LWS Geospace Storm Probes will link the solar and geospace systems. The Ionospheric-Thermospheric Storm Probes will determine the causes of middle-latitude ionospheric variability and irregularities that affect communications. The Radiation Belt Storm Probes will determine how the particles that affect astronauts and spacecraft performance are injected into the radiation belt, accelerated, distributed, and eventually lost.

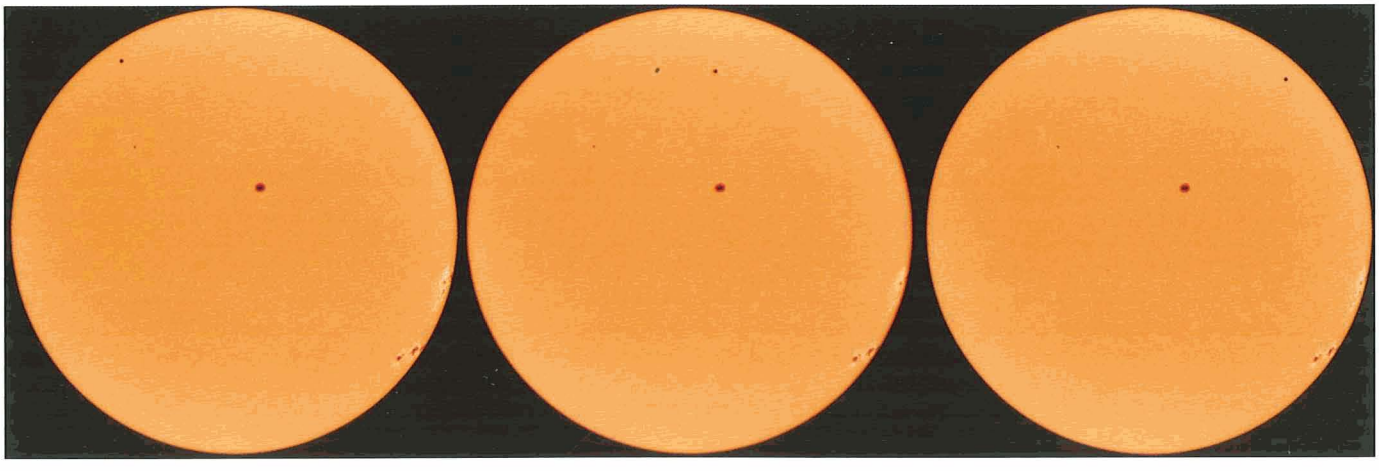
The next likely LWS mission requires sentinels in the inner heliosphere to measure how changing conditions inside Earth's orbit affect propagation of solar emissions directed toward Earth. ESA's Solar Orbiter offers an opportunity for partnership on one of the sentinels as part of the International Living With a Star (ILWS) Program. Subsequent mission candidates include a constellation of small spacecraft in the inner magnetosphere to

identify how the interaction between Earth's radiation belts, ring current, and plasmasphere produces energetic particles; a mission to discover how the low-latitude interactions among the upper layers of the atmosphere—mesosphere, thermosphere, ionosphere, and plasmasphere—affect communications; a cluster of simple probes held by solar sails, hours upstream from Earth in the solar wind, to measure the transient structures that will impact Earth; and a high-resolution investigation of the dynamics of the region between the visible Sun and its corona (solar transition region) that controls the stability of larger scale structures.

Key Sun-Earth Connection Technology Requirements

Progress in four key technology areas is vital for SEC's planned mid- and long-term missions:

- Spacecraft systems for affordable clusters and constellations of small, ultra-low-power satellites providing multipoint measurements of the connected Sun-Earth system
- Information technology that will allow ready access to and analysis of an unprecedented volume of data from multiple spacecraft in diverse locations and improved spacecraft autonomy to reduce spacecraft operations costs
- Scientific instruments with improved remote sensing and local measurement capabilities including speed, precision optics, collecting area, sensitivity, energy resolution, and angular resolution; also, very lightweight, low-power instruments
- Solar sails and other advanced propulsion systems that allow spacecraft to remain at crucial vantage points, such as hovering upstream in the solar wind, or to explore "uncharted" regions such as the Sun's poles, a near-solar heliosynchronous orbit, and the interstellar medium



Tiny Mercury crosses the face of the Sun in a phenomenon visible from Earth only 13 times a century. Mercury is the small object moving from left to right at the top of these SOHO images. A sunspot is also visible near the center of the solar disk. The 2004 Venus transit of the Sun will be the basis for a major set of education and public outreach activities. (Credit: SOHO/MDI/ESA/NASA)



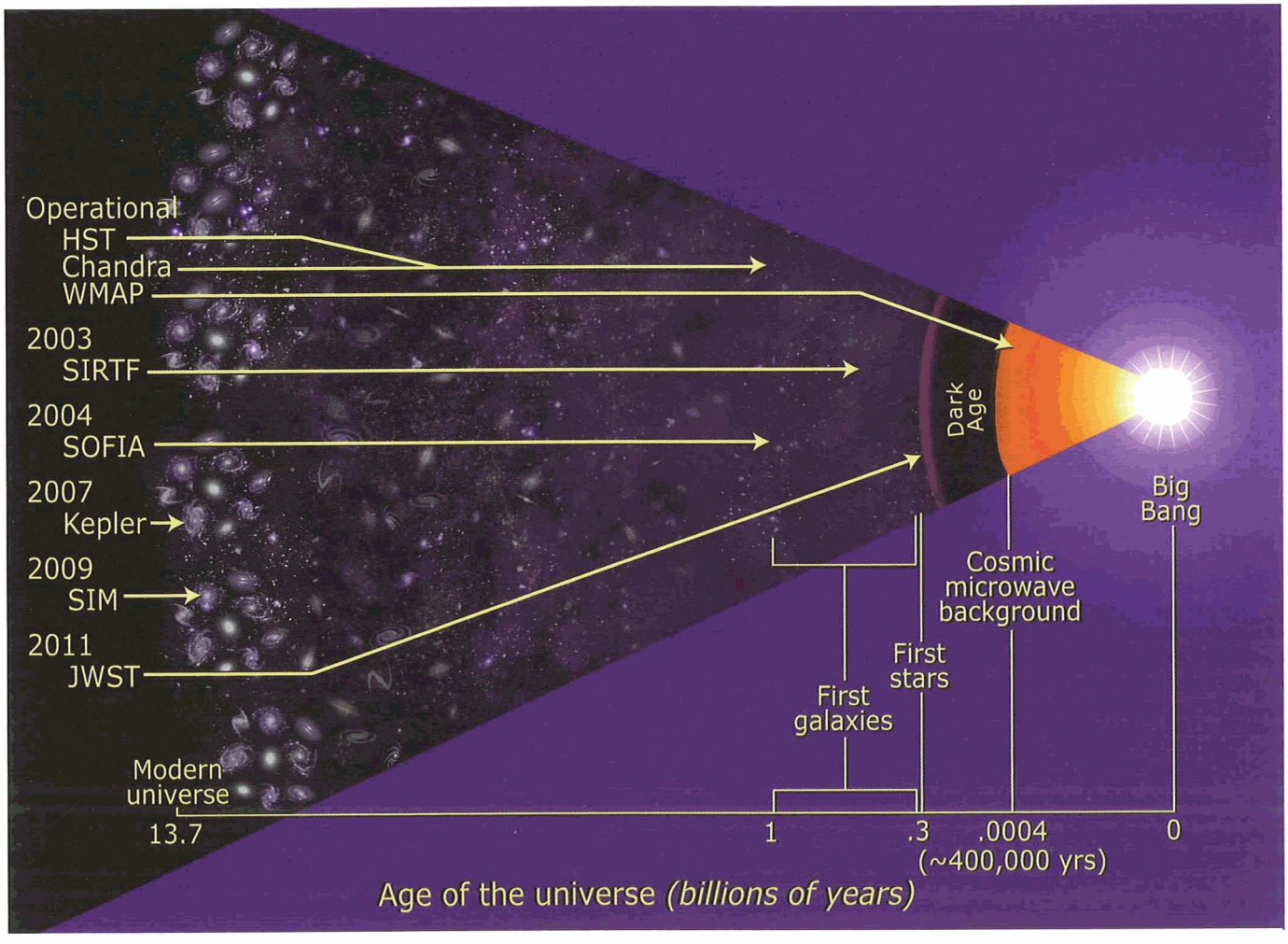


3.2.4 Astronomical Search for Origins

The Origins theme focuses on two questions: "Where did we come from?" and "Are we alone?" Although these questions are relatively simple, the scientific and technical challenges to answer them are complex. Today, the universe is full of structure, from giant galaxies to minuscule but complex single living cells. Our objective is to understand how astronomical structure came about, how stars and planets form, how the chemical elements are made, and, ultimately, how life originates.

Strategic objective 5.8.—Learn how galaxies, stars, and planets form and evolve.

Research on this objective aims to determine how the cosmic web of matter that emerged from the Big Bang organized into the first stars and galaxies, how different galactic systems of stars and gas form, and which of these systems can lead to planets and living organisms. It traces the condensation of gas and dust into stars and planets and seeks to detect planetary systems around other stars, with the ultimate goal of understanding planetary systems and their evolution.



Above: A cosmic perspective on Origins missions. By looking to ever-increasing distances, astronomers can essentially travel back through time. Origins missions, both current and planned, will study the formation of the earliest stars and the characteristics of galaxies, stars, and planets in the modern universe. (Credit: STScI/A. Feild and M. Livio) **Left**: The Andromeda galaxy is a nearby, large spiral galaxy similar to our own Milky Way. (Credit: NOAO/AURA/NSF/T.A. Rector, B.A. Wolpa)



Origins Education and Public Outreach Highlights

Sharing the results of the Origins quest with educators and the public requires as diverse a set of tools in public engagement as it does in science. Here are a few examples of such tools.

Public Outreach

ViewSpace is a series of multimedia presentations used by nearly 200 science centers, museums, and planetariums around the country to show regularly updated images from the Hubble Space Telescope and other NASA space science missions in their galleries. ViewSpace is currently being distributed via compact disc, but it will soon transition to an Internet distribution model that will allow automated delivery of the latest news and images from Origins missions as soon as the information is released.

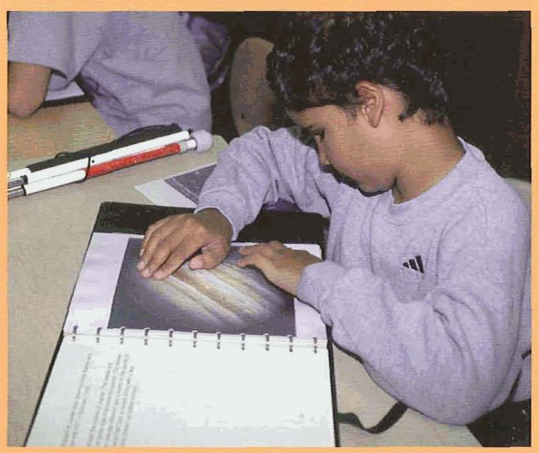


A ViewSpace installation in Honolulu, HI, brings recent images from Hubble Space Telescope to museum visitors. (Credit: Bishop Museum Planetarium)

Teachers and Students

Amazing Space is a set of interactive online activities and printed materials that use Hubble's discoveries to inspire and educate students about the wonders of the universe. More than 250 school districts in all 50 states use Amazing Space in a variety of ways, including as a resource for developing lesson plans, as a model for developing science education Web sites, and as a resource for providing current information not found in textbooks.

Touch the Universe: A NASA Braille Book of Astronomy is a 64-page book that makes the magnificent images taken by HST accessible to visually impaired students. Each image is printed in color, and then the pages are embossed so that color features are represented by various raised symbols and textures. The accompanying explanatory text is given in both Braille and large print so that readers of all visual abilities are able to view and read the book together.



A visually impaired student examines a tactile image of Jupiter in *Touch the Universe: A NASA Braille Book of Astronomy*. (Credit: Colorado School for the Deaf and Blind)

Future Plans

Beginning in 2004, hundreds of educators each year will have the opportunity to fly aboard the Stratospheric Observatory for Infrared Astronomy (SOFIA). The educators will work side by side with scientists during observing flights, participating in the data collection and research efforts.

About 250 million years after the Big Bang, what had been a calm and nearly formless sea of dark matter and hydrogen gas began to surge with a froth of complex forms of matter and energetic processes. The Wilkinson Microwave Anisotropy Probe (WMAP) has shown that star formation began before there were galaxies and that, when they died explosively as supernovae, these early stars produced the first spray of heavy elements. But it also appears that the birth of galaxies—by binding the stars and gas together to create great cosmic systems—was crucial to the buildup of these heavy elements to a level where planets and life became possible. The key steps on the road to life were the emergence of these enormous structures from the formless universe and the manufacture of vast amounts of heavy elements by stars.

We intend to investigate how the diversity of galaxies in today's universe emerged from the first galaxies and how stars and planets evolved. We will learn how the life cycle of stars creates the chemical elements needed for planets and life and determine if there is a region in our galaxy that is especially suited to the development of life: a "galactic habitable zone."

Astronomers have now identified the basic stages of star formation. The process begins in the dense cores of cold gas (molecular) clouds that are on the verge of gravitational collapse. It continues with the formation of protostars, infant stellar objects with gas-rich, dusty circumstellar disks that evolve into adolescent stars. Tenuous disks of ice and dust can remain after most of the disk gas has dispersed and surround these maturing stars. In these last stages of star formation, planets are born.

Direct detection of the first generation of stars will require the sensitivity of the James Webb Space Telescope (JWST). Observations with Hubble and JWST of exceedingly distant (high-redshift), and thus early, star formation and galaxies with supermassive black holes powering bright cores, called active galactic nuclei, will allow us to trace the buildup of galaxies over time. Observations by the Space Infrared Telescope Facility (SIRTF) and JWST will trace the energy budget of galaxy formation and early evolution. SIRTF will also characterize the large-scale infrared properties of



Colliding galaxies in the constellation Coma Berenices are nicknamed "The Mice" because of their long tails of stars and gas. The pair will eventually merge into a single giant galaxy.

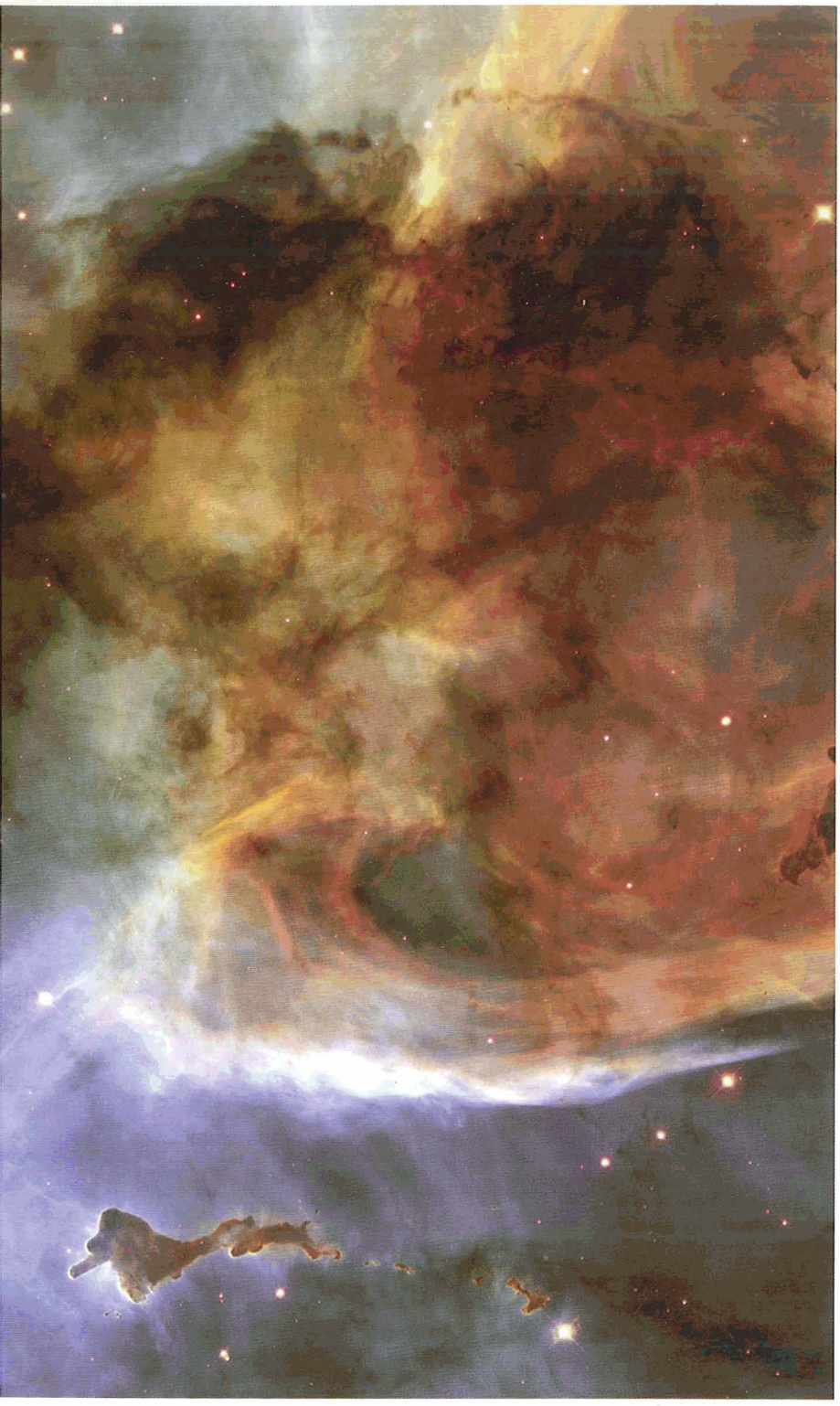
nearby galaxies to correlate star formation rates with properties of the interstellar medium.

