Volume 1: Goals, Objectives, Strategy

Space Physics Strategy-Implementation Study

The NASA
Space Physics Program
for 1995 to 2010

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Space Physics Strategy–Implementation Study

Volume 1: Goals, Objectives, Strategy

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A Report
to the
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of the
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~~511168~~

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Table of Contents

Appendix A

1.1 MIDS Panel Report

1.1.1 Disciplinary Themes

Space physics may be characterized by the following overarching theme:

> Space physics is the study of the heliosphere as one system; that is, of the Sun and solar wind, and their interactions with the upper atmospheres, ionospheres, and magnetospheres of the planets and comets, with energetic particles, and with the interstellar medium.

Space physicists have composed similar disciplinary definition statements since 1958, when the subject came into being with the discovery of the Earth's radiation belts by Explorer 1. These statements have changed slowly, reflecting the enduring and fundamental nature of our scientific concerns. What is new about the most modern version of the disciplinary theme above is the phrase "as one system." In the next twenty years, we will be able to study the entire heliosphere as a unified entity for the first time.

Research in space physics requires information and techniques from many scientific disciplines, but one discipline stands out:

> Space physics is, to a great extent, the study of naturally occurring plasmas. These are of many different types, including the partly-ionized, relatively cool plasmas of planetary ionospheres, the million-degree plasmas found in the solar corona, the solar wind, and planetary magnetospheres, and the highly-relativistic galactic cosmic ray plasma. They not only have very different physical scales, but each has within it phenomena occurring on a wide range of scales. The challenge for space plasma research is to relate large- and small-scale phenomena.

Understanding space plasmas requires concepts drawn from the frontier of modern theoretical research on the nonlinear interactions between large- and small-scale phenomena.

Finally,

> On the directly practical side, the knowledge acquired by space physics research is critically important to understanding the effects of energetic particles and solar variability upon the Earth's environment and to the human exploration of space.

The human exploration of space and the study of the terrestrial environment are enduring parts of NASA's mandate that will receive renewed emphasis in the coming years.

1.1.2 Themes Characterizing the Next Twenty Years

The "overarching themes" above are intended to describe who we are and what we do. Now we turn to themes that can convey a flavor of the space physics research we foresee in the next twenty years. In short, we say what's new about the space physics research NASA will carry out.

We will continue our exploration of the Earth's and Sun's space environment, we will achieve a new kind of scientific understanding, and we will create a new approach to the planning and management of space physics research.

1.1.3 Exploration

> We will go to the frontiers of the Solar System: the Sun and the interstellar medium.

Space physics will come to share the leadership in the exploration of the solar system with the planetary sciences. The next frontiers of solar system exploration are the very limits of the heliosphere—the Sun and the interstellar medium. These are space physics missions.

A spacecraft that is protected against the hostile environment of the solar corona and is also equipped with propulsion can be sent on a quick trip to the far reaches of the solar system, even beyond the frontier separating the heliosphere from the galaxy proper. Thus, by developing the technology necessary for a solar probe, we may also be developing technology for an interstellar probe, opening up the exciting possibility that the two missions can be carried out in a coordinated and cost-effective fashion. We can truly call these two: "frontier probes." It is also possible that NASA may be able to develop such a "Sungrazer" class of spacecraft for a variety of other objectives in space physics and planetary research.

Once we have studied the Sun and interstellar medium *in situ*, we will be in a position to start the integrated study of the entire heliosphere as one interacting system.

1.1.4 Understanding

To understand the interacting systems comprising the heliosphere, we must relate global behavior to small-scale physical processes. This requires us to integrate the panoramic three-dimensional view obtained by global images with multi-point *in-situ* measurements in every area of space physics.

Our exploration of the solar system started near the Earth and progressed outward. We have already learned much about the Earth's upper atmosphere, ionosphere, and magnetosphere, and about the solar wind in the Earth's neighborhood. We have come to understand that these are parts of a grand interacting system that derives its energy from the Sun—the heliosphere.

We have begun to appreciate that the heliosphere is basically cellular in structure, comprised of distinct but interacting regions—the mesosphere, the thermosphere, the ionosphere, the magnetosphere, the solar wind, and so on. The cells interact across the relatively thin layers that separate them. Today the challenge is to perceive the extent and behavior of each cell, and to understand the small-scale processes regulating their interactions, so as to progress toward a comprehensive understanding of the heliosphere as one interacting system.

Even within cells the important processes can occur on a daunting variety of space and time scales. The need to understand nonlinearly interacting global and microscopic processes on a hierarchy of scales is one of the central problems of late twentieth-century science. Space physics measurements have already partly revealed the hierarchy of scales, and the space physics community has had to evolve a research strategy that copes with two inherent limitations of experimental technique. The first of these limitations is that *in-situ* measurements characterize microprocesses, but only at one point in space at a time. The second limitation is that the global view provided by remote sensing often lacks the resolution needed to detect the important microprocesses. The research programs outlined in this document reflect a creative and thoroughly modern approach to these fundamental issues.

To carry out this new approach to our research, we must manage and plan it in a new way.

1.1.5 Approach

The evolution of space physics will force a more integrated approach to the planning and management of its research.

No one of us can predict with assurance what the words "integrated approach" actually mean, but it is already clear that a new mode of thinking, working, and organization is needed, one that mirrors on many different physical scales the integration of information that we hope to achieve in our research.

Integration, to us, means greatly increased integration of distributed information into knowledge through the use of electronic data exchange. It means the integration of theory and modeling into project conception and design as well as data analysis. It means the systematic integration of single spacecraft into spacecraft systems, in which the spacecraft itself is a subordinate part of the project.

In short, we will have to reconceptualize what the word "mission" means. In the future, we urge that NASA take a "knowledge-acquisition-systems" approach to the conception, design, and management of research projects in space physics.

Finally, the words "more integrated approach" mean that more attention must be paid to the appropriate distribution of research projects by size. NASA has long prided itself on the disciplinary balance of its overall space science program, and with good reason. However, one can also ask, "What is the appropriate balance between scales of research effort?"

The results of this planning workshop suggest that the present distribution of spacecraft projects by size may not be appropriate to space physics research in the future. The present OSSA plan has categories for moderate and major missions, costing between 0.5 and 1, and 1 and 2 billion dollars, respectively. Present decision rules specify that one major new start will be submitted to Congress each year, failing which, a moderate mission will be submitted. However,

> Space physics research will require a greatly expanded program of intermediate-scale spacecraft projects in the next twenty years.

The intermediate projects discussed in this document will cost less than 200 million dollars, and many will cost substantially less. A project may involve one or more spacecraft. In the past, such projects have been funded through the Explorer line item.

In the aggregate, intermediate projects comprise a critical element of the research programs of each of the subdisciplines in the Space Physics Division.

The mere fact that a project is relatively small does not mean that its scientific benefits will also be small. The importance of scientific knowledge cannot always be measured by the cost of acquiring it. The scientific programs we have defined here will require one intermediate new start each year. Such an intermediate project program could be as important to the progress of space physics as the current major or moderate mission lines.

Despite its recent augmentation, the Explorer budget is far from meeting the need in space physics, let alone astrophysics. This has led us to conclude that:

> Present OSSA resources and procedures are completely inadequate to meet the projected need for intermediate projects in the Space Physics Division.

1.1.6 Integration

In view of the above, we recommend:

> THAT THE OSSA STRATEGIC PLAN EXPLICITLY INCLUDE AN INTERMEDIATE PROJECT CATEGORY.

The present plan, which was designed to create scientific opportunity while attending to the backlog of delayed missions following the Challenger disaster, may well need modification for the period after 1994. We also recommend:

> THAT SPACE PHYSICS INTERMEDIATE PROJECT PROPOSALS BE SUBMITTED TO CONGRESS EVERY YEAR.

We understand Congressional reluctance to increase funding for line items—indeed this is one reason why the Explorer line has failed to keep up with inflation and scientific need. However, we are confident that the intermediate projects proposed here can win Congressional approval each year on their merits, once the case for the intermediate category has been made and is understood.

The simple act of establishing an intermediate project category could stimulate technological advances to reduce the cost and increase the flexibility of small and intermediate spacecraft projects. This would, in turn, encourage new industrial applications of space because projects of a scale appropriate to private organizations would become economically more attractive.

1.1.7 An Illustrative Timeline for Space Physics

As pointed out above, each Panel has defined the missions needed to carry out the highest priority science in its discipline. The charter of the Mission Integration and Divisional Science (MIDS) Panel is to integrate the individual discipline plans into a coherent timeline that reflects overall scientific priorities and takes into account such factors as the technological evolution required to implement each discipline's scientific objectives in a timely manner.

The MIDS Panel asked each disciplinary Panel to identify one major-, two moderate-, and five intermediate-class missions, together with the necessary advanced technology development, instrument development, and appropriate infrastructure issues for the period 1995 to 2010. These guidelines were based upon OSSA's anticipation that its overall budget, including the Space Exploration Initiative (SEI), could grow to approximately 5 billion dollars by fiscal year 1995.

The MIDS Panel then presumed that the Space

Executive Summary

Physics Division budget in this scenario could double from the present level of approximately 350 million dollars; and perhaps triple, to approximately 1 billion dollars per year, if the SEI were to be included. These guidelines then provided the framework for the construction of the timeline chart shown below.

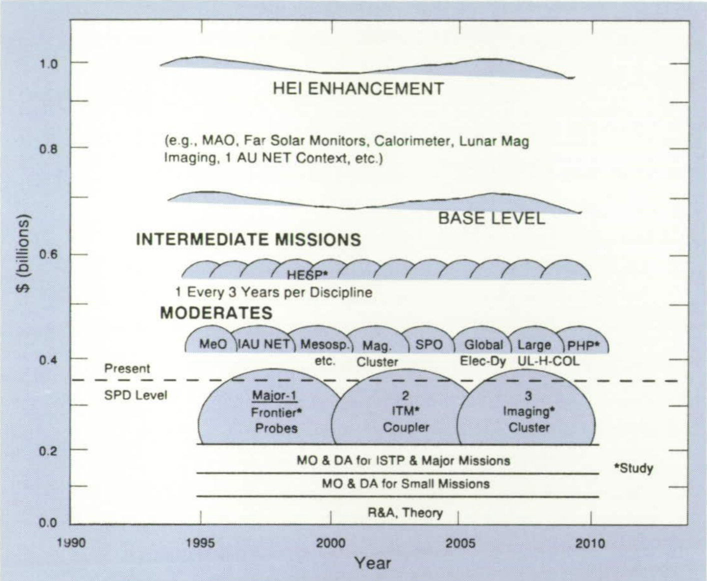

Figure 1.1–1 Illustrative timeline for space physics

The chart is strictly illustrative, since priorities will be firmly established only after the conclusion of the second workshop. It nevertheless shows that the research objectives identified by all four science disciplines, together with theory and the necessary infrastructure, can be achieved within the budgetary guidelines explained above.

Let us now describe some of the features of the timeline. We begin with the lowest entry in the chart, Research and Analysis (R & A) and Theory. These budget categories should grow to approximately 80 million dollars per year by 1995. Such an increase is absolutely essential for three reasons. First, the present R & A budget in the Space Physics Division is completely inadequate. The Space Physics Division was formed in the last three years and did not inherit an adequately funded program from the elements in the other divisions of OSSA from which it was assembled. Second, a substantial enhancement in Advanced Technical Development (ATD) funds will be critical to carrying out many of the future missions identified in the timeline. Finally, a substantial expansion in theoretical technology is needed to carry out the "Knowledge-Acquisition-System" approach implicit in the space physics research strategy outlined above.

The second level from the bottom, Mission Operations and Data Analysis (MO & DA) for small missions, represents that element of the Division's program that serves Explorers, including the anticipated expansion in the Small Explorer (SMEX) program. The third element in MO & DA recognizes the significant augmentation necessary for the Global Geospace Science/International Solar-Terrestrial Physics (GGS/ ISTP) missions in the mid-90's and the continuing data acquisition and analysis requirements for the missions identified at the next level. This next level represents the three major missions that had been identified prior to the last day of the workshop. Their descriptions can be found in the reports of the individual discipline Panels. The estimated funding requirement for each is assumed to be approximately 200 million dollars per year over a period of about 5 to 8 years.

The middle of the chart shows a potential time-ordering for the eight highest-priority moderate missions identified by each of the discipline areas. These are expected to cost about 150 million dollars per year with varying duration for each. Above the moderate mission line is the timeline for the proposed new intermediate class of missions. Here, we anticipate one new start each year in the range of 100 to 200 million dollars. The specific intermediate missions are identified in the reports of the individual Panels and are not shown explicitly in this chart. (One, however, the High Energy Solar Physics—HESP—mission, has been called out explicitly because it requires a technical study as early as possible.)

The timeline to this point represents a program that anticipates a doubling of the Space Physics Division's budget by 1995.

Above this line are enhancements stemming from the participation of the Space Physics Division in SEI. Even the few illustrative examples shown demonstrate the synergism between the scientific objectives of the various space physics disciplines and the requirements of SEI. For example, the Mars Aeronomy Orbiter (MAO) will not only study the physics of the Martian atmosphere but will also determine basic parameters for the design of the aerobraking systems of manned Mars Orbiters and Landers. Similarly, the Far Solar Monitors not only provide a stereoscopic view of solar processes, a central objective for solar physics since the beginning of the space era, but are also the only way to warn astronauts in transit to the Moon or Mars of impending life-threatening solar activity. Other projects, such as Lunar Magnetospheric Imaging, provide new basic science measurements which can only be done effectively from a lunar base.

The timeline above will undergo considerable evolution following the second workshop, in June. We are already aware that changes are needed in the moderate mission category because the Solar Physics Panel proposed to merge the Solar Polar Orbiter, a moderate mission, with the Far Solar Monitors into a single major mission called the Solar Stereoscopic Mission. The MIDS Panel did not have time to discuss the implications of this proposal. Furthermore, pre-Phase-A studies now in progress will clarify the technical feasibility and estimated costs of many of the proposed missions. These studies will have a major impact on the way in which our illustrative timeline evolves into a coherent plan.

1.2 Cosmic and Heliospheric Physics Panel Summary Report (Summary of the Cosmic and Heliospheric Physics Program for the Years 1995 to 2010)

The Cosmic and Heliospheric Physics Branch proposes a bold new program for the years 1995 to 2010 that is centered on two themes:

- The Next Frontier: The Global Heliosphere and Interstellar Space.
- Cosmic Particle Acceleration and the Evolution of Matter.