In pursuing this objective, we will investigate how cool molecular clouds act as the cradles of star and planet formation. We will determine how protoplanetary dust and gas disks develop into planetary systems, and we will search for evidence of planets in the disks around young stars. We will conduct a census of planetary systems around stars of all ages.

Disks of ice and dust can remain after most of the disk gas has dispersed, and they can surround maturing stars. In these last stages of star formation, planets are born.

First SIRTF, then the Stratospheric Observatory For Infrared Astronomy (SOFIA) and possibly a future, larger telescope, will determine the temperature, density, and velocity structure of molecular clouds. The JWST will be able to probe the most central regions of protostars. High-angular-resolution studies in the near-infrared with JWST and SIRTF and in the far-infrared with SIRTF and SOFIA are necessary to trace the distribution of important planetary constituents such as water, ice, silicates, and complex carbon





Details of the Keyhole Nebula as seen by Hubble. This nebula is a breeding ground for some of the hottest and most massive stars known.

molecules in the disks around young stars. SIRTF will provide the first hints about gas and dust dispersal, while larger telescopes such as JWST are ideally suited to track the evolution and map the structure of vestigial debris disks around nearby main-sequence stars. The Terrestrial Planet Finder (TPF) will distinguish between starlight and planetary radiation from the surrounding disk in order to possibly enable direct imaging of young protoplanets.

Strategic objective 5.9.—Understand the diversity of worlds beyond our solar system and search for those that might harbor life.

Toward the ultimate goal of finding life beyond our solar system, we ask what the properties of giant planets orbiting other stars are, how common terrestrial planets are, what their properties are, which of them might be habitable, and whether there is life on planets outside the solar system.

After centuries of speculation, we now know that there are indeed planets orbiting other stars. The extrasolar planets discovered so far seem to be gas giants like Jupiter. Earth-like worlds may also orbit other stars, but until now, our measurements lacked the precision needed to detect a world as small as Earth. The Kepler mission, surveying a myriad of distant stars, will be our first opportunity to find out how common it is for a star to have an orbiting Earth-sized planet. We will also learn how big these planets are and where they are located in relation to their stars' "habitable zones," where life as we know it may be possible.

Even before then, detailed studies of giant planets will tell us much about the formation and history of planetary systems, including our own. We have already made a first reconnaissance of the atmospheric properties of one such giant planet that passes directly in front of its star and allows us to probe its atmosphere, even if we cannot see the planet directly.

The Space Interferometry Mission (SIM) will be capable of detecting and measuring the mass of near-Earth-sized planetary bodies orbiting nearby stars. SIM will extend the census of nearby planetary systems into the range of rocky, terrestrial planets for the first time. This census will form

the core of the observing programs, providing a "target list" for subsequent missions.

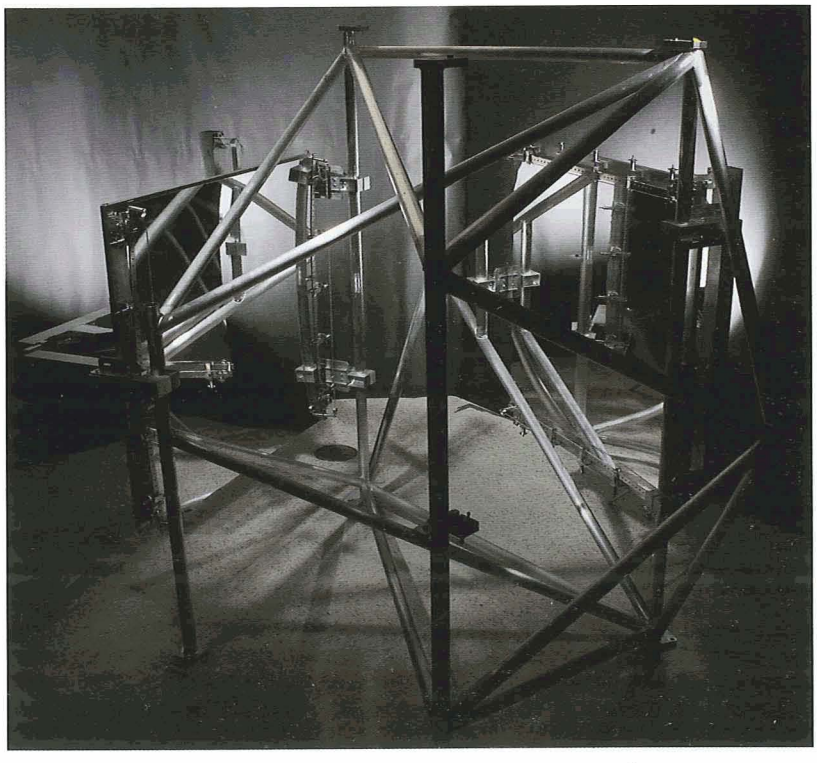
The flagship mission to carry forward the search for Earth-like worlds will be TPF, which will image nearby planetary systems and separate the extremely faint light of a terrestrial planet from that of its parent star.

Once we have found terrestrial planets orbiting nearby stars, we can then tackle two even more ambitious objectives: to determine which of these planets have conditions suitable for life and which, if any, show actual signs of past or present life. Studies are underway to learn about "biosignatures"—identifiable spectral features in a planet's reflected light—that can reveal past or present life on a planet. However, to take advantage of this new information, it will be necessary to develop follow-on space telescopes of unprecedented size and sophistication.

Key Astronomical Search for Origins Technology Requirements

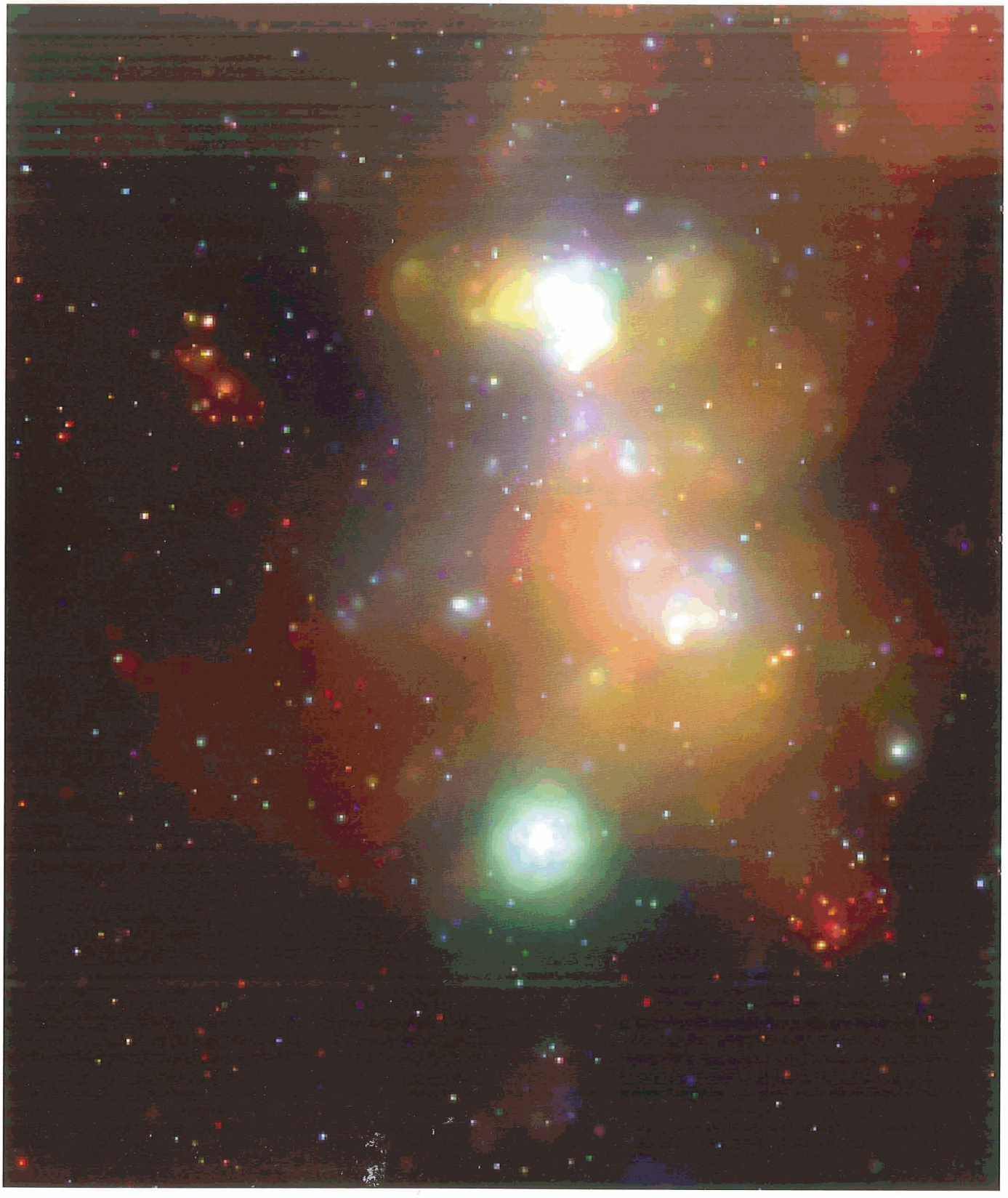
The Origins technology plan has two objectives. In the near term, technologies for observatories like SIM, JWST, and TPF must be matured and tested. These technologies include precision metrology and microdynamic disturbance reduction, rapid lightweight mirror panel fabrication and folded mirror deployment and alignment, and coronagraphic and advanced interferometric techniques.

For the longer term, it is necessary to begin establishing the new technological building blocks for very large space observatories to follow. These observatories will require advances in four key areas: large lightweight mirrors for all wavelengths, active systems for precise control of optical elements, new detectors to improve the efficiency of collecting radiation, and cooling technologies to minimize the infrared radiation from warm telescopes.



The Dual Anamorphic Reflector Telescope (DART) concept is one option for a future large-aperture telescope that combines very lightweight, precision support structures (shown here) and "gossamer" optical surfaces.



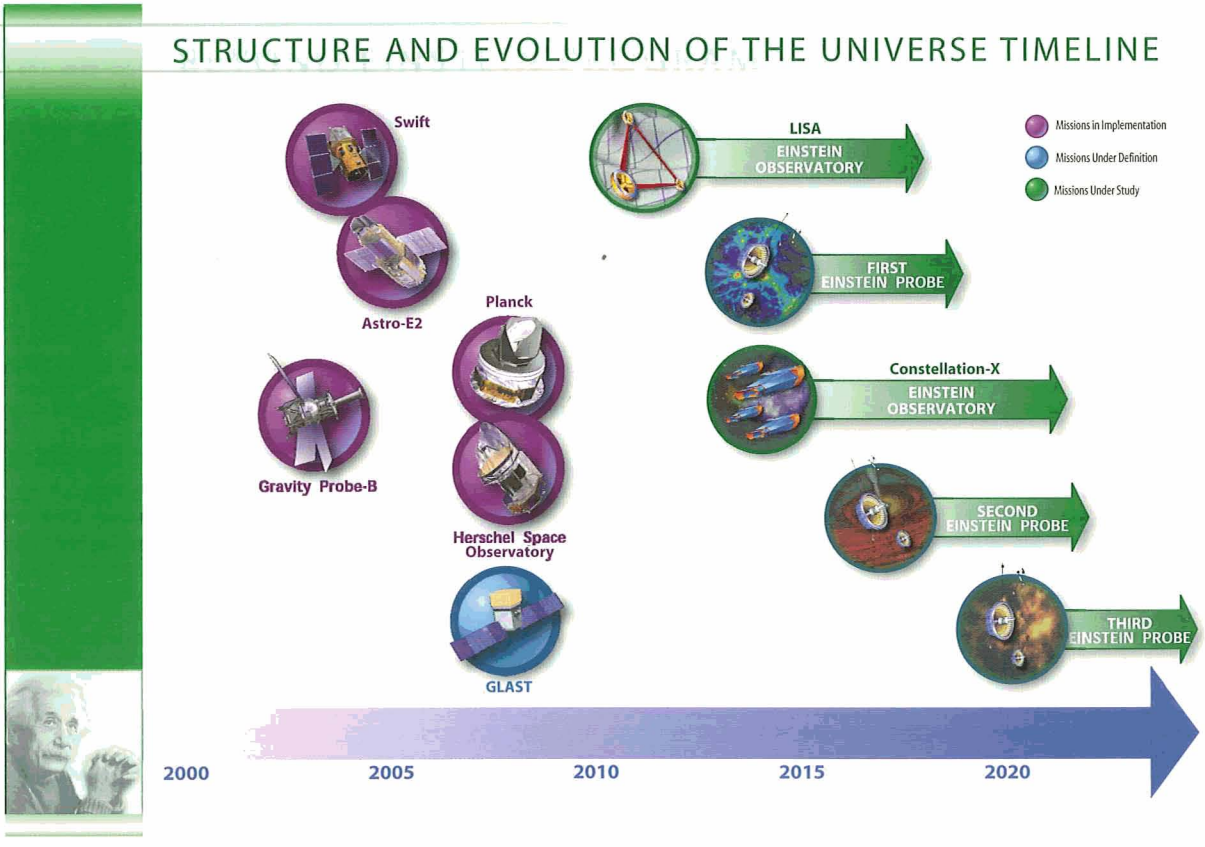


3.2.5 Structure and Evolution of the Universe

In the Structure and Evolution of the Universe (SEU) theme, we seek to explore and understand, at the most fundamental level, the dynamic transformations of energy in the universe, from the beginning of time to the present day and beyond, and to study the entire web of interactions that determine the evolution of our cosmic habitat. Existing and proposed SEU missions directly address several of the "Eleven Science Questions for the New Century" posed by the NRC's *Connecting the Quarks with the Cosmos* report. These include (1) What is the nature of the "dark energy?" (2) How did the universe begin? (3) Did Einstein have the last word on gravity? (4) How do cosmic accelerators work? (5) How were elements, from iron to uranium, made?

The theme comprises two science programs: the new Beyond Einstein program, the theme's highest priority, and the Cycles of Matter and Energy program. Both programs envision a suite of missions to achieve their science objectives. The Beyond Einstein program (see box) is dedicated to answering the most fundamental questions that one can ask about our universe: How did the universe begin? What is its ultimate fate? Is there a beginning to time? Does space have edges? How did the universe evolve over the eons from its initially formless state to its present complex structure?

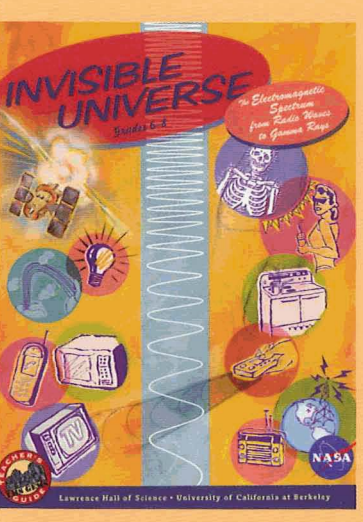
The Cycles of Matter and Energy program, the second of the SEU science programs, focuses on our dynamic universe. Stars are born, and stars die, with either the explosive demise of a supernova or the lingering, cold death of a white



Above: Of these upcoming SEU missions, the green ones are part of the Beyond Einstein Program. Herschel and Planck are two ESA missions in which we are partners. **Left**: This mosaic of several Chandra images of the central region of our Milky Way Galaxy reveals hundreds of white dwarf stars, neutron stars, and black holes bathed in an incandescent fog of multimillion-degree gas. (Credit: NASA/UMass/D. Wang et al.)

Structure and Evolution of the Universe Education and Public Outreach Highlights

The SEU theme's quest to answer fundamental questions about the universe offers an unparalleled opportunity to involve the public and the education communities in the excitement of cosmic exploration.



Invisible Universe guides learning about the electromagnetic spectrum.

Public Outreach

Cosmic Questions: Our Place in Space and Time is a traveling museum exhibition that invites visitors to explore fundamental questions and gain an understanding of recent discoveries about the origin, evolution, and structure of the universe. Nine NASA space science missions, 14 major science institutions or universities—including the National Science Foundation and Boston Museum of Science—and dozens of space scientists contributed their scientific expertise as well as data, images, and artifacts from their missions.

During its 2002 opening run at the Boston Museum of Science, Cosmic Questions had more than 350,000 visitors. Another 3 million visitors are anticipated in the 10 cities that Cosmic Questions will visit through 2005.

Teachers and Students

Classroom materials developed by individual SEU missions, or in conjunction with major SEU television specials or museum exhibitions, help students explore black holes and the nature of the universe, as well as motivate them to learn basic science concepts. As one example, the Swift gamma-ray burst mission's "Invisible Universe: The Electromagnetic Spectrum from Radio Waves to Gamma Rays" is a set of middle school classroom activities published as part of the Lawrence Hall of Science's GEMS series. GEMS guides are currently used in approximately 25 percent of the Nation's school districts.