Under the first of these two themes, we propose a coordinated exploration of the global heliosphere, eventually pushing beyond into the interstellar medium. This new thrust recognizes the fact that progress in essentially all areas of heliospheric and space physics is most effectively accomplished by direct exploration. To carry out this exploration we propose a series of Frontier Probes:

- A ***Solar Probe*** that would pass through the outer regions of the Sun's corona, carrying out *in-situ* measurements of plasma, fields, and energetic particles in the solar wind acceleration region.
- An ***Interstellar Probe*** that would perform comprehensive measurements of the structure and dynamics of the solar wind termination shock and heliopause, and then make a significant penetration into interstellar space to study *in situ* the plasma, fields, cosmic rays, and dust of the Galaxy.
- A ***Polar Heliosphere Probe*** that would use a Jupiter flyby to send a Pioneer or Ulysses-class spacecraft 10 to 20 AU out of the ecliptic into unexplored polar regions of the heliosphere.

The second theme of this program is addressed by missions that will probe cosmic acceleration processes on scales from interplanetary to interstellar space and extend our knowledge of cosmic rays and heliospheric particles to the upper end of the periodic table and to some of the highest-energy particles in the Galaxy. Missions that are proposed to address cosmic-particle acceleration and the evolution of matter include:

- An ***Ultraheavy Element Spectrometer*** for cosmic rays in the upper two-thirds of the periodic table, including uranium, thorium, and heavier elements used as clocks to date the nucleosynthesis of cosmic ray material.
- An ***Ultraheavy Solar/Galactic Isotope Explorer*** to measure the isotopic composition of $Z>28$ nuclei in solar flares and galactic cosmic rays.
- A ***Solar Wind Turbulence/Particle Acceleration and Transport Explorer*** consisting of a cluster of small, identical spacecraft performing detailed studies of interplanetary waves, turbulence, and associated particle acceleration and transport.
- A ***Matter/Antimatter Explorer*** that uses a permanent magnet spectrometer to identify low energy (<1 GeV) antiprotons, electrons, and positrons, and to search for anti-helium nuclei.

In addition to these dedicated missions, other significant scientific advances can be realized through opportunities in other programs. For example, a manned lunar base would permit construction of:

- A ***Lunar-Based Calorimeter*** to determine the composition and investigate the origin of cosmic rays up to the "knee" in the energy spectrum at 10^{16} eV .

In addition, second-generation experiments can be attached to the Astromag facility on the Space Station to conduct high-energy isotope, antimatter, and plasma investigations. Flights of opportunity are also on Mir and future planetary missions. Finally, a number of opportunities possible are identified for collaborative ventures on missions such as the Mercury Orbiter, solar-orbiting spacecraft, and other missions under consideration by other disciplines.

The new program proposed here builds on the current Cosmic and Heliospheric Program and extends it in several crucial areas. The scientific themes and objectives, and the new mission concepts that comprise the program are focused on key areas of investigation identified in recent reports by the Cosmic Ray and Heliospheric Program Working Groups. Key objectives include studies of the following topics:

- Origin, structure, and evolution of the solar wind—to establish the nature of the solar wind acceleration process, including evolution of the wind within 50 solar radii.
- Interaction of the heliosphere, solar wind, and interstellar medium —to investigate the nature and dynamics of the heliosphere, the solar wind termination shock, the heliopause, and the local interstellar medium.
- Fundamental microscopic and macroscopic plasma processes—to determine the role of waves and other transient phenomena in heating the corona, and to probe the nonlinear, turbulent plasma processes which accelerate energetic particles.
- Acceleration and transport of energetic particles—to comprehensively study the acceleration of solar, interplanetary, and galactic particles over many decades in energy to test shock-acceleration models on a wide range of scales.
- Origin and evolution of matter—to determine and compare the compositions of the solar corona, local interstellar medium, and galactic cosmic ray sources; identify nucleosynthesis processes that distinguish solar and galactic matter; and search for sources of antiparticles in cosmic rays.

A more complete description of our scientific goals and the mission concepts proposed to address these objectives is contained in the full report of the Cosmic and Heliospheric Physics Panel, which also includes several new initiatives put forth in an effort to enhance the research infrastructure.

1.3 Ionospheric–Thermospheric–Mesospheric Physics Panel Summary Report

The overall objective in the strategic plan for future ionospheric-thermospheric-mesopheric (ITM) research focuses on the development of a self-consistent concept of the ITM as a single, electrodynamic, chemically-active, and kinetically-reactive fluid which dominates the Earth's near-space plasma environment. To be self-consistent, the objective requires that the understanding of the ITM be global, cover the full spectrum of solar-terrestrial conditions, deal with all internal and external coupling mechanisms, and encompass quiescent and dynamic conditions carried to the limit of highly irregular and unstable modes.

The strategy plan has been developed with the recognition that the ITM has a uniquely important role in the solar-terrestrial system, for it is the geospace domain that provides the interface between interplanetary and lower atmospheric processes. It absorbs the bulk of the solar EUV/UV radiation and precipitating-particle energies, and supports, controls, and distributes currents and potentials ranging up to 10^6 amperes and hundreds of kilovolts, respectively. It is among the most complex naturally-occurring, weakly-ionized plasma domains accessible to *in-situ* diagnostics. It is a region with processes in the continuum, transitional, and free-molecular flow regimes. It involves positive and negative ion chemistry, global circulation, kinetics of neutral particle collisions, external and internal electric fields, and magnetically-induced anisotropies. It couples to the magnetosphere and heliosphere above, and the stratosphere below—responding to solar EUV/UV variations, coronal mass ejections, and high-speed streams from coronal holes on the one hand, and atmospheric tides, gravity waves, and lightning storms on the other.

The report presents a considered, forward-looking program of research which addresses the need for a comprehensive experimental investigation of the physical, chemical, dynamic, radiative, and energetic processes that couple the ITM system both within itself and with the heliosphere and magnetosphere above and the stratosphere below. The mission concepts build on the successes of previous NASA missions that have delineated aspects of the ITM system with sufficient clarity to allow the formulation of a set of definitive, critical, and substantive scientific questions for the future. These scientific questions relate to the temporal and spatial responses of the global and coupled ITM system to highly variable, solar-terrestrial controls. We know that the ITM is controlled from above by EUV/UV radiation from the Sun, energetic particles from the interplanetary medium and the magnetosphere, and the superimposed electric fields from solar wind-magnetosphere interactions. We know it responds dynamically with large variations in its charged and neutral particle density and energy distributions; its drifts, winds, and tides; and its polarization and dynamo electric fields. However, we do not know the global distributions of electric fields and thermospheric winds nor the specifications of EUV/UV radiation—the primary forces driving the system. Within this system we do not know the global distribution of intermediate plasma layers and their contributions to the critically important dynamo fields, and specific controlling influences of the metallic, atomic, and molecular ion inventory. In the cause-effect chain we do not understand the interplay of wind-shear forces and electric fields in the formation of intermediate layers, their global distributions, and control of upper F-region dynamics by field-line coupling of electric fields. Neither do we understand the physics controlling the mesosphere/lower-thermosphere interface, the upward and downward propagation of tides and waves and their ultimate coupling to the ionized constituents, and the cascade of energy between large- and small-scale structures. And we do not know long-term trends in mesospheric chemistry, nor the effects of global change due to anthropogenic causes. These issues are addressed aggressively in the strategy plan, with a spacecraft program which combines existing and developing technologies.

The report summarizes the scientific rationale for the program elements, starting with the definition of an overarching scientific theme and subthemes, and then developing specific scientific and mission-related objectives. Four new-start missions are described in further detail, one major and three moderate missions. The major mission, called the ITM Coupler (ITMC), is the centerpiece of the program and carries the highest priority. The three moderate missions are complementary to the ITMC and are responsive to a set of distinct scientific objectives. The Panel, however, also recognized the important need for smaller (SMEX and BEX) missions and included a set of specific mission candidates. In all cases the mission objectives are cast in the spirit of the broader theme of the ITM discipline, and the instrument complement and orbital requirements are designed to provide critical inputs to the fulfillment of the ITM goal.

1.4 Magnetospheric Physics Panel Summary Report

The Magnetospheric Physics Panel proposes a coordinated program of small, moderate, and major missions to address fundamental questions about the Earth's magnetosphere that ISTP will leave unanswered. At the same time, this program will generalize our understanding of magnetospheres through comparative magnetospheric studies.

The overall goal of the proposed terrestrial program is to develop a *global* picture of the magnetosphere as a dynamic system of interacting plasma domains and processes. The Panel has adopted and expanded the ISTP strategy of using a combination of imagers and multispacecraft clusters. The imagers will provide a macroscopic view of the dynamics and morphology of the magnetosphere, while the clusters will probe the transition regions, investigate the structures and microscale processes occurring there, and distinguish spatial from temporal variations. The proposed terrestrial magnetosphere program assigns a prominent role to small Explorer-class missions. Relatively inexpensive and requiring only modest lead-times, such missions are invaluable tools for investigating virtually all magnetospheric phenomena. Recommended terrestrial magnetospheric missions for the period 1995 to 2015 are the following:

- ***Inner Magnetosphere Imager (IMI).*** A single spacecraft in a high-inclination, elliptical orbit will use ENA, photon, and radio-wave imaging techniques to obtain global/macroscale images of the ring current, plasmasphere, inner edge of the plasma sheet, and the auroral oval. IMI will allow an initial assessment of how local processes determine the global dynamics of the magnetosphere. (Small mission)
- ***Auroral Cluster (AC).*** Four identically-instrumented spacecraft in a polar orbit will make multipoint plasma-and-fields measurements in the auroral acceleration region. The capability of varying the distances among the spacecraft will make it possible for the first time to distinguish between spatial and temporal effects on various scale sizes. (Small mission)
- ***Solar Wind/IMF Input Monitor (SWIIM).*** A single spacecraft in a double lunar swing-by orbit will provide continuous monitoring of solar wind density and flow velocity and the IMF in support of the other proposed magnetospheric missions. SWIIM will replace Wind when the latter is no longer operational. (Small mission)
- ***Magnetopause/Boundary Layer Explorer (MPEX).*** One or two spacecraft in polar orbit will investigate the dayside magnetopause at all latitudes and local times, the cusp and high-latitude nightside magnetopause, and the transition region in the near-Earth magnetotail between the ring current and the plasma sheet. The initially circular orbit will be modified during the course of the mission to permit in-depth exploration of these three major boundary regions. MPEX will focus on processes at the magnetopause coupling the solar wind and the magnetosphere, on the fate of ionospheric plasma in the neutral and plasma sheets, and on substorm processes. (Small mission)
- ***Active Field Line Tracing Experiment (AFLTE).*** Barium releases from Scout vehicles or spacecraft proposed for other missions will map magnetic field line topology. (Small mission)
- ***Magnetopause/Near-Plasma Sheet Equatorial Cluster (MNPSEC).*** A cluster of four spacecraft in equatorial orbit will make detailed measurements at the subsolar equatorial magnetopause and in the near-Earth magnetotail, two important yet underexplored magnetospheric regions. Observations at the subsolar magnetopause will yield valuable information about the still-inadequately-understood mechanisms involved in the transfer of mass, energy, and momentum from the solar wind to the magnetosphere. Measurements in the near-tail (≈ 7–10 R_E) will help in understanding substorm particle injection, cross-tail current disruption, the change in magnetic field topology from dipole to tail-like, and the mapping of field-aligned currents. Spacecraft will be equipped for plasma-and-fields measurements, including instrumentation on at least one spacecraft for measurement of energetic particles and thermal plasma. Spacing among spacecraft will be varied to distinguish between spatial and temporal variations. (Moderate mission)
- ***Imaging Super Cluster (ISC).*** Two spacecraft in highly elliptical polar and equatorial orbits will employ photon, ENA, and radio-wave imaging techniques to provide macroscopic images of the outer magnetosphere and the magnetotail. A cluster of four spacecraft will be maneuvered throughout the magnetotail (out to ≈ 250 R_E) to make simultaneous ***in-situ*** plasma-and-fields measurements; variable cluster configuration and spacing will allow spatial and temporal effects to be distinguished. ISC will answer questions both about the global morphology and behavior of the magnetosphere and about the microstructure and dynamics of the magnetotail. (Major mission)

In addition, SEI will present an opportunity to augment the above missions through lunar-based experiments. The *Lunar-Based Magnetospheric Imaging Observatory* would use EUV, ENA, and radio-wave imaging techniques for macroscopic studies of the magnetosphere. The *Lunar-Based Magnetopause Mapper* would employ radio telescopy to "sound" the magnetopause.

For comparative magnetospheric studies, the Panel proposes a moderate mission to Mercury and a major mission to Jupiter.

- ***Mercury Orbiter (MeO).*** Two spacecraft with comprehensive plasma-and-fields instrumentation as well as solar physics and planetology experiments will be placed into polar orbit around Mercury. One spacecraft will remain in a stable elliptical orbit, while the other will move progressively closer to the planet, surveying first the deep magnetotail and then the near-tail region. The MeO magnetospheric physics experiments will map the magnetic structure and plasma environment of Mercury's magnetosphere, investigate apparent substorm processes, and study the transfer of mass and energy from the solar wind.

- ***Jupiter Polar Orbiter (JPO).*** Galileo will leave unanswered important questions about the Io plasma torus and its interaction with the planet's magnetosphere and atmosphere. Two spacecraft in complementary high- and low-perijove polar orbits (or a single hybrid spacecraft capable of modifying its orbital regime) will investigate the temporal variability of the Io torus, Birkeland currents coupling the torus and magnetosphere with the ionosphere, and Jovian auroral processes. Spacecraft will be equipped with full plasma instrumentation.

The Panel also proposes to extend the parameter ranges available to comparative magnetospheric studies and to investigate specific magnetospheric plasma processes with a program of active perturbation experiments involving two small missions. The *Analog Magnetospheric Plasma Laboratory (AMPL)* will deploy a plasma diagnostic probe from STS or the Space Station to study the interaction of the Astromag with the ambient ionosphere. The *Energetic Injection Plasma Laboratory (EIPL)* will be deployed on a spacecraft in elliptical polar orbit; energetic particle accelerators, wave transmitters, and a plasma diagnostic probe will be employed to study particle beam-plasma and wave-plasma interactions and to provide remote sensing of ambient plasma structures.