Future Plans

Anticipated results from future Beyond Einstein missions and probes will lead to educational materials covering a wide range of topics that are part of the National Science Education Standards. For example, in examining evidence for the Big Bang, teachers and students can trace the underlying idea that scientific inquiry can address even the most ancient and difficult questions.

Similarly, the very nature of the Beyond Einstein program addresses the mandate in the American Association for the Advancement of Science's Benchmarks for Science Literacy that, by the end of 12th grade, "students should know that . . . many predictions from Einstein's theory of relativity have been confirmed on both atomic and astronomical scales. Still, the search continues for an even more powerful theory of the architecture of the universe."

Future Beyond Einstein missions will soon provide content for the *majority* of materials on these and related subjects in the Nation's classrooms.



The Milky Way serves as a gateway to the *Cosmic Questions* exhibition. (Credit: Smithsonian Astrophysical Observatory/Kevin Burke)

dwarf. Galaxies evolve, collide, and become transiently bright beacons seen across the entire universe. The patterns of exchange of matter and energy dictate the creation of solar systems and life itself.

Strategic objective 5.10.—Discover what powered the Big Bang and the nature of the mysterious dark energy that is pulling the universe apart.

Einstein's General Theory of Relativity predicted the expansion of the universe. But we still have not determined the motive force that helped power the Big Bang and made our universe as large as it is, allowing stars and galaxies to form and life to evolve. Einstein's theory also predicted the presence of a ubiquitous, invisible energy that causes the universe to accelerate. Although we now have evidence it exists, we have not begun to understand the origin and nature of this dark energy.

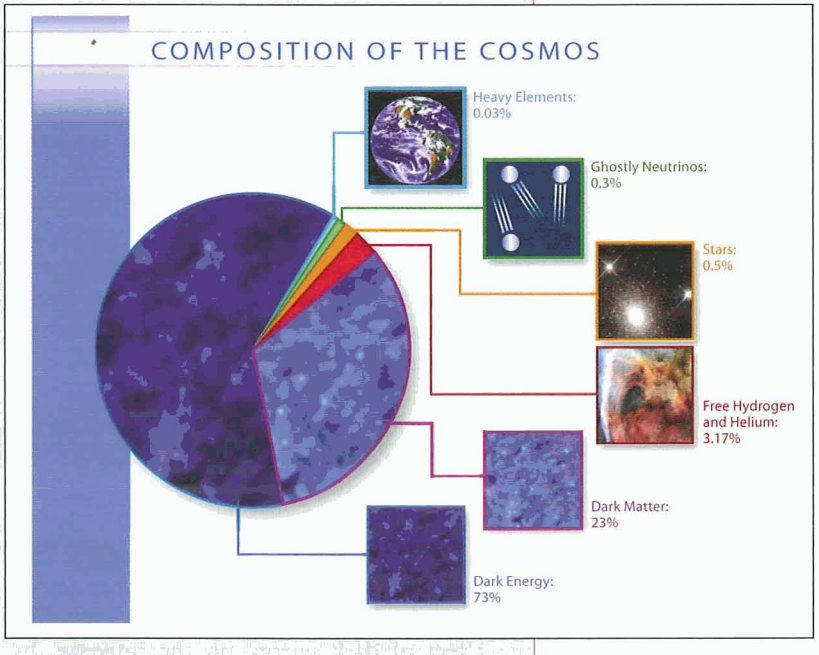
The inflationary universe theory explains how the universe grew from very small to very large within the first tiny fraction of a second of its existence. This theory also predicts that we can directly view this birth of the Big Bang by looking at the

Beyond Einstein

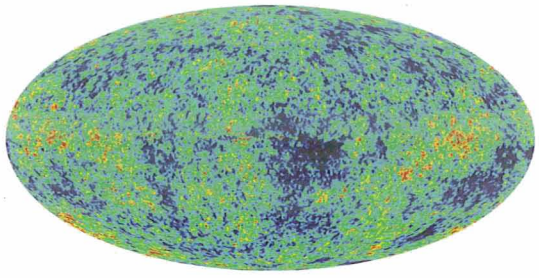
Einstein and his successors, in their attempts to understand how space, time, and matter are connected, made three predictions: first, space is expanding from a Big Bang; second, space and time can tie themselves into contorted knots called "black holes" where time actually comes to a halt; third, space itself contains some kind of energy that is pulling the universe apart. These predictions seemed so fantastic that Einstein himself regarded them as unlikely, yet they have turned out to be true. But Einstein's theory alone cannot answer such questions as (1) What powered the Big Bang? (2) What happens to space, time, and matter at the edge of a black hole? and (3) What is the actual nature of the mysterious dark energy pulling the universe apart? To answer these, we need to go beyond Einstein, to explore new theories that predict unseen dimensions and entire universes beyond our own. This is the quest of the Beyond Einstein missions, to help usher in the next revolution in understanding our universe with crucial investigations that can be done only in space.

The Beyond Einstein mission line has two Einstein Observatories: the Laser Interferometer Space Antenna (LISA), a deep-space-based gravitational wave detector that will open our eyes to the as yet unseen cosmic gravitational radiation, and Constellation-X, which, through X-rays, will tell us what happens to matter at the edge of a black hole. Three moderate-sized, scientist-led probes will answer "What powered the Big Bang?" (an inflation probe), "How did black holes form and grow?" (a black hole finder probe), and "What is the mysterious energy pulling the universe apart?" (a dark energy probe). The final element is a program of technological development, theoretical studies, and education and public outreach, supporting the mission line and pointing toward two future "vision" missions: a Big Bang observer and a black hole imager. The vision mission goals are, respectively, to detect gravitational waves directly from the earliest moments of the Big Bang and to image matter near the edge of a black hole.

The Beyond Einstein missions will connect humans to the vast universe far beyond the solar system. They will extend our senses beyond what we can imagine today—to the largest and smallest things, the beginnings and ends of time and space.



The familiar matter of our universe—stars, humans, planets—composes only a small fraction of the total contents of the universe.



A "baby picture" of the universe at the age of only 400,000 years, taken by the Wilkinson Microwave Anisotropy Probe (WMAP). Slight variations in the intensity of the microwave background (red through blue) are precursors to the structures we see in today's universe.

gravitational radiation—wavelike ripples in space-time—that was produced then and continues to propagate through the universe now. Gravitational radiation may uniquely allow us to see back to the first fraction of a second of the universe. Evidence for inflation can also be found through subtle patterns in the cosmic microwave background, the universal sea of low-energy photons produced when electrons and protons first combined to form neutral hydrogen atoms approximately 400,000 years after the Big Bang.

After its early and brief period of inflation, the universe has continued to grow in accordance with Einstein's theory of gravity. The growth, shape, size, and destiny of the universe are determined by a tug-of-war among visible matter, dark matter, and dark energy. Visible matter composes only about 4 percent of the universe, while dark matter makes up about 23 percent and dark energy makes up about 73 percent. We still do not know the nature of 96 percent of the content of the universe! The newly discovered dark energy, a repulsive, antigravity type of force whose origin is a complete mystery, dominates the evolution of the universe today, accelerating the expansion rate and sending galaxies farther and farther apart.

The Laser Interferometer Space Antenna (LISA) will measure gravitational radiation generated by a variety of astrophysical phenomena, including the effect of dark energy on the universe, by determining precise distances to sources of gravitational radiation. LISA, to be undertaken jointly with the European Space Agency, will also search for gravitational waves created during the earliest moments of the Big Bang, beginning our quest to see back nearly to time's origin.

Constellation-X will inform us about the nature of dark matter and dark energy by observing their effects on the formation of clusters of galaxies. Visible matter is attracted to the gravity of filaments of dark matter that thread the universe, creating its weblike structure. Hydrogen gas falls onto these filaments and heats to high temperatures, glowing brightly in X-ray light like jewels on a necklace.

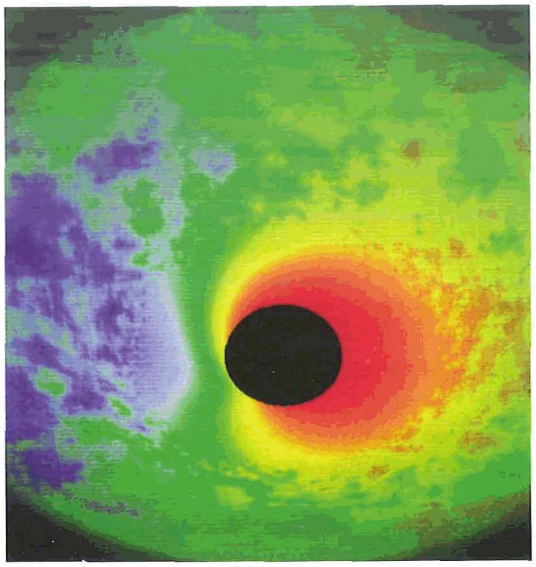
A dark energy Einstein probe will investigate the expansion rate of the universe over the last several billions of years. Since dark energy has dominated the universe's energy content during this time, we can learn from this investigation whether dark energy is constant or varying over time. If it is constant, then dark energy is an energy that comes from the vacuum of space itself. If not, then it may show signs of a richer structure predicted by string theory, in which space-time has more dimensions than we perceive with our senses.

In a manner complementary to LISA, an inflation Einstein probe will seek the imprint of primordial gravitational waves on the relic cosmic microwave background. This will test inflation theory of the very early universe and will also test physics at energy levels that are currently inaccessible by any other means.

Strategic objective 5.11.—Learn what happens to space, time, and matter at the edge of a black hole.

Einstein's theory of space and time can be tested by experiments within the solar system, such as high-precision ranging measurements. Gravity Probe-B is a polar-orbiting satellite that will measure, to unprecedented precision, remarkable effects due to the distortion of space-time created by the spinning mass of our Earth as predicted by Einstein's General Theory of Relativity.

The greatest extremes of gravity in the universe today exist at the edges of black holes. Matter captured by the strong gravity of a black hole falls inward, accelerating to speeds close to that of light. This infalling gas, including gas from stars



Simulation of X-ray radiation around a black hole that will be mapped by the Constellation-X mission.

shredded by the intense gravity fields, heats up dramatically, producing large quantities of X-ray radiation that can be studied to learn what happens near the edge of a black hole, beyond which time comes to a standstill and matter disappears from view forever. By measuring such X-rays, we can observe the slowing of time near the surface of a black hole, as Einstein predicted, and investigate how infalling matter releases energy there. We can also observe the evolution of black holes in distant galaxies and quasars and determine their role in the evolution of their host galaxies.

Constellation-X will greatly extend our capability for high-resolution X-ray spectroscopy. Its key goals are to use atoms falling into a black hole as probes of space-time by tracking spectral features close to the black hole's event horizon, the theoretical black hole "surface." Constellation-X will also trace the evolution of black holes with cosmic time by obtaining detailed spectra of the most massive of these objects at the cores of galaxies throughout the universe.

When neutron stars or stellar-mass black holes fall into a supermassive black hole, they generate ripples in space-time called gravitational waves. By observing the waveforms of these ripples, we can map the knotted structure of space and time around a black hole and determine whether the predictions of Einstein's theory are correct, including the freezing of time and the dragging of space around a black hole. The merger of two supermassive black holes, believed to occur during collisions between galaxies, is a catastrophic event in space-time that produces gravitational waves detectable throughout the entire universe. These waves are gravitational "recordings" of every massive black hole merger that has ever happened.

LISA will, perhaps, provide us with the first direct detection of gravitational radiation, a phenomenon predicted by Einstein's theory of gravity. It will detect supermassive black hole mergers that occur several times a year throughout the universe and will provide us with precise maps of the deformed structure of space-time near the surface of a black hole, testing Einstein's theory.

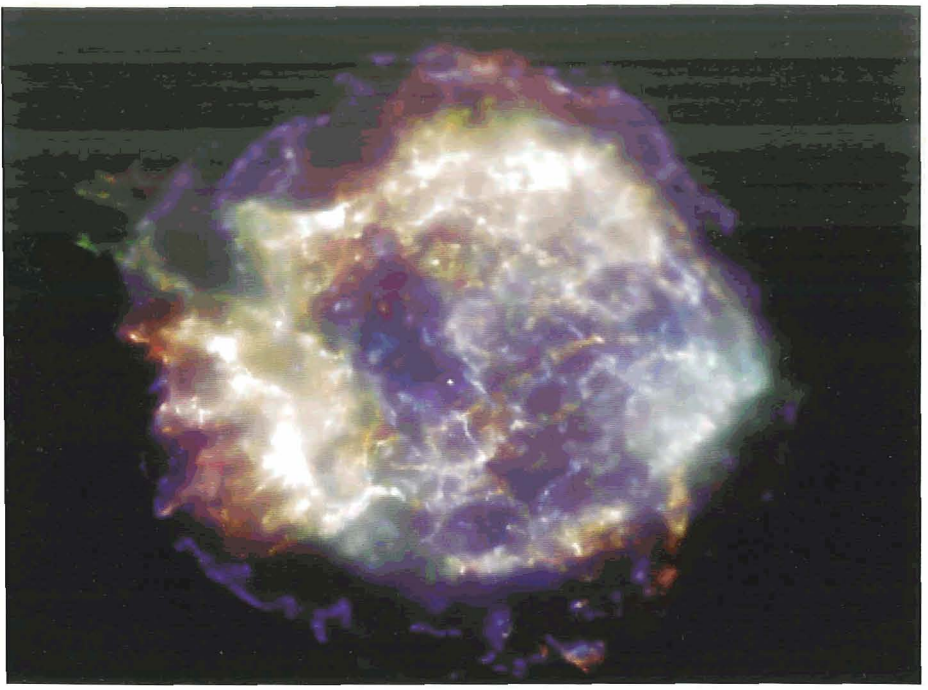
A black hole finder Einstein probe will perform the first all-sky imaging census of accreting black holes—ones into which stars and gas are falling—ranging from supermassive black holes in the centers of galaxies, to intermediate black holes produced by the very first stars, to stellar-mass black holes in our own galaxy.

Strategic objective 5.12.—Understand the development of structure and the cycles of matter and energy in the evolving universe.

The universe is governed by cycles of matter and energy. Even as the universe expands, pockets of atomic matter and dark matter collapse by the force of gravity to form galaxies and clusters of galaxies. Dense clouds of gas within galaxies collapse to form stars, in whose centers all of the elements heavier than hydrogen and helium are produced. When stars die, they eject some of these freshly produced, heavier elements into space, forming galactic clouds of gas and dust in which future generations of stars are born, beginning another cycle of matter.

The luminous energy from the Sun and stars comes from thermonuclear fusion, in which hydrogen and helium gas are burned, leaving as "ash" the heavier elements. When a star's fuel is consumed, its life ends. For the most massive stars, the end comes as a supernova: the stellar core collapses to a neutron star or black hole,





Chandra image of the gas remnant of a supernova explosion, Cassiopeia A. Exploding stars like this one are sources of heavy elements such as iron, calcium, and oxygen.

releasing vast quantities of energy that cause the supernova to momentarily outshine its host galaxy. This energy strongly affects the environment of nearby stars and is believed to be responsible for cosmic rays, atomic particles moving at nearly the speed of light that constantly bombard Earth. Supernovae have also been associated with other extraordinary phenomena, such as gamma-ray bursts and cosmic jets.

The aim of the Cycles of Matter and Energy program is to understand these cycles and how they created the conditions for our own existence. To understand how matter and energy are exchanged between stars and the interstellar medium, we must study winds, jets, and explosive events. To understand the formation of galaxies, we need to map the "invisible" universe of dark matter that helped nucleate these structures, observe the gas expelled during the birth of galaxies, and witness the birth of the first black holes and their effect on the formation of galaxies.

An Explorer mission called Swift will contribute to our understanding of the cycles of matter and energy. Swift's goal is to determine the origin of gamma-ray bursts, the most powerful explosions known to occur in the universe. Swift will search for bursts in the gamma-ray, X-ray, ultraviolet, and optical regions of the electromagnetic spectrum. Swift will rapidly point at gamma-ray bursts within seconds of their detection and simultaneously observe the burst with instruments in all of these wavelengths. It will also send a message to robotic telescopes on Earth to do the same.

The Gamma-ray Large Area Space Telescope (GLAST) will measure gamma rays emitted by a variety of extremely energetic objects, such as quasars. A quasar is a galaxy in which large quantities of gas are falling onto a supermassive black hole that occupies the galaxy center, releasing huge amounts of gravitational energy. This energy goes into the creation of cosmic jets, which shine as sharp beacons in the gamma-ray region of the electromagnetic spectrum. By measuring the spectra of these emissions, GLAST will explore the details of the complex interactions that occur in these "cosmic cauldrons."