Finally, the Panel proposes an enhanced theory and modeling effort to complement the above observational program. Theory and modeling will have the dual function of providing guidance during the mission design phases and of synthesizing the unprecedented amount of data to be gathered during the missions.

1.5 Solar Physics Panel Summary Report

1.5.1 General

During the coming decades, solar research will explore the limits of what can be observed. At one extreme we expect to explore, beginning with OSL, the smallest physical scales at which fundamental solar processes take place. At the other extreme, the Sun can only be understood by a global viewpoint; *i.e.*, when considered and observed at a wide range of spatial, temporal, and spectral scales from multiple locations for a determination of structure in three dimensions, using time series which have a length of a considerable fraction of the magnetic-activity cycle period, and simultaneous viewing of the solar surface.

1.5.2 Major Themes

(1) Identification of the variable nature of the Sun as key in the modulation of the volume of the solar system and the heliosphere.

(2) Investigation of the shorter-term variations associated with the evolution of the magnetic activity cycle. Flares, active regions, coronal holes, and their associated high-speed wind structures are all shorter-term consequences of the activity cycle which directly influence the solar neighborhood.

(3) Investigation of the magnitude and significance of longer-period solar variability and its influence on various component elements of the solar system and heliosphere. These elements range from the changes which are observed over fractions of a day to those which occur over the range of the magnetic activity cycle.

1.5.3 Scientific Questions

Interior of the Sun. What is the nature of that part of the Sun which lies below the photosphere? What are the dominant structures and physical processes of the interior, and how do these evolve over the time-scales of interest?

Generation of the Magnetic Activity Cycle. What are the physical processes which determine the generation of a magnetic variation in the star? Of what significance is this variation in the modulation of other objects and structures in the solar system?

Energy Storage and Release. How is non-potential magnetic energy stored in the Sun, and how is this magnetic energy converted into other kinetic and thermal forms of energy? How are the energetic particles accelerated to high velocities as the active regions evolve and change?

Solar Activity. What are the physical processes which govern the nature of the plasma structures found in the solar atmosphere in active regions? How are dynamic processes initiated and maintained in the upper layers of the Sun and out into the heliosphere?

Solar Wind and Solar Interaction. What physical mechanisms couple the variability of the Sun to the other elements of the solar system, such elements as the magnetospheres and atmospheres of planets, the modulation of cosmic rays, and the structure of the plasma flowing away from the Sun in the form of solar wind?

1.5.4 Measurements

These scientific themes and objectives require a large variety of solar measurements. They may be grouped into three broad categories:

(1) Simultaneous measurements of the Sun from new vantage points, including the solar poles, multiple azimuths in the ecliptic, and the near-Sun region.

(2) The quest for higher spatial resolution in all temperature regimes of the solar atmosphere.

(3) The long-term measurement of solar radiative and particle outputs which affects plasma and atmospheric processes throughout the solar system.

1.5.5 Missions

Orbiting Solar Laboratory (OSL). High spatial resolution, coupled with appropriate spectroscopic diagnostics required to measure basic plasma parameters (temperatures, densities, velocities, magnetic fields, and chemical abundances), is required to probe the structure of the solar atmosphere and acquire the basic data needed to provide empirical constraints and insights concerning the fundamental physical processes responsible for plasma heating and the transport of mass and energy at, and between, different levels of the solar atmosphere.

High Energy Solar Physics (HESP). It is essential to acquire high-resolution imaging and spectroscopy of high-energy radiations during the maximum of Cycle 23. The impulsive phase of a solar flare, for example, can energize both protons and electrons to relativistic energies in a short time in flare kernels whose size has never been resolved. Sub-arcsecond imaging and high-resolution gamma ray spectroscopy ($R > 1000$) are needed, along with simultaneous photospheric and coronal imaging (from OSL if possible), to provide the context of the flare.

Global Solar Mission (Solar Polar Orbiter, Ecliptic Network). Simultaneous measurements from multiple vantage points (over the poles and in the ecliptic) using familiar techniques will provide fundamental new data for understanding the solar interior, atmosphere, and magnetic activity cycle.

Solar Probe plus Context. The Solar Probe will acquire unique, detailed measurements of particles and fields along its flight path which is expected to approach to within four solar radii of the Sun. These highly unique, critical data will be placed in a context of the larger-scale, time-varying structure of the solar atmosphere. Remote-sensing imaging and spectroscopic measurements made from Earth orbit while the Solar Probe flies close to the Sun are required for provision of critical data on the lower atmospheric sources of the outflowing plasma sampled *in situ* by instruments on the Probe.

Solar Outputs and Solar Variability. The output of the Sun ("as a star") must be measured continuously so that the effects of its variability on the Earth and space plasmas can be studied.

Solar Physics on Space Station Freedom. The Ultra-High-Resolution Extreme Ultraviolet Spectroheliograph, a set of solar XUV telescopes, has been selected for early deployment on the Space Station. A second-generation attached payload element, the Pinhole/Occulter Facility, will contain advanced coronal and high-energy instruments. A capability for small attached payloads would be valuable for innovative instrument development and student involvement.

Small Missions. Small solar missions discussed include: Solar Variability Explorer, Solar Composition Explorer, Solar IR Explorer, Coronal Imager, Solar EUV/XUV Explorer, Solar Luminosity Explorer, Flare Radiation Budget Explorer, Tomographic Hectometric Explorer, Flare Build-Up Explorer, Soft X-ray Spectroscopic Explorer, Hard Radiation Anisotropy Mission, Heliospheric Tomography Mission, Ultra-High-Resolution EUV Explorer, Neutral Atomic Imager, and Gamma-Ray Spectroscopy Mission.

1.5.6 The Space Exploration Initiative

Hard photons and solar cosmic rays present a substantial health hazard for astronauts outside the terrestrial magnetosphere. The state-of-the-art in flare physics is inadequate for predicting these health hazards. A concerted effort to improve the knowledge of flares must be made before manned missions into deep space. This requires missions (*e.g.*, OSO and HESP) for conducting the required basic research and deployment of a global network, initially for data-gathering and research, and ultimately for operation as a warning system. The lunar surface offers interesting advantages for some types of solar instrumentation such as radio interferometers, gamma-ray observatories, and some types of very high-resolution optical instruments.

1.5.7 Supporting Research and Technology

The quality and quantity of science from future solar missions such as Solar-A, SOHO, and OSL depend on the vitality of the solar science community. Observational advances require development of new instrumental and observational techniques which exploit both existing and state-of-the-art technology. Because of these factors, we recommend a major augmentation to the funding for solar suborbital programs (including establishment of a solar balloon program) and advanced technology development. We also recommend significantly increasing the level of support for the solar research and analysis program, and for the NASA Space Physics Theory Program (SPTP).

1.6 Theory Panel Summary Report

1.6.1 General

During 22 to 26 January 1990, the Space Physics Division of the National Aeronautics and Space Administration hosted a Strategy-Implementation Study meeting in Baltimore, Maryland. This meeting was organized to help define an optimal course of space plasma research for the coming decade. The Study's Theory Panel was a unique one, made up of researchers from the various areas constituting the discipline of space physics.

Drawing upon comments following the Theory Panel presentation at the January meeting, Panel discussions at the meeting, and lengthy correspondence among the members following the meeting, the Panel drafted and refined a twenty-page report of past contributions made by theorists in delineating space physics systems, the state of theory in the field, and recommendations for maximal future gains in our understanding of space physics through the use of theory.