Key Structure and Evolution of the Universe Technology Requirements

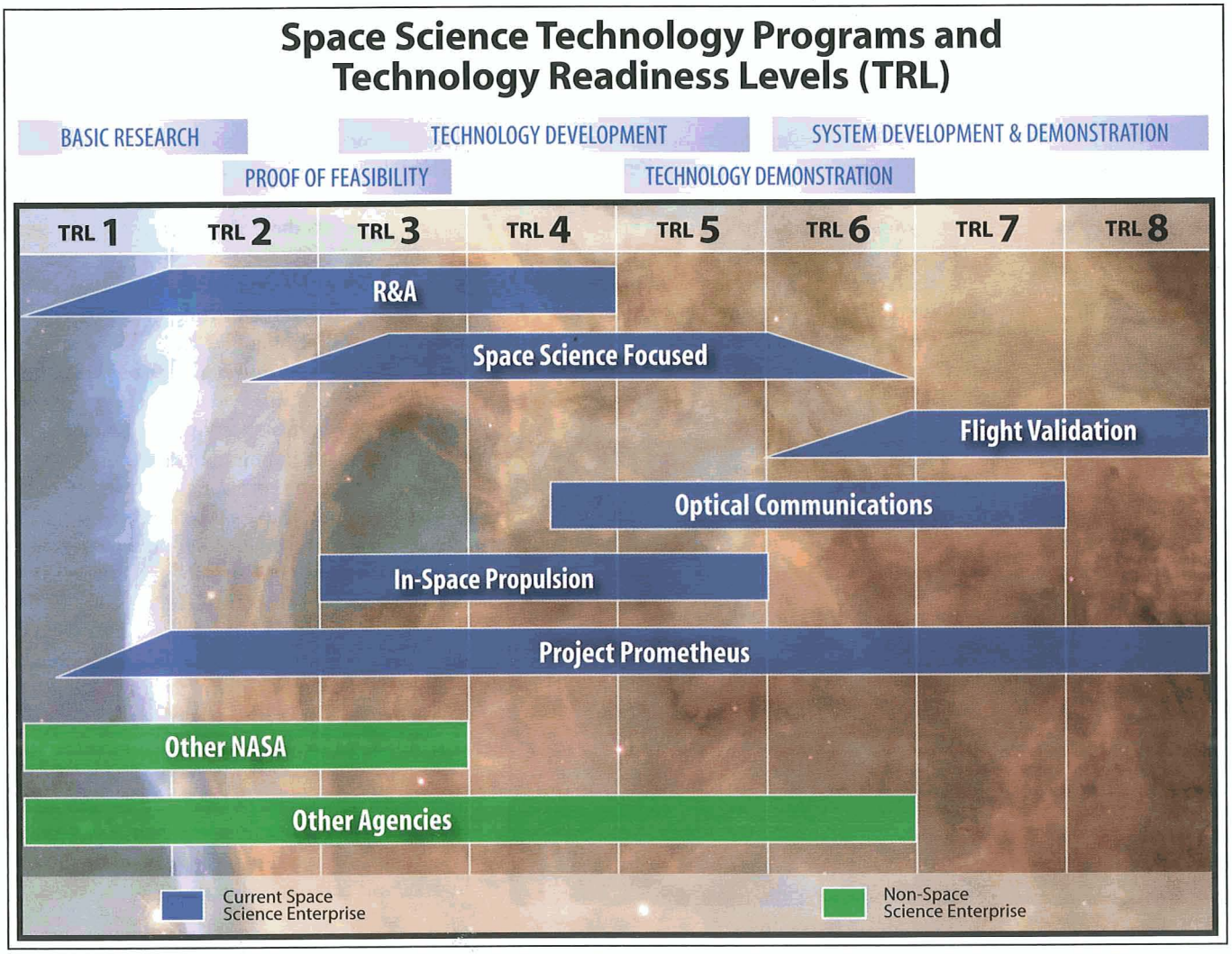
The Beyond Einstein program demands many improvements in technology. Constellation-X will need lightweight optics and cryogenic X-ray calorimeters. To keep LISA's test masses free of nongravitational forces, sensitive positional monitoring units coupled to extremely low-force thrusters are required. LISA will also need very stable laser measurement systems. These will enable LISA to detect the subtle remnants of gravitational radiation that will alter the distances between spacecraft, separated by millions of kilometers, by less than the width of a proton. The vision missions, a black hole imager and a Big Bang observer, need still greater precision in spacecraft pointing and control. The Einstein Probes require the study of a broad range of technologies, such as large-array microwave bolometers and gigapixel optical and infrared detectors, to permit us to choose the most effective approach to achieve their science goals.

3.3 Technology Investments

As discussed in the theme sections, each theme has special, critical technology requirements. In addition, there are technology needs common to all space science missions. This section presents a summary of both the unique and the common, all of which are strategic investments in our ability to meet our objectives.

The Space Science Enterprise prepares a Technology Implementation Strategy, updated in parallel with the Enterprise Strategy, every 3 years. It includes the Space Science Enterprise Technology Blueprint, which is updated semiannually to reflect changes of requirements and technology advances. As with our other programs, we use competitive selection through NASA Research Announcements for nearly all technology efforts. We also collaborate with the other science Enterprises and the Aerospace Technology Enterprise (AT) to define requirements and leverage development activities.

Technology programs have three key phases. First, we strive to develop new and better technical approaches and capabilities in response to needs established for space-based scientific measurement systems. Where necessary, we then validate these capabilities in space so that they can be confidently

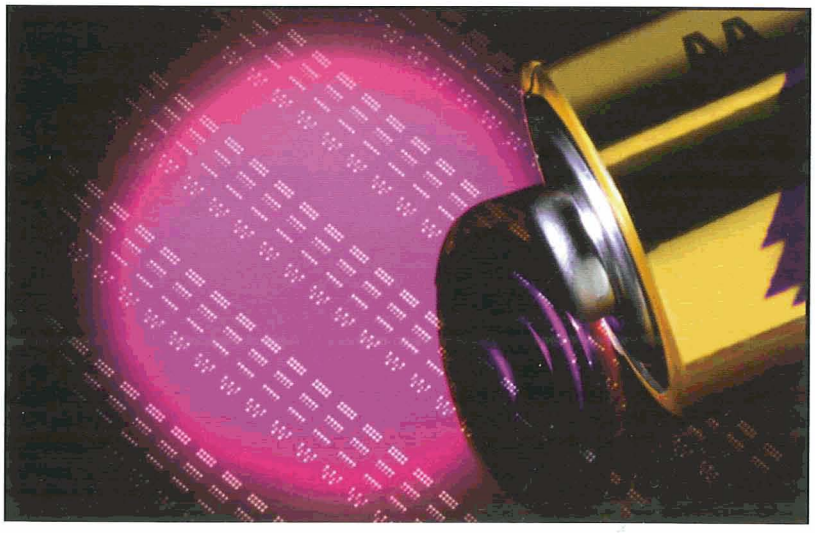


The Space Science Enterprise incorporates technology developed in programs within and outside the Agency to enable future missions.

applied to science flight projects. Finally, we apply these improved and demonstrated capabilities in the science missions and ultimately transfer them to U.S. industry for public use. The relationships among the technology programs are illustrated on the previous page.

Acquiring new technical approaches and capabilities.—When mission concepts are sufficiently mature to begin detailed definition, we derive instrumentation, systems, and infrastructure requirements. Technology development is focused on satisfying these requirements ("mission pull" technologies).

Less mature technology research ("vision pull")—often pursued in close collaboration with the AT—is focused on more general measurement challenges. These are formulated on the basis of priorities established by the NRC and by study groups who work with the science and technology communities. The challenges are designed to stimulate the breakthrough innovation that will enable new measurement approaches and mission concepts. Two recent initiatives (In-Space Propulsion and Project Prometheus) are particularly noteworthy examples of vision pull technologies derived from advanced studies. A balance between mission pull and vision pull ensures the adequacy and resiliency of technology available to future science missions.



Dozens of miniature batteries on a thin-film substrate are dwarfed by a standard AA battery. Thin-film battery technology has the potential to replace bulky power systems on spacecraft by locating energy sources closer to the subsystems needing power.

Validating new technologies in space.—Technologies that are at a medium level of maturity are examined periodically to identify those promising candidates that could add significant value to future missions if demonstrated convincingly in an operational setting. Concepts from among these candidates are then selected competitively and are funded for space validation principally through the New Millennium Program and also through flights of opportunity. Ground validation of technologies not requiring space flight validation is accomplished through the focused technology programs of the space science themes.

Applying and transferring technology.—The technical requirements of the missions are often unique, due to the nature of the scientific undertaking. Nevertheless, by comparing requirements and occasionally by aligning mission requirements that may be met by coordinated technology development and application, we seek efficiency through identifying common needs. This results in reduced mission costs and shortened development time across the programs.

To ensure that the next generation of space science spacecraft is more capable and more reliable, we need new technologies to endow spacecraft with more onboard power for greater communication bandwidth, data analysis, and autonomy. Propulsion capability must improve to reach deep space with more capable payloads, in less time, with the ability to carry out a wider range of scientific programs. New telescopes require much larger apertures for higher resolution images and spectra. Constellation technology is needed to enable efficient, simultaneous data collection at dispersed locations. All of space science depends on continuing advances in sensors and detectors in the areas of sensitivity, accuracy, and wavelength range. These advances, coupled with efficiencies in power and mass requirements, will lead to more cost-effective missions, both in the near-Earth environment and farther out in the solar system. Many of these capabilities will also be invaluable for a future program of integrated human and robotic exploration.

During the preparation of the Enterprise Strategy, the theme roadmap teams derived the

key technical capabilities needed to implement their missions. The capabilities are synthesized into the Technology Blueprint—and summarized here—under three main headings: Remote Observing Technology, Technology for In Situ Exploration, and Space Systems Technology.

3.3.1 Remote Observing Technology

Future remote observing systems in space will require improved sensitivity, higher angular resolution, and broader spatial and wavelength coverage. These requirements can be met by technology advances in four subsystem areas: space optics, advanced sensors and instruments, constellations of spacecraft, and advanced coolers. In turn, advances in these subsystems require progress in several technical disciplines: optics, controls, structures, materials, nanotechnology, coatings, information processing, microelectronics, thermal engineering, and systems analysis and modeling.

Several planned space telescopes require larger but much lighter and more precise primary mirrors than can now be produced. Achieving this requires new space optics concepts coupled with advanced materials, structures, and controls. For example, some of the large primary mirrors will not fit within launch-vehicle fairings and need to be made and launched as segments to be deployed or assembled and then aligned in space to simulate a continuous high-precision optical surface.

Sensor and instrument technology advances are needed to provide new observational capabilities for astrophysics, space physics, and solar and planetary science remote sensing, as well as vehicle health awareness. There are immediate needs for large-format array detectors and lightweight precision optics and coatings. Focal plane arrays that cover a larger area with a large number of pixels are needed to examine larger areas of the sky, both for efficient operation and to measure the dynamics of complex phenomena. Large-area, high-efficiency, and high-read-out speeds are needed for deep-sky surveys.

Advanced light sensors, particularly with higher response and lower noise in the far infrared and ultraviolet regions of the spectrum, are essential for observing systems of the next generation. Spectroscopy is required to discover extrasolar planets suitable for supporting life. Spectroscopy also enables scientists to understand the chemistry and physics of the gas and dust cloud surrounding a star in the planetary system formation stages of its evolution. New technology is needed to dramatically increase the efficiency of spectroscopic instruments used in conjunction with space observatories.

For some missions, constellations of smaller spacecraft can emulate a single large primary mirror through a technique called interferometry, essentially a mixing of light waves, now done on Earth with radio and optical telescopes. Each of the spacecraft in such constellations must be precisely controlled, however. Distance-measuring techniques, such as advanced wavefront metrology, and active surface control to shape and focus mirrors are also needed for segmented, synthetic, and interferometric aperture systems. Planet-finders employing interferometry will require coronagraphy and high-resolution imaging through active surface control and optical surfaces that are intrinsically ultraprecise and smooth.

Advanced capabilities, coupled with efficiencies in power and mass requirements, will lead to more cost-effective missions, both in the near-Earth environment and farther out in the solar system.

One of the challenges in constellation control is achieving precision positional and pointing accuracy for each element of a constellation. This requires very high-precision microthrusters and systems for sensing, metrology, and control. Tiny satellites that can easily fit in one's hand carrying out in situ measurements will require less positional and pointing precision, but they may number in the tens or hundreds in a given constellation, requiring breakthroughs in the cost of constellation operations, most likely achievable through increased spacecraft and ground-system autonomy.

Another key challenge for spacecraft clusters and constellations is reducing the unit cost of the craft through the development of detectors, instruments, and integrated systems that are smaller, lighter, and more fault-tolerant and that use less power. Technologies developed to achieve these specific requirements for constellations will directly benefit all future missions, even those



Table 3.—This summary of theme technology requirements reflects priority space science investments in technology.

	Space Science Enterprise Themes				
	Solar System Exploration	Mars Exploration	Sun-Earth Connection	Astronomical Search for Origins	Structure and Evolution of the Universe
Remote Observing Technology					
Optics: lightweight mirrors and active optics				●	●
Remote sensors/detectors/instruments	●	●	●	●	●
Coolers			●	●	●
GNC*: constellation control, metrology			●	●	●
Technology for In Situ Exploration					
Robotics and planetary access	●	●			
Power for surface systems	●	●			
Entry, descent, and landing	●	●			
Ascent	●	●			
GNC*: rendezvous and sample capture	●	●			
Technology for extreme environments	●		●		
Planetary protection and sample handling	●	●			
In situ instrumentation	●	●	●		
Space Systems Technology					
Avionics	●		●		
Communications	●	●	●	●	●
GNC*: includes pointing, disturbance reduction	●		●	●	●
Information technology/autonomy	●	●	●	●	●
Power	●	●	●		●
Propulsion	●	●	●		
Structures/materials	●		●	●	●
Thermal control and environmental effects	●	●	●	●	●

* GNC: Guidance, navigation, and control



composed of single spacecraft, through reduced cost and increased reliability.

Advances in long-life cryocoolers and space-radiative coolers, which lower the temperature of the instrument environment to near absolute zero, are needed to control the unwanted background radiation and noise at the focal plane of imaging instruments.

3.3.2 Technology for In Situ Exploration

Two categories of measurements fall under the classification "in situ": (1) sampling of solids, gases, or fields on planetary or lunar surfaces and (2) direct detection of fields and particles in space.

In coming decades, planetary exploration will change its focus from remote observation to in situ exploration and sample-return missions. This means landing, selecting and digging samples, and bringing them back home. The key requirements for in situ planetary measurements are entry, descent and landing, robotics and planetary access, planetary protection, rendezvous and sample capture, and technology for extreme environments.

The most pressing need in "entry-descent-landing" (EDL) is safe, accurate, autonomous landing on the surfaces of planets and small bodies. The EDL techniques for small bodies and large bodies, and bodies with or without an atmosphere, are significantly different from each other.

Robotics and planetary access include roaming the surface and digging underneath. Increased autonomy is crucial in enabling rovers to travel longer distances across Mars. Balloons and aircraft above Mars could carry instruments to measure the atmosphere and regions on the surface not accessible from orbit or with a rover. Subsurface access by means of drills, penetrators, and impactors is vital to the investigation of sedimentary climate records on Mars and for investigations of water and other volatiles on Mars and other planetary bodies. Titan and Venus require instruments that fly across these alien worlds.

Planetary protection and sample handling are needed to avoid transporting to planetary bodies any Earth organisms that could contaminate the planet, appear in returned samples, or interfere with in situ instruments attempting to detect life. Instruments are needed to detect organisms at extremely low levels, along with robust cleaning methods for spacecraft. After samples are returned to Earth, they must be handled properly to prevent inadvertent release of potentially harmful material.

Autonomous rendezvous and sample capture are essential for sample-return missions. They require the ability to autonomously locate, track, and capture a small sample canister in orbit or deep space for return to Earth.

Technologies for extreme environments are essential for in situ missions. Access to the surface of Venus and the depths of the Jupiter atmosphere to conduct definitive measurements of bulk composition requires instruments tolerating pressure of nearly 100 times sea-level air pressure and temperatures approaching 500 °C. They must also be resilient to extreme deceleration loads during planetary entry. For missions to the Jupiter system using nuclear propulsion, we will need radiation hardening to increase spacecraft tolerance to both the natural radiation of the Jupiter environment and the neutron radiation from the power source.

New technology makes possible steady improvements in many types of in situ instrumentation, including extending the range of particle detectors to higher and lower energies; achieving higher energy resolution at high energies; developing novel electric and magnetic field measurement techniques; and developing more effective techniques for measuring particle densities, compositions, and winds. In particular, more powerful digital electronics components make possible the development of enhanced burst memory and onboard processing applied to all types of in situ measurements.

Similarly, future in situ field and particle measurements will require new technology development for the extreme environments they confront. One crucial requirement is the development of heat shielding with weight, size, and thermal isolation suitable to protect satellite systems and science instruments on a spacecraft deployed to within four solar radii of the Sun, much closer to the Sun

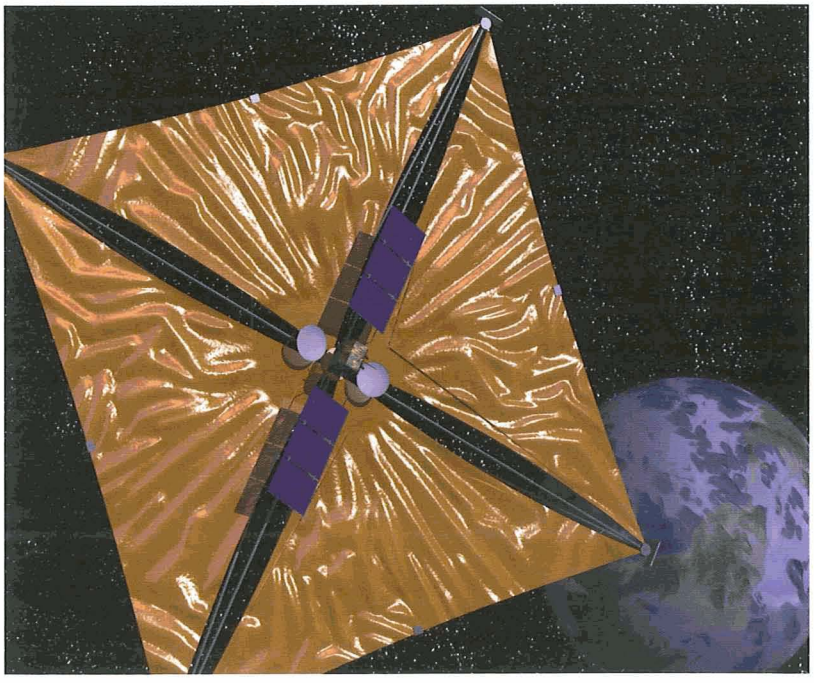


than Mercury. Another critical requirement is a dust shield to protect satellite systems and instruments from impacts of high-velocity particles in the inner solar system. In addition, hardened components for selected instruments must be developed for such spacecraft to provide certain measurements that cannot be made from behind a heat shield.