1.6.2 Summary of Recommendations Made by the Theory Panel

1.6.2.1 Support for Theory Research

The science of space physics has progressed well beyond the initial exploratory phase; significant advances in the future will come only from the close interaction of experiment and detailed theoretical models. At present we believe a healthy balance exists between theory and experiment in NASA's Space Physics Division. We therefore strongly recommend an increase in the SPTP and R & A theory budgets that will keep pace with the increase in the funding recommended by the Panel as a whole for the experimental program. The increased SPTP and R & A budgets would be used to promote a healthy research and analysis program for the support of theoretical space plasma research independent of missions and mission programs, and provide ongoing support for experimental efforts. To this end, the following modifications to existing theory programs are recommended:

(1) Appoint a Visiting Senior Scientist for R & A overseeing across all disciplines in Space Physics.

(2) Install a small Management Operations Working Group to oversee the entire theory program.

(3) Restructure SPTP management along the lines of Flight Projects with a NASA Headquarters Program Scientist and a Project Scientist.

(4) Include a Deputy Study Scientist for Theory on all future mission studies with incorporation where appropriate.

(5) Increase basic theory research funding. This is absolutely required if any significant advances are to be made in the field.

1.6.2.2 Research Structure

The following recommendations are concerned with building the permanent infrastructure and with interdisciplinary research:

(1) Investigate means of increasing the number of tenured faculty in theoretical space physics. Such an increase would require a long-term trend of increased agency funding.

(2) Investigate approaches to creating a framework within which cross-disciplinary research may be enhanced. One possible avenue would be to give funding priority to applications using multidiscipline approaches.

Both studies should be conducted with consideration of the extent to which these needs can be accommodated within the present framework of theory programs, or alternatively whether new institutional structures such as Centers for Space Theory or Interdisciplinary International Coordinated Workshops are required. In addition, the following programs should be initiated immediately to stimulate interdisciplinary research

Frontiers of Space Physics Initiative Objective:

Directed, focused research on fundamental problems in space physics that are of direct relevance to present and future space physics missions such as the nature of turbulence, the acceleration and transport of particles, the coupling of micro and macro physics, the coupling of local and global dynamics, and non-classical plasmas. Would include both experimentalists and theorists as a next generation of CDAW type studies.

Format: Series of iterated workshops. The start of each workshop could be staggered, for example, one per year. Each iterated workshop would concentrate on a single topic.

Duration: Three years per workshop with perhaps three meetings being held per workshop, meeting once per year.

Funding: Could range from a lower bound of meeting funding alone ($50K per workshop) to an upper bound wherein investigators would be funded ($1000K per workshop).

Topics: To be chosen by Theory Working Group in consultation with HQ branch MOWGs.

At the higher funding level an NRA could be issued for competitive funding of up to 20 investigators (theorists and experimentalists) per workshop.

Fellowships

A young investigator fellowship program should be established, loosely patterned after the NAS–NRC fellowships, to provide a number of prestigious post doctoral fellowships at the universities. The fellowships would be funded directly by NASA, at either the division or, if possible, OSSA level, using new funds. Applications would be made by a recent Ph. D. and an established researcher, with the award being made available in a time of several months.

The graduate student fellowship program should be augmented.

1.6.2.3 Computational Support

There is an unfulfilled need for computational support for theory. This need will grow in future decades. The following enhancements and studies are recommended:

(1) Workstation acquisition by researchers participating in theory programs where justified.

(2) Increase availability of supercomputer support for researchers in theory programs where required.

(3) Establish a study group to investigate new computer architectures which will be of use to theory researchers.

1.6.2.4 Theory-Data Closure

It is imperative that explicit measures be taken in the earliest stages of space physics missions to assure improved theory-data closure. This means that every mission announcement of opportunity (AO) should require that such closure be achieved within that mission. It is recommended that the quality, breadth, realism, and innovation of the theory-data closure elements of proposals (in response to mission AO's) be judged as specific, high-priority parts of the proposal evaluation process.

Finally, it is recommended for presently-defined missions, in order to initiate activity in this critical-need area, that NASA consider the release of an AO specifically to solicit new, effective ideas on achieving rapid, dramatic improvements in innovative theory-data interplay.

Theory has made significant contributions to the advancement of space physics. Continued efforts to make theory available to experimentalists, and funding in line with the demands made on theory, will promote the ability of theorists to meet the needs of experimentalists and even to exceed them.

2.0 Report of the Cosmic and Heliospheric Panel

2.1 The Cosmic and Heliospheric Physics Program for the Years 1995 to 2010

The Cosmic and Heliospheric Branch proposes a bold new program for the years 1995 to 2010 that is centered on the following two themes:

- The Next Frontier: The Global Heliosphere and Interstellar Space.
- Cosmic Particle Acceleration and the Evolution of Matter.

Under the first of these, we propose a coordinated exploration of the global heliosphere, eventually pushing beyond into the interstellar medium. This new thrust is centered around two new spacecraft: a Solar Probe that would pass through the outer regions of the Sun's corona; and an Interstellar Probe that would penetrate the solar wind termination shock and heliopause, and make a significant penetration into interstellar space. This proposed program of global heliospheric exploration also includes a Polar Heliosphere Probe that would take advantage of a Jupiter swingby to penetrate ~20 AU out of the ecliptic plane, instruments on missions of opportunity such as planetary probes, and a Coordinated Outer Heliospheric Observation program based on the unique opportunity provided by the fleet of NASA spacecraft presently in the outer heliosphere.

The second theme of this program is addressed by proposed missions that will probe cosmic acceleration processes on scales from interplanetary to interstellar space, and extend our knowledge of cosmic and heliospheric particles to the upper end of the periodic table and to some of the highest-energy particles in the Galaxy. This program includes two new missions to observe the elemental and isotopic composition of solar and galactic ultraheavy ($Z>30$) nuclei and a Lunar-Based Calorimeter that will measure the composition of ultra-high energy cosmic rays near the "knee" in the cosmic ray spectrum at $\sim 10^{16}$ eV, as part of the Space Exploration Initiative. Also proposed are new concepts for Explorer missions to study particle acceleration and transport, solar-wind turbulence, and to search for evidence of cosmic dark matter; new Space Station experiments to attach to Astromag; and possible measurements of opportunity on Mir and future planetary missions. Finally, a number of opportunities are identified for collaborative ventures on missions such as Mercury Orbiter that are under consideration by other disciplines, and several new initiatives are proposed in an effort to enhance the research infrastructure.

The scientific themes, objectives, and new mission concepts that comprise this proposed program are also described in two recent reports by the Cosmic Ray and Heliospheric Program Working Groups. The reports are entitled *The NASA Cosmic Ray Program for the 1990's and Beyond* and *Heliospheric Science in the 1990's.* These reports also summarize the elements of the current Cosmic and Heliospheric Program, including missions planned for launch in the 1990's. The program described here builds on the current and planned program, and extends it with definitive strides in several critical areas.

2.2 Recent Accomplishments

2.2.1 Origin, Structure, and Evolution of the Solar Wind

- Establishment of the nature of the heliospheric current sheet, thereby explaining interplanetary sector structure.
- Discovery of the variation of solar wind speed with heliomagnetic latitude.
- Discovery of corotating and merged interaction regions in the outer heliosphere.
- Development of quantitative models of high-speed solar wind streams and their relation to coronal holes.
- Discovery that coronal mass ejections are associated with many solar particle events.