3.3.3 Space Systems Technology

The space systems technology category serves all space science flight programs. It encompasses the eight components that make up a modern space system: communications, power, propulsion, avionics, information and autonomy, guidance and control, thermal control and environmental effects, and structures and materials.

Communications data transfer rates are a major limiting factor on science return from space missions, especially from spacecraft at planetary distances. Increased data rates are a critical need that may be met by emerging technology in X- and Ka-bands, as well as optical communication. The Enterprise is leading a new initiative to develop and demonstrate optical communications capabilities (see box). Data compression tools and increased local communications capabilities are also needed.



Solar sail propulsion may enable space science missions, both far out into the solar system and in orbits necessary, but not currently possible, to study the interaction between the Sun and Earth.

Power and propulsion technology requirements include higher efficiency power systems, advanced chemical and solar electric propulsion, micropropulsion systems, solar sails, and aerocapture. Project Prometheus, which focuses on advanced radioisotope power generators and space-qualified nuclear reactors, is a major effort to meet these requirements. Project Prometheus will also develop advanced power conversion and propulsion subsystems that will be applicable across a broad range of missions.

Technology needs in avionics include high-performance yet power-efficient and even ultra-low-power processors, memory, sensor interfaces, data bus and architecture, packaging, and interconnects.

Information and autonomy technologies typically involve shifting decisionmaking from Earth to the spacecraft. There is also a need for more onboard responsibility in "housekeeping," including monitoring, diagnosis, and response. Key areas that are being addressed include autonomy, reliable software, modeling and simulation, improved onboard computational resources, science data analysis, and knowledge discovery. While spacecraft designs are typically evolutionary, the pace of development in information technology is revolutionary, leading to a significant lag in infusion of state-of-the-art techniques into Space Science Enterprise missions. Steps have been undertaken to quicken the infusion process for new information technology.

Needs for guidance, navigation, and control (GNC) technology include sensors and actuators with unprecedented precision and the ability to reduce spacecraft disturbances, to design trajectories, to estimate flight path and metrology, and to control attitude. Trajectory design technology is particularly needed for solar-electric propulsion and solar sail missions. Flight-path estimation is needed for in situ missions involving aerobots or landers.

Thermal control and environmental effects requirements run the gamut from protection of spacecraft and instruments near the Sun or at Venus, to protection from cold environments at outer planets or near comets, to spacecraft accommodation of cooled detectors and optics on observatories.

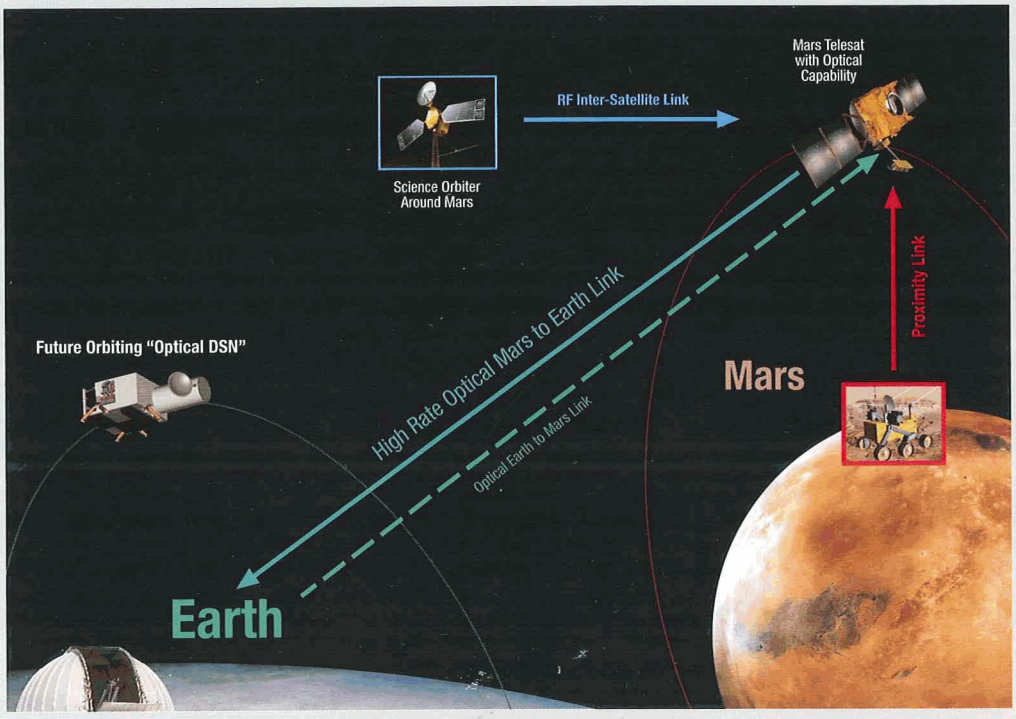
Structures and materials requirements include light structures that retain strength, stability, and stiffness; balloon materials for harsh environments; membrane materials and booms for gossamer structures such as solar sails and large apertures; multifunction spacecraft structures; and simulation and testing of material performance and durability in space.

Optical Communications

A new class of exploration missions, powered by nuclear fission, may include tours of multiple targets, extended orbital and surface stay times, and high-power science instruments—all of which lead to much larger quantities and higher rates of data return. Limitations in deep-space communication are a bottleneck to scientific discovery and public outreach.

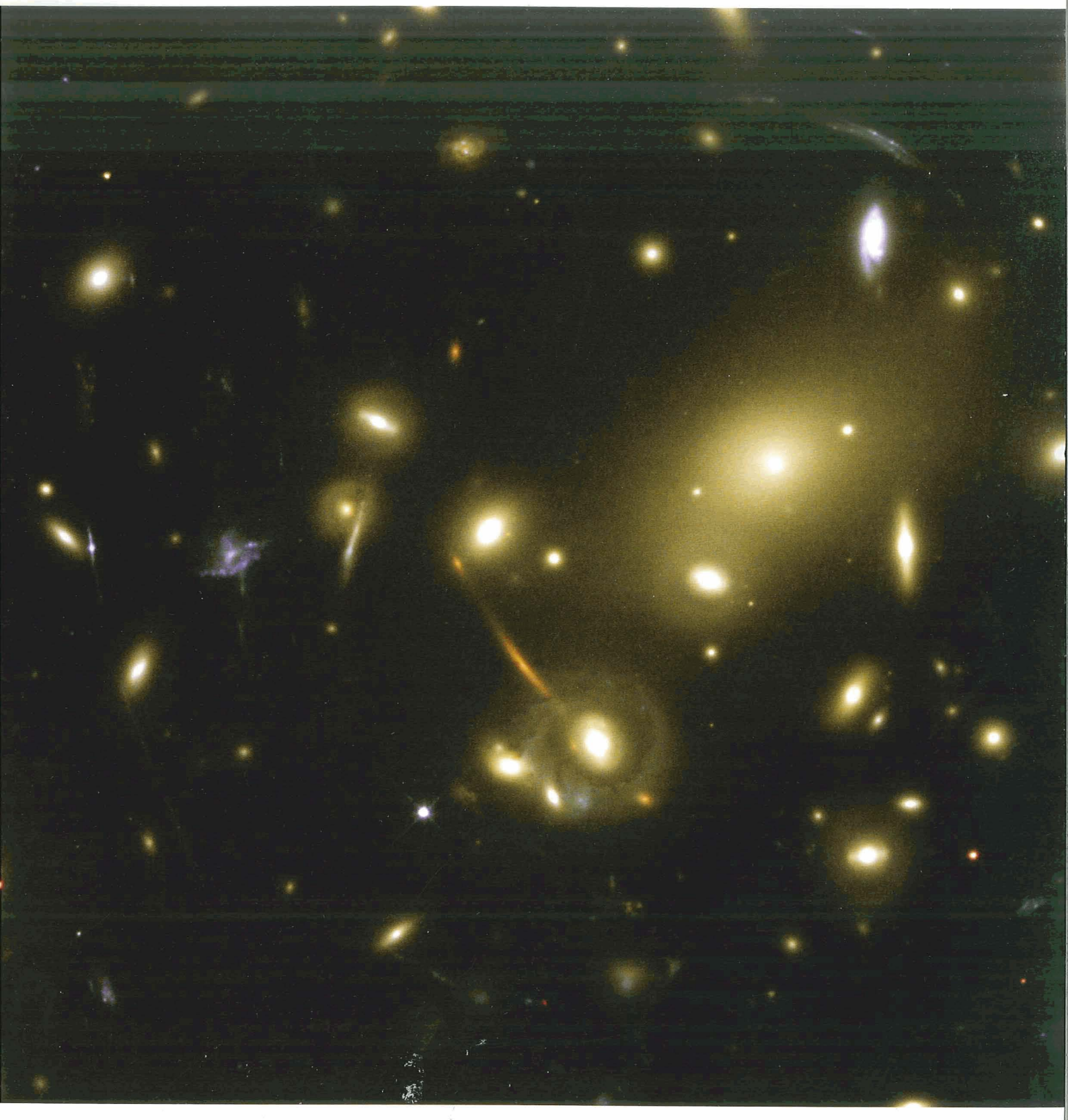
The use of optical/laser communications technology will enable dramatic improvements in science data rates and will lower the cost per byte of data returned. The anticipated improvement is analogous to switching from an old 14.4-speed dial-up modem to Ethernet connectivity.

The Optical Communications Initiative consists of both technology development and flight demonstration. We will complete the technology development of high-power lasers, capable of delivering vast quantities of scientific data from deep-space missions, as well as the development of the infrastructure of ground optical receivers to complement the Deep Space Network. Because optical communications' potential must be demonstrated and quantified under operational conditions, the Optical Communications Initiative will demonstrate critical space and ground technologies in this decade and perform a flight demonstration of high-data-rate communication from Mars in the 2010 timeframe.





4 Strategy Implementation





4 Strategy Implementation

4.1 Principles and Policies

NASA has adopted a common set of implementing strategies to ensure that the entire Agency is working safely and efficiently together. The Space Science Enterprise has incorporated these strategies into our management practices as described in the Space Science Enterprise Management Handbook. Table 4 illustrates the Enterprise's implementation of these strategies.

Our approach to accomplishing science objectives is also founded on a set of fundamental principles that govern Enterprise decisionmaking processes.

Use scientific merit as the primary criterion for program planning and resource commitment.—To optimize quality and preserve scientific integrity, the Enterprise uses open competition and scientific peer review as the primary means for establishing merit for its flight programs. In planning, the first rule is to complete missions already started, except in the case of insurmountable technical or cost obstacles.

Base the Enterprise Strategy on Agency science objectives and structure its research and flight programs to implement these objectives.—We update our strategy every 3 years. Science objectives are set in partnership with the scientific community, and mission formulation is based on these objectives within policy and budget constraints established by the Administrator, the President's Office of Management and Budget (OMB), and Congress. The Enterprise defines

Light from more distant galaxies passing through the galaxy cluster Abell 2218 is deflected by the cluster's enormous gravitational field, much as an optical lens bends light. This gravitational lensing causes the arc-like pattern spread across this picture.



missions via its strategic planning process and incorporates missions formulated by the scientific community through peer-reviewed competition.

Aggregate consecutive missions that address related science goals into "mission lines."—Mission lines are programs of related missions that share broad science goals. A stable funding profile for a series of related missions promotes continuity and flexibility in budget and technology planning. The first obligation is to meet flight-rate commitments for existing lines. Then the Enterprise structures flight programs according to science priorities to establish new lines.

Preserve safety as NASA's number-one priority; this includes mission success and environmental safety.—A project will not be approved for implementation until reserves appropriate to its level of technical risk and a clear technology path to successful implementation are demonstrated. Testing and reviews will be adequate to provide positive engineering assurance of sound implementation. Resource shortfalls will not be relieved by deviating from proven safety, engineering, and test practices. Implementation of comprehensive controls on potential biological contamination from missions to or from other worlds is mandatory.

NASA Implementing Strategy	Space Science Enterprise Implementation
IS-1.—Achieve management and institutional excellence comparable to NASA's technical excellence.	
Human capital	Participate in strategic human capital initiatives. Support young researchers through competitive grants. Collaborate on higher education science materials.
Competitive sourcing	Mission and instrument Announcements of Opportunity (AOs). R&A NASA Research Announcements (NRAs). Senior Reviews for extended operations.
Financial management	*Space Science Enterprise Management Handbook*, which outlines financial management procedures.
Budget and performance integration	Theme structure with science objectives aligned with budgets. *Space Science Enterprise Strategy*, and IFMP implementation.
IS-2.—Demonstrate NASA leadership in the use of information technologies.	Planetary Data System, NSSDC, National Virtual Observatory, Virtual Solar Observatory.
IS-3.—Enhance NASA's core engineering, management, and scientific capabilities and processes to ensure safety and mission success, increase performance, and reduce cost.	Implement NPG 7120.5b through the *Space Science Enterprise Management Handbook*, which incorporates requirements for systems engineering and reviews.
IS-4.—Ensure that all NASA work environments, on Earth and in space, are safe, healthy, environmentally sound, and secure.	Space Science Enterprise principles and policies as articulated in the *Space Science Enterprise Strategy*.
IS-5.—Manage risk and cost to ensure success and provide the greatest value to the American public.	Implement NPG 7120.5b through *Space Science Enterprise Management Handbook*, which incorporates requirements for risk management.

Table 4.—The Space Science Enterprise uses management and budget processes, as well as competitive selections, that are aligned with NASA's implementing strategies.



Ensure the active participation of the research community outside NASA, which is critical to success.—The outside community contributes vitally to strategic and programmatic planning, merit assurance via peer review, mission execution through participation in flight programs, and investigations supported by research grants programs. NASA science and technology programs conducted at the universities play an important role in maintaining the Nation's academic research infrastructure and in supporting the development of the next generation of science and engineering professionals.

Maintain essential technical capabilities at the NASA Centers.—NASA Center staff provide enabling support to the broader research community by serving as project scientists, maintaining "corporate memory," providing engineering support, and operating unique facilities. These staff scientists also compete with external researchers to fund their own research.

Ensure vigorous and timely interpretation of mission data, requiring that acquired data be made publicly available as soon as possible after scientific validation.—Other than in exceptional cases, data must be released within 6 months of acquisition and validation. In addition, Principal Investigators are required to publish their results in peer-reviewed literature. All data are archived by NASA in publicly accessible data archives for the long-term use of the science community and the public.

Apply new technology aggressively within the constraints of prudent stewardship of public investment.—The relationship between science and technology is bidirectional: scientific goals define directions for future technology investment and development, while emerging technology expands the frontier of possibilities for scientific investigation. To maintain the balance between risk and reward, new technologies are demonstrated, wherever possible, via validation in flight before incorporation into science missions.

Convey the results and excitement of our programs through formal education and public engagement.—To ensure the infusion of fresh results from our programs into education and public engagement efforts, each flight project must have an education and outreach component. The Enterprise has established a nationwide support infrastructure to coordinate the planning, development, and dissemination of educational materials and works closely with NASA's Education Enterprise.

Structure cooperation with international partners to maximize scientific return within the framework of NASA policy guidelines, Enterprise strategic priorities, and sound risk-management principles.—Most of the Enterprise's flight programs have international components. In establishing these cooperative relationships, as indeed in all other aspects of our program, funding is allocated to U.S. participants through competitive peer review. Funding for foreign participants in U.S. missions is provided by the respective foreign government or sponsoring entity, and these participants are likewise selected via the competitive peer-review process. NASA-supported investigators partnered with foreign entities must observe the same policies for prompt availability of data obtained from cooperative missions as data from purely domestic U.S. projects.

The Enterprise's resulting cooperative agreements with foreign partners are typically bilateral, even on programs that have multiple foreign partners. The respective roles and responsibilities of the parties for these arrangements are specified and negotiated by NASA's Office of External Relations in close coordination with the Department of State.

4.2 Partnerships

To accomplish its objectives, the Space Science Enterprise relies on contributions from a great diversity of partnerships. Closest to home, this includes relationships with other Enterprises governed by the "One NASA" principle. This represents a commitment to the shared Vision and Mission and integrated planning across Enterprises and NASA Centers.

From here, the circle of partnerships extends beyond NASA to other Government agencies with charters and capabilities different from NASA's but still essential to space science programs.



Additionally, researchers in the university community have played a central role in NASA's space science program since the founding of NASA, and a corps of external organizations has more recently become actively involved in the Enterprise's broad and vigorous education and public outreach program. In implementing competitive sourcing, NASA looks to industry to purchase goods and services of all kinds, so their availability from the private sector is essential for success. International partnerships also provide significant contributions to space science.

4.2.1 One NASA

The Space Science Enterprise benefits from collaboration with and reliance on the other Agency Enterprises (see box). Partnership with the NASA Centers (see box p. 72) is also vital to the implementation of the Space Science Enterprise's programs.

Space Flight Enterprise.—The Space Flight Enterprise provides launch services and launch vehicles, access to and manifesting for International Space Station attach points, Shuttle manifesting for experiments and servicing missions, and crew training for Hubble servicing. The Space Flight Enterprise also manages the Tracking and Data Relay Satellite System (TDRSS) and the NASA Integrated Services Network.

The Space Science Enterprise manages the Agency's Optical Communications Initiative, which will improve all communication systems, as well as our ability to explore Mars. This technology will be essential to enabling any future human exploration undertaken jointly with the Space Flight Enterprise. Both the Earth Science and the Biological and Physical Research Enterprises may have applications and provide requirements for this new technology.

Aerospace Technology Enterprise.—The Space Science Enterprise and the Aerospace Technology Enterprise collaborate to develop technologies necessary for achieving long-term science goals. In most cases, the Aerospace Technology Enterprise invests in technology's earliest stages, guided by concept studies that indicate the priority investments that need to be undertaken. As a technology matures, it becomes the responsibility of the Space Science Enterprise to advance it further and apply it to specific missions.

Earth Science Enterprise.—The Space Science and Earth Science Enterprises share a number of resources, including the Deep Space Network, which is managed by the Space Science Enterprise. The Earth Science Enterprise provides all Agency science missions with ground network support.

Both the Earth and Space Science Enterprises support NASA's participation in the U.S. Global Change Research Program. Earth science missions support our Living With a Star (LWS) Program by providing data on total solar irradiance. In return, LWS will provide space-weather data inputs for global models of Earth's atmosphere, including observations of irradiance; energetic particles; and ionospheric, mesospheric, and thermospheric conditions.

Biological and Physical Research Enterprise.—Along with the Earth Science Enterprise, the Biological and Physical Research Enterprise participates in formulating the Astrobiology Program and supports aspects of it. The Biological and Physical Research Enterprise also develops experiments that may help characterize the martian environment and its suitability for future human exploration.

Education Enterprise.—The Education Enterprise provides overall direction and coordination of the NASA education program. The Space Science Enterprise's education and public outreach program is a major component of this comprehensive Agencywide education program.

4.2.2 U.S. External Partnerships

The Space Science Enterprise has established and maintains active relationships with a number of other Federal agencies and programs, outside organizations, and international partners (see table 5). In some of these relationships, NASA is a customer; in some, a collaborator.

National Science Foundation.—As the two primary Federal agencies involved in the support of astronomy, solar physics, and other space sciences, NASA and the National Science Foundation (NSF) have a broad portfolio of past, current, and future collaborations. Currently, NASA and NSF jointly fund planet search programs, astrobiology science and technology investigations for

Principal Enterprise Partnerships

Space Flight Enterprise

- Functional and operational requirements for new technologies
- Spaceport launch facilities
- Integrate payloads
- Conduct experiments on the Space Shuttle and on the ISS
- Service space telescopes
- Launch robotic spacecraft on expendable launch vehicles
- Rocket propulsion testing
- Communications and data services
- Education and public outreach programs

Aerospace Technology Enterprise

- Advanced technology development and transfer
- Aerospace Technology Enterprise assets
- Systems analysis capabilities
- Technology problem-solving expertise
- Commercial technology transfer to Enterprises
- Orbital Space Plane
- Airborne sciences
- Education and public outreach programs

Space Science Enterprise

- Functional and operational requirements for new technologies
- Functional and operational requirements for launch vehicles
- Manage Deep Space Network
- Manage optical communications development
- Manage Astrobiology Program
- Provide space weather data
- Education and public outreach programs

Biological and Physical Research Enterprise

- Functional and operational requirements for new technologies
- Functional and operational requirements for launch vehicles and ISS
- Biomedical research
- Operational protocols
- Physical science design and safety standards
- Data measurement for Mars related to sustainable human presence and safety
- Education and public outreach programs

Earth Science Enterprise

- Functional and operational requirements for new technologies
- Functional and operational requirements for launch vehicles
- Study of Sun-Earth connection
- Adapt Earth system models to other planets
- Assist in improving aviation safety
- Study effects of global change on human health
- Ground network services
- Education and public outreach programs

Education Enterprise

- Guidance and integration of other Enterprises' education programs
- Linkages of NASA education programs to other Enterprises' future competencies and skill requirements
- Public outreach programs

Key

- Supports Space Flight Enterprise
- Supports Aerospace Technology Enterprise
- Supports Space Science Enterprise
- Supports Biological and Physical Research Enterprise
- Supports Earth Science Enterprise
- Supports Education Enterprise



exploring planets, long-term interdisciplinary studies of life in extreme environments, ground-based investigations in support of NASA missions, and technology development for the National Virtual Observatory.

The NSF is also responsible for supporting U.S. scientific activities in the Antarctic. In partnership with the Smithsonian Institution, NSF and NASA collaborate on the collection and curation of Antarctic meteorites. NASA and NSF have a joint program to use Antarctica as an analog for the space environment in developing long-range plans for solar system exploration. Finally, NSF provides operational and logistical support for Antarctic ballooning campaigns, including NASA's long-duration balloon missions. None of these activities would be possible without the stewardship role that NSF performs for Antarctic-based research programs.

The NSF is one of the major supporters of science education in the U.S. The NSF jointly sponsors many of the Space Science Enterprise E/PO programs.

Department of Energy.—The Department of Energy (DOE) is an essential partner to many NASA space science activities. The DOE has provided high-density nuclear power systems to NASA for more than 30 years. Radioisotope thermoelectric generators, built and provided to NASA by DOE, enabled a wide range of solar system exploration missions—from Apollo and Viking to Voyager, as well as Galileo and Cassini-Huygens. The DOE, in partnership with NASA, is developing the next generation of radioisotope power systems and space fission reactors. The DOE also supports work on power conversion interfaces.

The DOE develops instruments and sensors for NASA's space science missions, particularly through its national laboratories. Data from DOE missions also support the International Living With a Star Program and its predecessor, the International Solar Terrestrial Physics Program. The DOE also provides access to reactor environments for astrobiology research on extremophiles.

Department of Defense.—The Enterprise and the Department of Defense (DOD) rely on each other programmatically and scientifically. Shared launches, shared satellites, and joint use of facilities enable us to function more efficiently and effectively with limited resources. The agencies share interests in forecasting the sometimes disruptive effects of space weather on communications, navigation, and radar and in understanding

Field Centers

Much essential focused technology is developed at the NASA Centers, and they are important repositories of Enterprise corporate memory and lessons learned. The Jet Propulsion Laboratory and Goddard Space Flight Center are Space Science's primary supporting Centers. The former is the Enterprise's chief source of technical and management support for Mars and solar system exploration, the latter for astronomy, physics, and Sun-Earth Connection science. These two Centers are also the only two allocated the responsibility for program and project management of Space Science flight missions and, as such, interact with every program in Space Science. Ames Research Center manages the Enterprise's Astrobiology Program. Other Centers are engaged in technology development, science activities, and evaluation of new and ongoing missions.

The Centers provide vital support to the outside research community by providing expert knowledge and specialized test and development facilities. Center scientists and technologists also compete for funding for original investigations of their own. This has a dual advantage in that, in addition to advancing the state of our knowledge intrinsically, these "in-house" research efforts keep Center scientists' skills sharp and enhance their scientific currency.

The Centers are also important contributors to the implementation of the Space Science Enterprise's E/PO program.



Development of the Mars Exploration Rovers, launched in 2003, was managed by JPL for the Mars Exploration Program.

the constraints that variable conditions in space near Earth place on spacecraft design, reliability, and control. The DOD has an operational interest in space-weather models and data. Both DOD and NASA participate in the multiagency Community Coordinated Modeling Center, which supports the transition of space-weather data from research to operational use.

NASA's Living With a Star Program relies on DOD to help set research priorities to address challenges that come from increased reliance on space and space-weather-sensitive systems. Space science researchers depend on data from DOD satellites, such as the Solar Mass Ejection Imager that has been launched on a Space Test Program mission, and from ground-based observing networks, such as the Improved Solar Observing Optical Network. Laboratories sponsored by the Office of Naval Research and the Air Force Office of Scientific Research provide invaluable scientific, technical, and engineering expertise for many NASA programs.

Department of Commerce.—Many NASA investigations depend on Department of Commerce (DOC) facilities, such as the National Institute of Standards and Technology for standards for calibration of instruments.

The Sun-Earth Connection Division, particularly the Living With a Star (LWS) Program, partners with elements of the DOC such as the National Oceanic and Atmospheric Administration's (NOAA) Space Environment Center for collection, analysis, and dissemination of data; it provides data models and analysis tools for use by the DOC and relies on NOAA for solar remote sensing observations and local magnetospheric data. NASA currently has no plans to obtain routine but crucial in situ measurements of solar wind conditions at L1 after current missions end; however, NASA stands ready to collaborate with NOAA as recommended in the NRC Solar and Space Physics decadal survey.

Universities.—Universities play a crucial role in achieving space science objectives. University investigators, who perform basic research and analyze data from space science missions, are often funded through NASA Research and Analysis programs. University scientists are often Principal Investigators of space science flight missions. Scientific experts from universities populate space science advisory committees, working groups, and peer-review committees, providing essential advice and input. Finally, through competitive grants, NASA supports students and young investigators as they acquire experience through the Research and Analysis programs and develop into faculty members, instrument builders, and Principal Investigators of flight missions.

Education and Public Outreach Cooperating Partners.—The NASA Space Science education and public outreach (E/PO) program complements the large investments in education being made by school districts, individual states, and other Federal agencies, particularly by the National Science Foundation, the Department of Education, and the Smithsonian Institution. We rely on partnerships with these organizations, as well as with education-oriented professional societies, education departments at colleges and universities, and major curriculum developers to leverage our space science content, technical expertise, and E/PO resources into efforts that have major national impact.

Other partners assist us in extending the reach of our education and public outreach efforts. Such partners include educational and scientific professional societies such as the National Science Teachers Association, special interest organizations such as the National Organization of Black Chemists and Chemical Engineers, and community organizations such as the Girl Scouts. Public broadcasting documentaries and other such projects designed to reach large audiences are also leveraged in similar ways. We are currently collaborating with more than 500 external organizations, and an additional 1,500 organizations have hosted E/PO events.

Finally, the universities, laboratories, NASA Centers, and industry contractors who carry out our space science missions and research programs are also essential partners. Because our education and public outreach efforts are embedded within their missions and programs, these partners have the primary responsibility for developing and implementing education and public outreach

	External Partnerships							
	NSF	DOE	DOD	DOC	Universities	Industry	E/PO Partners	International
Joint science funding	●							●
Science instruments	●	●			●	●		●
Science expertise	●	●	●		●			●
Research facilities, labs		●	●	●	●			●
Technology	●	●	●		●	●		
Launch vehicles			●			●		
Antarctic facilities	●							
Radiation-hardened parts						●		
High-density power systems		●						
Nuclear materials		●						
Shared launch facilities			●					
Operational data (weather, etc.)			●	●				
Operational requirements			●	●				
Satellite tracking			●					
Peer review					●	●	●	
Advisory committees	●				●			
Education expertise	●				●		●	
Exhibition expertise	●						●	

Table 5.—The Space Science Enterprise relies on external organizations for support in critical areas.



projects that capitalize on unique mission science and technology.

Industry.—The aerospace industry plays a central role in the design, engineering, manufacture, construction, and testing of both large and small space missions; in the design, development, testing, and integration of advanced instruments; and in the development of advanced spacecraft, instrument, mission operations, and information system technologies. Many industry capabilities have been developed for commercial applications with NASA core technology support. The resulting extensive space industry infrastructure is available for use for space science purposes.

While the Space Science Enterprise partners with industry in many areas, one of the most critical of these dependencies is for launch vehicles. NASA's space science missions are typically flown on small spacecraft and have been dependent on vehicles developed for low-Earth orbit communications constellations. Because the market for small- to mid-sized launch vehicles cannot be sustained solely by the space science mission flight rate, the options for affordable access to space for small missions are dwindling. With the development of the Delta-IV and Atlas 5, the opportunities to fly multiple spacecraft on a single launch vehicle are increasing. However, flying multiple spacecraft presents significant logistical hurdles.

4.2.3 International Cooperation

The Space Science Enterprise's cooperative relationships with foreign space agencies form a special category of partnership. Provision for international partnerships was explicitly highlighted in the Space Act of 1958, NASA's founding charter, and the intervening four decades have seen a long series of fruitful joint scientific activities that have greatly enriched the U.S. space science programs.

International cooperation brings several important advantages to Enterprise programs. First, it enables U.S. science to benefit from relevant expertise from around the world; this expertise includes synergistic capabilities not only in fundamental science, but also in engineering and technical knowledge. Further, foreign participation in Enterprise flight projects and U.S. participation in foreign projects can often significantly enhance the capability of a flight mission by adding instruments or other enhancements otherwise unavailable.

4.3 Resources

Human Resources

The Enterprise recognizes the national need for increasing the numbers of students who enter careers in science, technology, engineering, and mathematics in general, and space science in particular. To this end, the Space Science Enterprise's E/PO program is aimed at inspiring precollege students from a diverse range of backgrounds to pursue careers in these areas. Through its research grants, the Enterprise supports graduate and postdoctoral students explicitly for the purpose of producing new generations of space scientists. As the Space Science Enterprise moves into new research fields, research funds are used to foster the creation of new research communities. For example, astrobiology required a focused effort to create a new research field and community. Another example: Project Prometheus will require the reinvigoration of nuclear engineering as a discipline and a significant investment in U.S. universities as integral elements of the program.

The Office of Human Resources (OHR), in collaboration with human resources organizations at each Center, provides NASA with the strategic and tactical means to attract, recruit, retain, and develop the human capital needed to perform the Agency's functions successfully. OHR has developed an integrated Workforce Planning and Analysis and Competency Management System to track the competencies that the Agency needs and possesses among its civil service staff. The Space Science Enterprise also works with OHR to define specialized competencies needed in the future, such as nuclear engineering for Project Prometheus or gravitational physics for the LISA mission.

The Enterprise participates in and fully supports strategic initiatives and traditional programs—such as internships, intergovernmental personnel assignments, recruitment initiatives, and education programs—designed to ensure that human capital requirements are met.



Capital Resources

Through allocation of resources for the full cost of each program, the Space Science Enterprise will ensure that those Centers executing its programs develop and sustain the facilities and infrastructure needed to carry out the goals and objectives of the Enterprise and the NASA Vision.

Following the concepts and strategies of the NASA Facilities Engineering Functional Leadership Plan and the Agency's Real Property Strategic Plan, the Space Science Enterprise will work with the Facilities Engineering Division to develop programs and plans for the continual improvement of its ability to support its mission and programs.

For the Center managed by the Space Science Enterprise, the Jet Propulsion Laboratory, we ensure that requirements are incorporated into the Center Implementation Plan and supported by the Center Master Plan. The Deep Space Network (see box) is an example of a critical facility, used by the entire Agency, for which the Enterprise has stewardship.

4.4 Evaluation

The Enterprise's programs range from fundamental research and technology development to flight mission development and operations. Determining the best allocation of resources is a major challenge and requires deeper and broader expertise than NASA can provide internally. As a result, the Enterprise depends on a wide spectrum of independent science and program status assessments to inform its decisionmaking. A majority of the participants in these reviews are drawn from the scientific community outside of NASA, although NASA personnel and technical consultants also play a role.

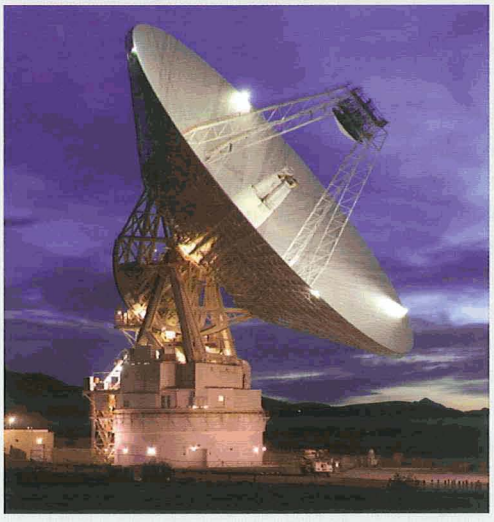
The evaluations range from merit evaluation of scientific proposals, through periodic assessments of science achievement and the status of the field, to strategic scientific and tactical programmatic recommendations.

Peer Review of Proposals

A bedrock principle for all of the Space Science Enterprise's programs is that of external peer review

Deep Space Network

The NASA Deep Space Network (DSN) is a global network of antennas that supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe, as well as selected Earth-orbiting missions. The DSN currently consists of three deep-space communications facilities placed at longitudes approximately 120 degrees apart around the world: at Goldstone, in California's Mojave Desert; near Madrid, Spain; and near Canberra, Australia. This strategic placement permits continuous observation of spacecraft as Earth rotates and helps to make the DSN the largest and most sensitive scientific telecommunications system in the world. The antennas and data delivery systems make it possible to acquire telemetry data from spacecraft, transmit commands to spacecraft, track spacecraft position and velocity, perform very-long-baseline interferometry observations, measure variations in radio waves for radio science experiments, gather science data, and monitor and control the performance of the network. The instruments flown on spacecraft are now capable of taking more data than the DSN can capture. Increased aperture capacity and wider bandwidth are required to support NASA science in the coming years.