2.2.2 Interaction of the Heliosphere, the Solar Wind, and the Interstellar Medium

- Direct detection at 1 AU of "pickup" helium which originates in the neutral interstellar medium.
- Measurements of Lyman-alpha and HeI solar photons resonantly backscattered from the neutral interstellar gas.
- Discovery and understanding of the "anomalous" cosmic rays as an intrinsic component of the

solar-wind/interstellar-medium interaction.

- Preliminary determination of abundances of neutral atoms in the local interstellar medium using anomalous cosmic rays.
- Demonstration and explanation of the 22-year nature of the solar modulation cycle.

2.2.3 Fundamental Microscopic and Macroscopic Plasma Processes

- Measurement of detailed structure of quasi-parallel and quasi-perpendicular collisionless shocks.
- Discovery of Alfvénic fluctuations in the solar wind.
- Establishment of links between microscopic plasma processes and particle acceleration in solar wind structures.
- Discovery of the extended cometary foreshock consisting of very-large-amplitude waves and evolving pickup ion distributions.

2.2.4 Acceleration and Transport of Energetic Particles

- Discovery that the heliosphere is a copious source of energetic-particle populations.
- Discovery of a one-to-one correspondence between shocks and energetic-particle populations.
- Achievement of a quantitative understanding of the acceleration of ions by shocks.
- Demonstration that the charge-to-mass ratio is the principal organizing factor for flare-to-flare composition variations.
- Association of ^{3}He-rich flares with hot coronal regions.
- Discovery of two major classes of solar-particle events—large, gradual flares and small, impulsive flares.
- Measurement of interplanetary protons from solar-flare neutron decay.
- Measurement of large-scale intensity gradients of cosmic rays in the heliosphere.
- Demonstration of the effect of the large-scale magnetic-field and merged-interaction regions on cosmic ray modulation.
- Determination that cosmic ray modulation depends on the sign of the particle charge.
- Recognition that supernova shock waves can accelerate galactic cosmic rays to very high energies.

2.2.5 The Role of Cosmic Rays in Galactic Processes

- Discovery of unexpectedly large fluxes of high-energy cosmic ray antiprotons and positrons.
- Determination of the average lifetime of cosmic rays in the Galaxy using radioactive Be-10.
- Establishment of the energy-dependent path length of high-energy cosmic rays in the Galaxy.
- Establishment of the effects of synchrotron energy loss on cosmic ray electrons.
- Establishment of the effects of cosmic rays on interstellar gas dynamics.

2.2.6 The Origin and Evolution of Matter

- Coronal abundance determinations for more than 20 elements.
- Discovery that galactic cosmic rays, solar flare nuclei, and solar coronal material are fractionated with respect to solar photospheric material.
- Survey of cosmic ray composition of elements over the entire periodic table.
- Discovery of nucleosynthesis differences in the isotopic composition of galactic cosmic ray source material and solar system matter.
- Identification of the contributions of rapid and slow neutron-capture nucleosynthesis processes in cosmic rays.
- Limits on the contribution of dark matter candidates to the flux of cosmic ray antiprotons.

2.3 Science Themes and Objectives

2.3.1 Themes

The heliosphere is a vast region, extending from the Sun to interstellar space, that is created by the continually expanding corona, or solar wind, which forces out interstellar magnetic fields and plasma to distances of ~100 AU (see Fig. 2.3–1). Among the multitude of diverse phenomena occurring in the heliosphere is the acceleration of energetic particles at sites that include solar flares, travelling and corotating interplanetary shocks, comets, and the solar-wind termination shock.

Some of these acceleration processes are illustrated in Fig. 2.3–2, while Fig. 2.3–3 shows the resulting typical energy spectra. Of the particles observed, those with the highest energy are the galactic cosmic rays, which originate beyond the heliosphere, elsewhere in the Galaxy. The objective of the Cosmic and Heliospheric Branch is the study of heliospheric phenomena and their interface with the Sun, the interstellar medium, and the Galaxy, focusing in particular on studies of plasma and energetic particles ranging from the solar wind to galactic cosmic rays.

Progress in cosmic and heliospheric physics over the past few years has been due largely to two key developments: the exciting exploratory discoveries of Pioneer and Voyager in the outer heliosphere, aided by theoretical interpretations; and, in the case of cosmic ray physics, the exposure of sophisticated new particle spectrometers in space and on balloons. We can expect this progress to continue during the next decade, assuming that Ulysses is launched, that the Pioneer and Voyager missions continue to be tracked, and that the impressive array of instruments for the recently selected ACE, Astromag, HNC, POEMS, and SAMPEX missions are indeed flown. To build on this program, and assure that this progress continues into the years 1995–2010, the following two themes emerge:

- The Next Frontier: The Global Heliosphere and Interstellar Space.
- Cosmic Particle Acceleration and the Evolution of Matter.

The first of these themes recognizes the clearly demonstrated fact that progress in essentially all areas of heliospheric and space physics is most effectively accomplished by direct exploration. The second theme recognizes that particle acceleration is ubiquitous in nature, and that comprehensive studies of accelerated particles can provide unique information on the origin and history of accelerated samples of matter, including the nucleosynthesis processes that shaped their original abundances; the various chemical, nuclear, and plasma processes that have subsequently caused these compositions to evolve; and the processes that have resulted in these particular samples of matter being accelerated to high energy.

Within these themes, the cosmic and heliospheric program proposed for the future will also be guided by the following key principles:

- ***Exploration.*** The key to understanding the structure and dynamics of the heliosphere, discovering new examples of particle acceleration, and discovering cosmic ray constituents such as antimatter, is to push back present boundaries using instrumentation at the forefront of technology.
- ***Probing the Boundaries.*** The most exciting physics can often be found in the exploration of boundary regions. Examples include the interface between the Sun and solar wind, that between the interplanetary and the interstellar media, and the interface between high-energy particles and cosmology.
- ***Comprehensive,* in-situ *Observations.*** The past decades of space exploration leave no doubt that there is no substitute for comprehensive ***in situ*** studies as keys to discovering and understanding new phenomena.
- ***Multi-Spacecraft Observations.*** Past experience has shown that this is the key to separating spatial and temporal effects.