The 70-meter-(230-foot)-diameter antennas are the largest, and therefore the most sensitive, DSN antennas. They are capable of tracking spacecraft more than 16 billion kilometers (10 billion miles) from Earth.

applied to proposals submitted in response to open and broadly advertised research solicitations. Such reviews are carried out by panels of highly qualified scientists, engineers, and managers, all of whom have been screened for their competence in their respective fields, as well as for freedom from conflicts of interest for the proposals they are asked to examine. Typically, every proposal is read in detail by several panel members and then discussed in an open forum to arrive at a consensus opinion.

Although the details of review criteria vary depending on the nature of the solicitation, they can almost always be classified into one of three main categories: scientific and/or technical merit, including the competence of the proposer and the proposed plan of research; relevance to NASA's objectives as given in the solicitation; and realism and reasonableness of the proposed cost and management plan. Additional, secondary criteria may also be stated: for example, furthering NASA's objectives in education and public outreach and increasing the involvement of small, minority, or woman-owned businesses. A NASA selection official makes the final choice from among the best proposals as allowed by the available budget and influenced by consideration of program balance necessary to achieve overall program objectives.

Senior Reviews for Extended Operations

With rare exceptions, space science spacecraft are able to continue operating in a productive manner well after their "prime" missions have been achieved and, therefore, to return valid science data either for the refinement of their original objectives or to accomplish an entirely new set of objectives. For example, the International Sun-Earth Explorer satellite was sent to study a comet after the completion of its primary mission of studying the solar wind input to Earth's magnetosphere. Although such extended operations are frequently low in cost—typically only a few percent of the original cost of the mission itself—funds available for Mission Operations and Data Analysis (MO&DA) are limited.

Therefore, in order to prioritize those missions that seek continued operation—perhaps as many as a half dozen or more yearly—the Senior Review process is carried out every two years. A panel of distinguished, senior scientists not involved in the candidate missions is assembled to review, in detail, each mission that seeks support for continued operations and to recommend, in priority order, further MO&DA funding for the next three years. Senior Reviews have been carried out for the last decade and have proven to be a fair process that is accepted by the science communities for determining which missions should be continued and which should be terminated. In a few such cases, missions slated for termination have been turned over to non-NASA institutions, typically universities, where they are used for student training.

Committees Chartered Under the Federal Advisory Committee Act (FACA)

NASA's senior FACA-chartered advisory body, the NASA Advisory Council, advises the Administrator. The Council has a number of subordinate committees that serve an analogous purpose for the Enterprises; the Space Science Enterprise's advisory body, which reports to the Associate Administrator for Space Science, is the Space Science Advisory Committee (SScAC). The SScAC provides scientific, technical, and programmatic advice to the Enterprise on behalf of the broader outside research community. The Committee also transmits information about policies and decisions of the Enterprise to its constituent research community members. The SScAC typically meets three times per year, as do each of four science theme subcommittees.

In addition, the SScAC has a major role in assessing the Enterprise's scientific performance as part of the Agency's annual Government Performance and Results Act (GPRA) performance report. Once a year, the Enterprise prepares a self-assessment of the status of the space science program in terms of the strategic objectives and research focus areas. The SScAC receives its subcommittees' response to this self-assessment and delivers an independent assessment for incorporation into the Agency's annual performance report.

The Planetary Protection Advisory Committee (PPAC) advises NASA on all programs, policies, and plans pertinent to the Agency's responsibilities for biological planetary protection. The committee provides a forum for advice on interagency coordination



and intergovernmental planning and recommends appropriate planetary protection categorization.

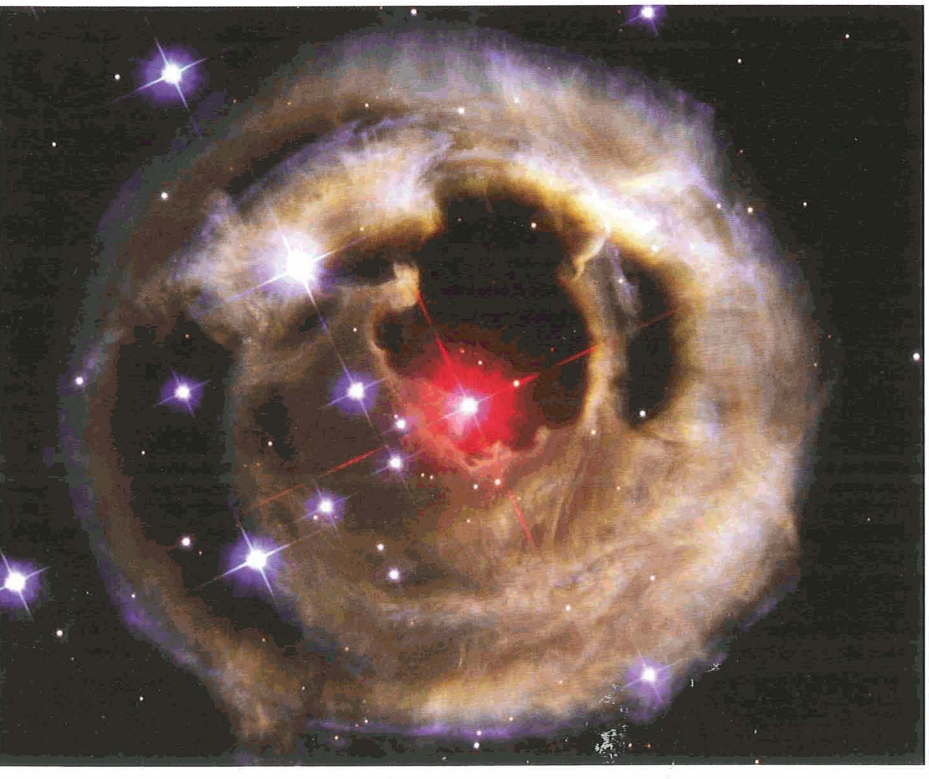
The chairs of the SScAC and PPAC sit, ex officio, on the NASA Advisory Council, providing a conduit for the Committees' views to be offered as independent advice at the Administrator's level.

Finally, the National Astronomy and Astrophysics Advisory Committee (NAAAC) is chartered by Congress to provide advice to NASA on the coordination of its astronomy program with that of the National Science Foundation.

National Research Council (NRC)

In addition to the input received from the SScAC, the Space Science Enterprise also solicits and receives independent advice from boards and committees of the NRC. Unlike the SScAC, the NRC appoints its own members and sets its own meeting agendas; the Agency's only control over studies performed by the NRC is to set their terms of reference and negotiate a schedule and cost for the studies. Particularly valuable reports developed by the NRC are the "decadal surveys" carried out in the various fields of space science. These surveys engage large parts of their constituent scientific communities to assess the state of knowledge in their fields and prepare recommendations for the next 10 years. These surveys provide clear guidance for Agency decision making and also serve to build consensus within the highly diverse fields.

A burst of light from the bizarre star V838 Monocerotis is spreading into space and reflecting off surrounding shells of dust to reveal a spectacular, multicolored bull's-eye. (Credit: NASA/ESA/ H. E. Bond, STScI)



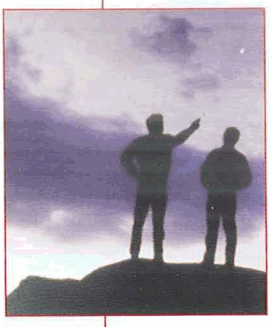
The Space Studies Board and its science discipline committees are the Enterprise's principal independent source of strategic science advice. The Board and each of its standing discipline committees typically meet three times per year to work on assigned Enterprise advisory tasks.

Management Reviews

The *NASA Strategic Management Handbook* establishes that the Agency's programs are to be overseen by a hierarchy of Program Management Councils (PMCs). The Agency PMC at NASA Headquarters is responsible for evaluating proposals for new programs, providing approval recommendations to the Administrator, and assessing programs of high visibility or cost to ensure that NASA is meeting its commitments. Other PMCs are established at the Enterprise level (EPMC), at the assigned project Center, at supporting NASA Centers, and at lower levels within each Center as required. Similar to the Agency PMC, these councils evaluate project cost, schedule, and technical content to ensure successful performance.

The "governing" Program Management Council for a specific project is the highest level PMC that regularly reviews that project. The PMC convenes meetings whenever major programmatic decisions are needed, such as confirmation of a project to transition from formulation to implementation or termination reviews. In addition, monthly flight program reviews are held to assess program and project progress and performance against the program-level requirements, cost plans, and development schedules.

Various independent performance assessments are conducted by external teams throughout a project's life cycle and reported to the governing PMC.



5 Beyond the Horizon





5 Beyond the Horizon

In the continuing quest for discovery, we seek clues from the past that can help us in the future and lessons from distant bodies that can teach us about our home planet. The future holds the promise of understanding the universe as a system of interacting matter and energy, radiation and particles, minerals and water.

Imagine understanding completely how the Sun varies and how it interacts with Earth. Imagine deploying the most powerful exploration craft ever to uncover the mysteries of the outer planets. And imagine looking from the Sun to the comets—and beyond—for those markers that signify the presence of life. Beyond our own small community of planets and our familiar star, imagine finding the remnant ripples in gravity from the Big Bang, uncovering the secrets of the dark energy that pervades the universe, and taking pictures of a black hole. Imagine finally reading the whole story of how galaxies, stars, and planets came to be.

The future of space science really consists of understanding the past. With ever greater capabilities, we seek to connect with the elements, planets, and universe that brought us into being. How and when did the amazing events in the chain leading to our existence take place? Could they have happened elsewhere? Will they happen again? In seeking answers to these questions, humankind can reflect on its place and its destiny in the universe.





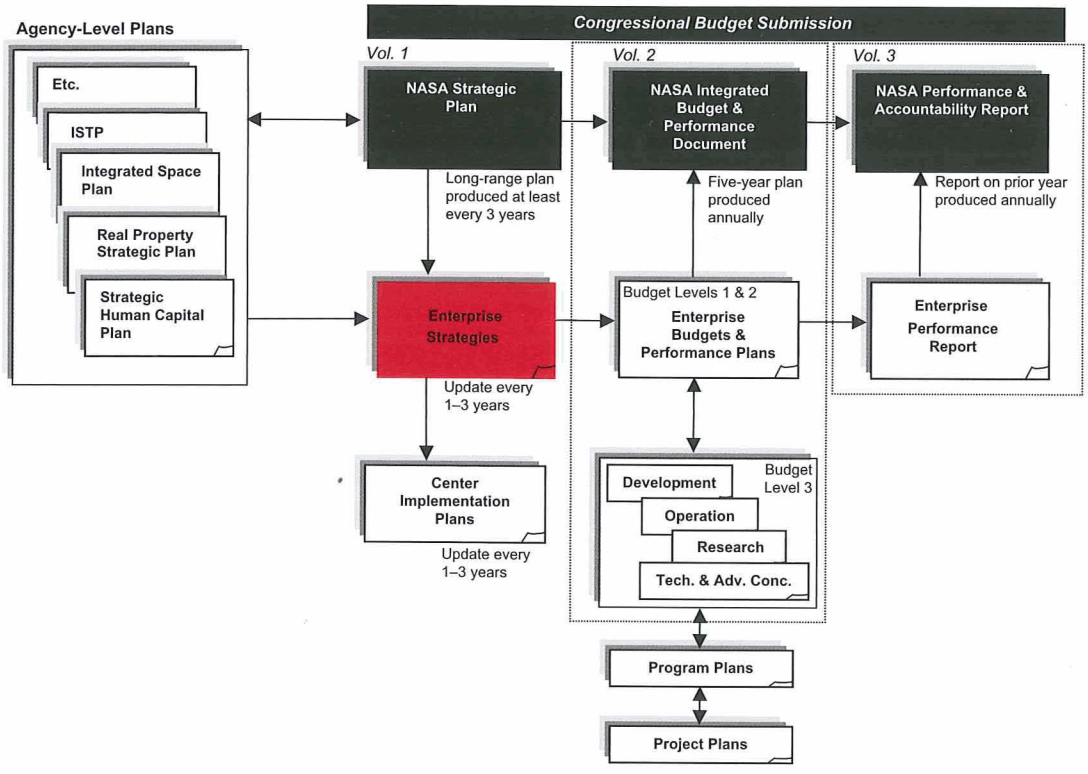
Appendices

Appendix 1

Relationship to Agency Planning

The Agency's planning process includes the development of a Strategic Plan, the annual budget, and a performance plan. The Strategic Plan is a 5-year plan, updated every 3 years, that defines the Agency's goals and objectives. The NASA Enterprises base their planning on the strategic emphasis, implementing strategies, goals, and objectives outlined in the Strategic Plan. In addition, Enterprise budget planning and performance reporting are directly traceable to the Agency-level documents.

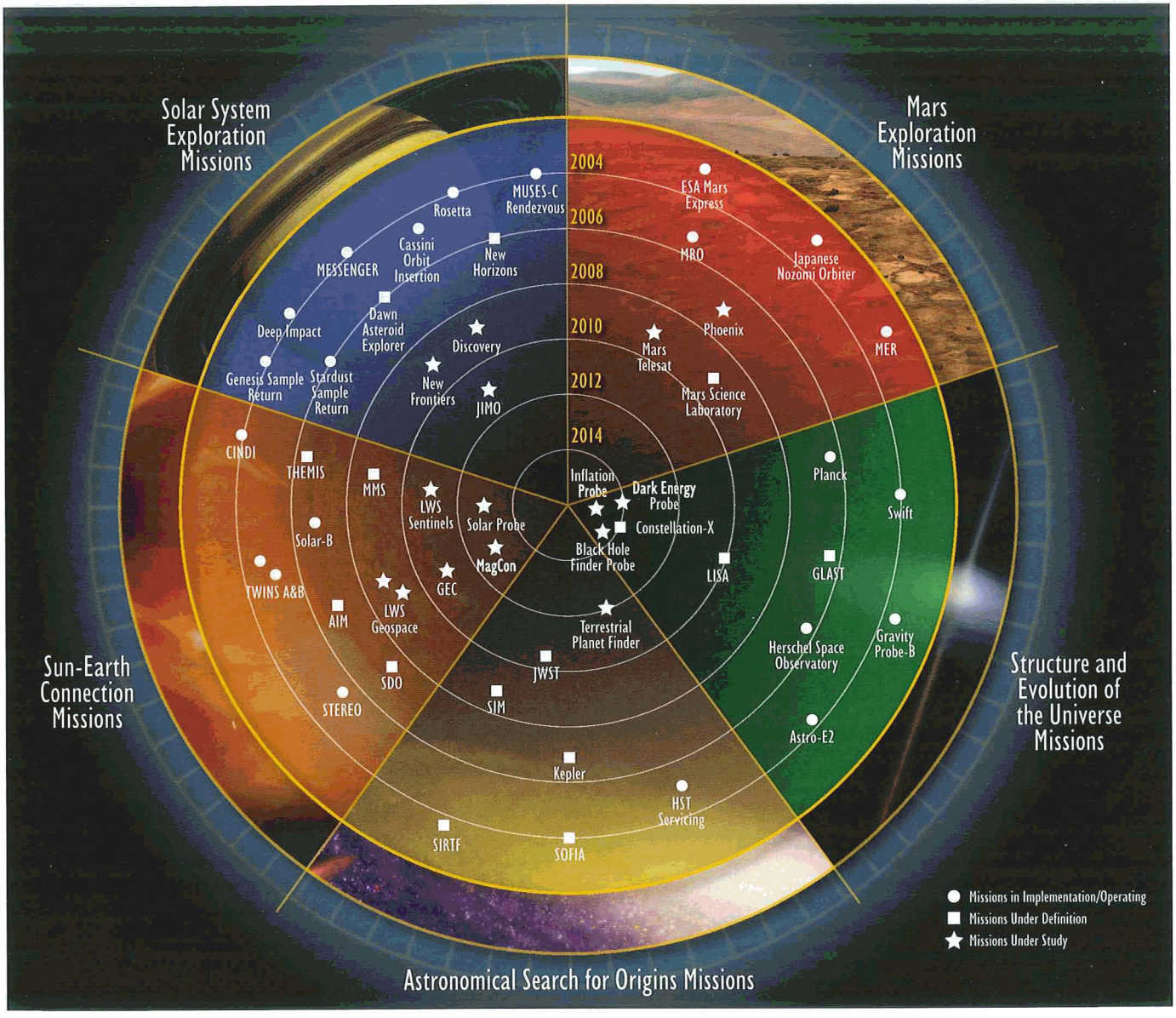
The Enterprise Strategy communicates the results of the Agency and Enterprise planning processes to the NASA stakeholders and other audiences listed below.



Stakeholder/Audience	Enterprise Strategy Function
Executive and Legislative Branches	Communicate purpose and value of investments
NASA Employees	Achieve alignment within the Enterprise and Agency
Other NASA Enterprises	Strengthen inter-Enterprise collaboration
Science Community	Document consensus on objectives and priorities
Contractor Community	Communicate programmatic objectives and priorities
Interagency, International, and Commercial Partners	Establish basis for future collaborations
The Public	Inform and inspire

Appendix 2

Summary of Space Science Missions



In this decade, the Space Science Enterprise will develop and fly a rich suite of missions in every science theme. We are also investing in the research, technology, and mission concepts for the decades to come.

Appendix 3 Science Goals, Objectives, and Research Focus Areas

Strategic Goal 1.—Understand the Earth system and apply Earth system science to improve the prediction of climate, weather, and natural hazards.

Space Science Theme	Strategic Objective	Research Focus Areas
SEC	1.3 Understand the origins and societal impacts of variability in the Sun-Earth connection.	• Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere and affect Earth. • Specify and enable prediction of changes to Earth's radiation environment, ionosphere, and upper atmosphere. • Understand the role of solar variability in driving space climate and global change in Earth's atmosphere.
SSE	1.4 Catalog and understand potential impact hazards to Earth from space.	• Determine the inventory and dynamics of bodies that may pose an impact hazard to Earth. • Determine the physical characteristics of comets and asteroids relevant to any threat they may pose to Earth.

Strategic Goal 5.—Explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.

Space Science Theme	Strategic Objective	Research Focus Areas
SSE	5.1 Learn how the solar system originated and evolved to its current diverse state.	• Understand the initial stages of planet and satellite formation • Study the processes that determine the characteristics of bodies in our solar system and how these processes operate and interact. • Understand why the terrestrial planets are so different from one another. • Learn what our solar system can tell us about extrasolar planetary systems.
	5.2 Understand how life begins and evolves and determine the characteristics of the solar system that led to the origin of life.	• Determine the nature, history, and distribution of volatile and organic compounds in the solar system. • Identify the habitable zones in the solar system. • Identify the sources of simple chemicals that contribute to prebiotic evolution and the emergence of life. • Study Earth's geologic and biologic records to determine the historical relationship between Earth and its biosphere.
Mars	5.3 Understand the current state and evolution of the atmosphere, surface, and interior of Mars.	• Characterize the present climate of Mars and determine how it has evolved over time. • Investigate the history and behavior of water and other volatiles on Mars. • Study the chemistry, mineralogy, and chronology of martian materials. • Determine the characteristics and dynamics of the interior of Mars.
	5.4 Determine if life exists or has ever existed on Mars.	• Investigate the character and extent of prebiotic chemistry on Mars. • Search for chemical and biological signatures of past and present life on Mars.
	5.5 Develop an understanding of Mars in support of possible future human exploration.	• Identify and study the hazards that the martian environment will present to human explorers. • Inventory and characterize martian resources of potential benefit to human exploration of Mars.



Strategic Goal 5.—Explore the solar system and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere.

Space Science Theme	Strategic Objective	Research Focus Areas
SEC	5.6 Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.	• Understand the structure and dynamics of the Sun and solar wind and the origins of magnetic variability. • Determine the evolution of the heliosphere and its interaction with the galaxy. • *Understand the response of magnetospheres and atmospheres to* external and internal drivers.
	5.7 Understand the fundamental physical processes of space plasma systems.	• Discover how magnetic fields are created and evolve and how charged particles are accelerated. • *Understand coupling across multiple scale lengths and its* generality in plasma systems.
ASO	5.8 Learn how galaxies, stars, and planetary systems form and evolve.	• Learn how the cosmic web of matter organized into the first stars and galaxies and how these evolved into the stars and galaxies we see today. • Understand how different galactic ecosystems of stars and gas formed and which ones might support the existence of planets and life. • Learn how gas and dust become stars and planets. • Observe planetary systems around other stars and compare their architectures and evolution with our own.
	5.9 Understand the diversity of worlds beyond our solar system and search for those that might harbor life.	• Characterize the giant planets orbiting other stars. • Find out how common Earth-like planets are and see if any might be habitable. • Trace the chemical pathways by which simple molecules and dust evolve into the organic molecules important for life. • Develop the tools and techniques to search for life on planets beyond our solar system.
SEU	5.10 Discover what powered the Big Bang and the nature of the mysterious dark energy that is pulling the universe apart.	• Search for gravitational waves from the earliest moments of the Big Bang. • Determine the size, shape, and matter-energy content of the universe. • Measure the cosmic evolution of the dark energy, which controls the destiny of the universe.
	5.11 Learn what happens to space, time, and matter at the edge of a black hole.	• Determine how black holes are formed, where they are, and how they evolve. • Test Einstein's theory of gravity and map space-time near event horizons of black holes. • *Observe stars and other material plunging into black holes.*
	5.12 Understand the development of structure and the cycles of matter and energy in the evolving universe.	• Determine how, where, and when the chemical elements were made, and trace the flows of energy and magnetic fields that exchange them between stars, dust, and gas. • *Explore the behavior of matter in extreme astrophysical* environments, including disks, cosmic jets, and the sources of gamma-ray bursts and cosmic rays. • Discover how the interplay of baryons, dark matter, and gravity shapes galaxies and systems of galaxies.



Appendix 4
Acronym List

AO	Announcement of Opportunity
ASO	Astronomical Search for Origins
AT	Aerospace Technology Enterprise
CME	coronal mass ejection
DA	Data Analysis
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DSN	Deep Space Network
E/PO	education and public outreach
EDL	entry-descent-landing
EPMC	Enterprise Program Management Council
ESA	European Space Agency
GEC	Geospace Electrodynamic Connections
GEMS	Great Explorations in Math and Science
GI	Guest Investigator
GLAST	Gamma-ray Large Area Space Telescope
GNC	guidance, navigation, and control
GPRA	Government Performance and Results Act
HST	Hubble Space Telescope
ILWS	International Living With a Star
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IS	Implementing Strategy
ITAR	International Traffic in Arms Regulations
JIMO	Jupiter Icy Moons Orbiter
JWST	James Webb Space Telescope
LISA	Laser Interferometer Space Antenna
LWS	Living With a Star
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MGS	Mars Global Surveyor
MIDEX	Medium-class Explorer
MO&DA	Mission Operations and Data Analysis
MSL	Mars Science Laboratory
MUSES-C	Mu Space Engineering Spacecraft-C
NAAAC	National Astronomy and Astrophysics Advisory Committee
NASA	National Aeronautics and Space Administration
NEO	Near-Earth Object
NICMOS	Near Infrared Camera and Multi-Object Spectrograph



NOAA	National Oceanic and Atmospheric Administration
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
NSSDC	National Space Science Data Center
NVO	National Virtual Observatory
OHR	Office of Human Resources
OMB	Office of Management and Budget
PI	Principal Investigator
PMC	Program Management Council
PPAC	Planetary Protection Advisory Committee
R&A	Research and Analysis
RFA	Research Focus Area
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
RTG	radioisotope thermoelectric generator
SDO	Solar Dynamics Observatory
SEC	Sun-Earth Connection
SET	Space Environment Testbeds (program)
SEU	Structure and Evolution of the Universe
SIM	Space Interferometry Mission
SIRTF	Space InfraRed Telescope Facility
SMEX	Small Explorer
SOFIA	Stratospheric Observatory For Infrared Astronomy
SOHO	SOlar and Heliospheric Observatory
SScAC	Space Science Advisory Committee
SSE	Solar System Exploration
STEREO	Solar TErrestrial RElations Observatory
STP	Solar Terrestrial Probes
TDRSS	Tracking and Data Relay Satellite System
THEMIS	THermal EMission Imaging System
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TPF	Terrestrial Planet Finder
TRACE	Transition Region And Coronal Explorer
U.S.	United States
WMAP	Wilkinson Microwave Anisotropy Probe



Appendix 5

Enterprise Concurrence and Acknowledgments

Space Science Enterprise Concurrence

Edward J. Weiler, Associate Administrator
Christopher J. Scolese, Deputy Associate Administrator
J. David Bohlin, Deputy Associate Administrator for Science
Kenneth W. Ledbetter, Deputy Associate Administrator for Programs
Marc S. Allen, Director for Advanced Programs and International Coordination
Orlando Figueroa, Director for the Mars Exploration Program
Richard R. Fisher, Director for the Sun-Earth Connection Division
Colleen N. Hartman, Director for the Solar System Exploration Division
Anne L. Kinney, Director for the Astronomy and Physics Division
Alan Newhouse, Director for Project Prometheus, the Nuclear Systems Program
Jeffrey D. Rosendhal, Director for Education and Public Outreach
Harley A. Thronson, Director for Technology

Enterprise Strategic Planning Working Group

Lisa D. May (Lead), Special Assistant for Strategic and International Planning
Jay T. Bergstralh, Solar System Exploration
Phillipe Crane, Astronomical Search for Origins
Victoria P. Friedensen, Project Prometheus
James B. Garvin, Mars Exploration Program
Hashima Hasan, Research and Analysis
Paul Hertz, Astronomy and Physics/Explorer Program
Todd Hoeksema, Sun-Earth Connection
Michael A. Meyer, Astrobiology
Carl B. Pilcher, Astrobiology
Philip J. Sakimoto, Space Science Education and Public Outreach
Michael H. Salamon, Structure and Evolution of the Universe
George Tahu, Mars Exploration Program
Harley A. Thronson, Space Science Technology
Giulio Varsi, Space Science Technology
Melissa Kennedy, Lead Graphic Designer
Lisa Jirousek, Lead Editor
Jeffrey McLean, Printing Specialist

One NASA Enterprise Planning Team

James J. Gorman, Education Enterprise
Lisa A. Guerra, Biological and Physical Research Enterprise
Jenny S. Kishiyama, Aerospace Technology Enterprise
Lisa D. May, Space Science Enterprise
Philip L. Sunshine, Space Flight Enterprise
Gregory J. Williams, Earth Science Enterprise

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Mission Bay Strategic Planning Workshop Participants, November 2002

David Akin, University of Maryland
Joseph Alexander, Spaces Studies Board, NRC
Marc Allen, NASA Office of Space Science
Dennis Andrucyk, NASA Office of Aerospace Technology
Jacqueline Barber, University of California
Charles Beichman, NASA Jet Propulsion Laboratory
Michael Belton, Belton Space Exploration Initiatives, LLC
Jay Bergstralh, NASA Office of Space Science
Omer Blaes, University of California, Santa Barbara
James Breckinridge, NASA Jet Propulsion Laboratory
Michael Calabrese, NASA Goddard Space Flight Center
Richard Capps, NASA Jet Propulsion Laboratory
Giacomo Cavallo, European Space Agency (ESA)
Andrew Cheng, Johns Hopkins Applied Physics Laboratory
Andrew Christensen, The Aerospace Corporation
Philippe Crane, NASA Office of Space Science
James Cutts, NASA Jet Propulsion Laboratory
Paul DeMinco, NASA Goddard Space Flight Center
David Des Marais, NASA Ames Research Center
Michael Devirian, NASA Jet Propulsion Laboratory
Michael Drake, University of Arizona
Alan Dressler, Carnegie Observatories
Charles Elachi, NASA Jet Propulsion Laboratory
Doug Erwin, Smithsonian Institution
Jack Farmer, Arizona State University
Henry Ferguson, Space Technology Science Institute
Orlando Figueroa, NASA Office of Space Science
Richard Fisher, NASA Office of Space Science
Kathryn Flanagan, Massachusetts Institute of Technology
Jeffrey Forbes, University of Colorado
Wendy Freedman, Carnegie Observatories
Stephen Fuselier, Lockheed Martin Advanced Technology Center
James Garvin, NASA Office of Space Science
Judy Gobert, Salish Kootenai College
Tom Greene, NASA Ames Research Center
Ian Griffin, Space Telescope Science Institute
Colleen Hartman, NASA Office of Space Science
Hashima Hasan, NASA Office of Space Science
David Hathaway, NASA Marshall Space Flight Center
Rod Heelis, University of Texas, Dallas
Paul Hertz, NASA Office of Space Science
Todd Hoeksema, NASA Office of Space Science
Garth Illingworth, University of California, Santa Cruz
Hajime Inoue, Institute of Space and Astronautical Science (Japan)
Martin Israel, Washington University, St. Louis
Bruce Jakosky, University of Colorado
William Jeffrey, Office of Science and Technology Policy

Roberta Johnson, University Corporation for Atmospheric Research
Gerald Joyce, The Scripps Research Institute
Judy Karpen, Naval Research Laboratory
David Kendall, Canadian Space Agency
Anne Kinney, NASA Office of Space Science
Werner Klinkmann, German Aerospace Center (DLR)
Sheri Klug, Arizona State University
Paul Knappenberger, Adler Planetarium
Edward Kolb, Fermi National Accelerator Laboratory
Martin Kress, Battelle Memorial Institute
Louis Lanzerotti, Lucent Technologies, Bell Labs
Dave Lavery, NASA Office of Space Science
John Leibacher, National Solar Observatory
Dan Lester, University of Texas
Eugene Levy, Rice University
Fuk Li, NASA Jet Propulsion Laboratory
Shannon Lucid, NASA Chief Scientist
Jonathan Lunine, University of Arizona
Gary Martin, NASA Space Architect
Lisa May, NASA Office of Space Science
Michael Meyer, NASA Office of Space Science
Michael Moore, NASA Office of Space Science
Jeremy Mould, National Optical Astronomy Observatory
Toshifumi Mukai, Institute of Space and Astronautical Science (Japan)
Neil Murphy, NASA Jet Propulsion Laboratory
John Mustard, Brown University
Firouz Naderi, NASA Jet Propulsion Laboratory
Marian Norris, NASA Office of Space Science
Jonathan Ormes, NASA Goddard Space Flight Center
Sterl Phinney, California Institute of Technology
Carl Pilcher, NASA Office of Space Science
Martin Ratcliffe, International Planetarium Society
P. Diane Rausch, NASA Office of External Affairs
Geoffrey Reeves, Los Alamos National Laboratory
Douglas Richstone, University of Michigan
Guenter Riegler, NASA Office of Space Science
Jeffrey Rosendhal, NASA Office of Space Science
John Rummel, NASA Office of Space Science
Bruce Runnegar, University of California
Vincent Sabathier, Centre National d'Études Spatiales (France)
Philip P. Sakimoto, NASA Office of Space Science
Donald Savage, NASA Office of Space Science
Chris Schwartz, NASA Goddard Space Flight Center
Jim Spann, NASA Marshall Space Flight Center
Robin Staffin, U.S. Department of Energy
James Stith, American Institute of Physics
Steven Suess, National Space Science & Technology Center
Michelle Thomsen, Los Alamos National Laboratory
Harley Thronson, NASA Office of Space Science
Ann Marie Trotta, NASA Office of Space Science
Kathleen Turner, Department of Energy
Michael Turner, University of Chicago
Timothy Van Sant, NASA Goddard Space Flight Center
Giulio Varsi, NASA Jet Propulsion Laboratory
Edward Weiler, NASA Office of Space Science
Nicholas White, NASA Goddard Space Flight Center
Belinda Wilkes, Smithsonian Astrophysical Observatory

Space Science Advisory Committee

Andrew B. Christensen (Chair), The Aerospace Corporation
David L. Akin, University of Maryland
Charles A. Beichman, NASA Jet Propulsion Laboratory
Alok Das, Air Force Research Laboratory
David W. Deamer, University of California, Santa Cruz
Michael J. Drake, University of Arizona
Alan M. Dressler, Carnegie Observatories
Jack D. Farmer, Arizona State University
Heidi B. Hammel, Space Science Institute
David Hathaway, NASA Marshall Space Flight Center
Roderick A. Heelis, University of Texas, Dallas
Garth D. Illingworth, University of California, Santa Cruz
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Paul H. Knappenberger, Adler Planetarium and Astronomy Museum
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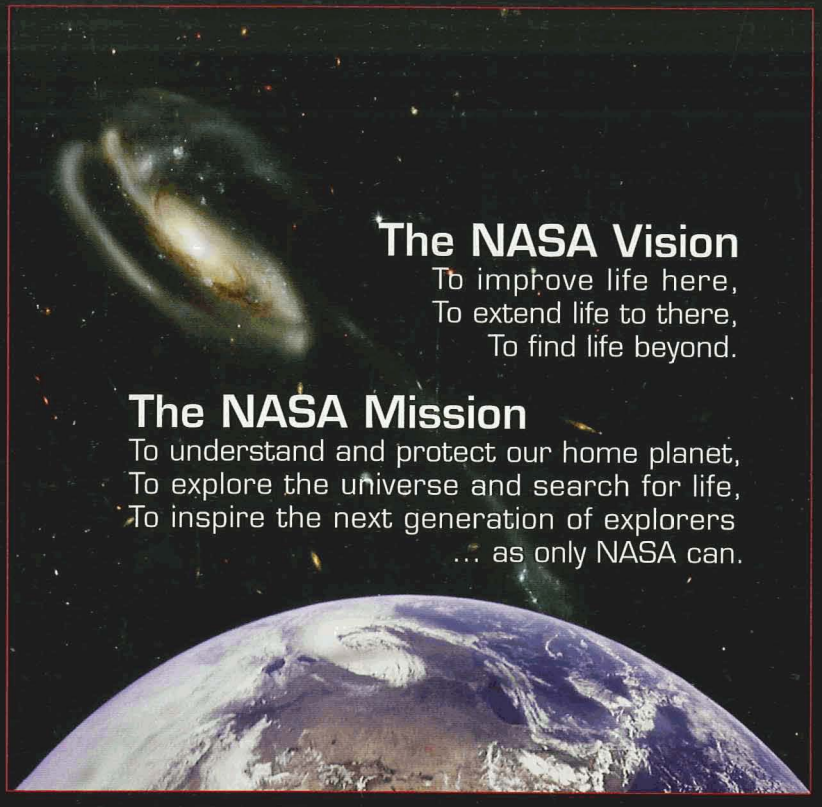
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