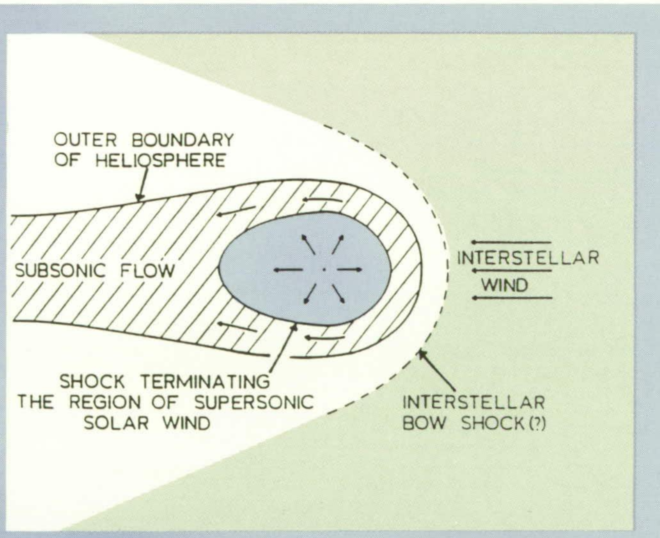

Figure 2.3–1. A schematic illustration of the heliosphere

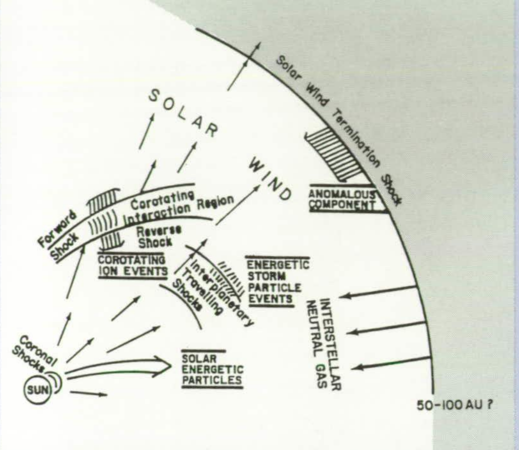

Figure 2.3–2. Illustration of some of the populations of energetic particles accelerated in the heliosphere

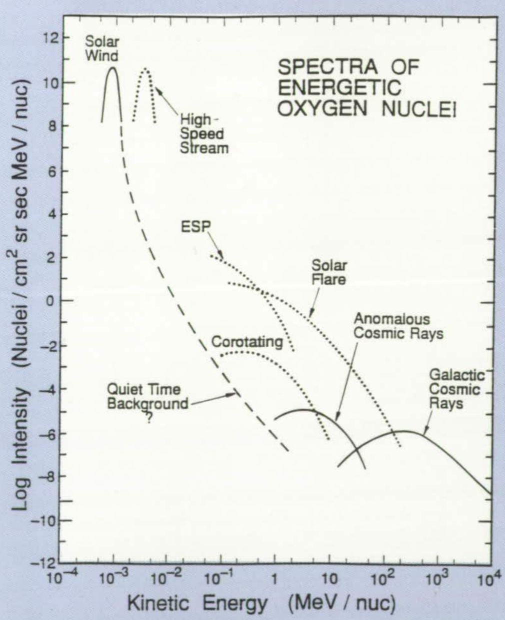

Figure 2.3–3. Typical energy spectra of energetic oxygen nuclei from various heliospheric particle populations

- ***State-of-the-Art Instrumentation.*** Over the past few years there have been dramatic developments in our ability to measure the charge, mass, and energy spectra of plasma and energetic particles ranging from solar wind energies to hundreds of GeV/nucleon. What is needed are opportunities to expose these new instruments in interplanetary space.

2.3.2 Scientific Objectives

2.3.2.1 Origin, Structure, and Evolution of the Solar Wind

The large-scale structure of the heliosphere is principally determined by the variation of the solar wind mass-flux density and flow speed over solar latitude, solar longitude, and time. *In-situ* and remote sensing measurements of solar wind properties from ~ 4 solar radii to the outer heliosphere will allow us to:

- Establish the nature of the solar wind acceleration process.
- Determine the heating and evolution of the solar wind within 50 solar radii of the Sun, including transport of heavy ions from the photosphere to the corona.
- Identify the regions where slow solar wind originates.
- Relate changes in the solar magnetic field to observed changes in the interplanetary field strength over a solar cycle.
- Investigate the origin and magnetic topology of coronal mass ejections.

2.3.2.2 Interaction of the Heliosphere, the Solar Wind, and the Interstellar Medium

The particles and fields of the nearby interstellar medium are excluded from the heliosphere by the bubble of solar wind in which the solar system is embedded. Exploratory *in-situ* measurements within and beyond the boundaries of the heliosphere will accomplish the following:

- Investigate the large-scale structure and dynamics of the heliosphere as it responds to solar variations on a variety of time scales.
- Investigate the acceleration of "anomalous"

and galactic cosmic rays at the solar wind termination shock, including possible *in-situ* observations.

- Measure directly particles and fields in nearby interstellar space, and investigate their role in the energy balance of the Galaxy and in shaping the heliosphere.

2.3.2.3 Fundamental Microscopic and Macroscopic Plasma Processes

The heliosphere is a large volume of plasma extending from the Sun to the heliopause whose particle densities, magnetic field strengths, and energy densities range over many orders of magnitude. *In-situ* studies of fundamental processes in this unique plasma laboratory will make it possible to do the following:

- Investigate the role of waves and other transient phenomena in heating the corona and driving the solar wind.
- Explore the mechanisms responsible for heat conduction in the solar wind.
- Probe in detail the nonlinear, turbulent plasma phenomena responsible for particle acceleration at planetary and interplanetary foreshocks, cometary "bow waves," and the solar wind termination shock.
- Develop an understanding of the wave-particle interactions which generate Type III radio bursts and VLF radio emissions recently discovered in the outer heliosphere.
- Distinguish between possible solar and interplanetary sources of Alfvén waves in the solar wind, and develop a theoretical understanding of these waves.

2.3.2.4 Acceleration and Transport of Energetic Particles

Particle acceleration is ubiquitous in nature and is one of the fundamental problems in space physics. Comprehensive studies of solar, interplanetary, and galactic particles spanning many decades in energy will test shock acceleration models on a wide range of scales, and allow us to implement the following:

- Study particle acceleration and interaction processes in solar flare events with orders-of-magnitude increases in sensitivity.
- Study particle acceleration and transport in interplanetary and interstellar space.
- Search for evidence of continuous cosmic ray acceleration by supernova shock waves.
- Investigate the mechanisms and sites responsible for accelerating the highest-energy particles in our Galaxy.

2.3.2.5 The Origin and Evolution of Matter

The diverse populations of high-energy particles arriving near Earth provide samples of matter from other regions of the solar system and the Galaxy. Comprehensive studies of the composition of these particles will make it possible to carry out the following:

- Determine and compare the compositions of the solar corona, the local interstellar medium, and galactic cosmic ray sources.
- Identify nucleosynthesis and galactic evolutionary effects that distinguish solar system and galactic matter.
- Determine the time scales for the nucleosynthesis, acceleration, and confinement of galactic cosmic ray nuclei.
- Identify the origins of antiprotons and positrons in cosmic rays, and search for anti-nuclei and other exotic particles of galactic or extragalactic origin.
- Search for evidence of the contribution of dark matter candidates to the flux of cosmic ray antiprotons.

2.4 Required Science Measurements

The Cosmic and Heliospheric program for 1995–2010 builds on the existing program of selected missions which will be in place or are scheduled for launch during the 1990's (see section 2.4.1). The Global Heliosphere Program depends on the Coordinated Outer Heliosphere Observations (COHO) support for continued tracking of Voyager, Pioneer, and other existing spacecraft, as well as the revolutionary new insights which will accrue from the Ulysses flight over the solar poles. The SAMPEX mission will determine the source material for the anomalous cosmic ray component, and advance our knowledge of solar and galactic cosmic ray acceleration. Instruments on the Wind mission will give new insights into particle acceleration in solar flares and interplanetary shocks. ACE and Astromag will perform definitive measurements of the isotopic composition of the elements up through the iron region, covering source materials from the solar wind to the galactic cosmic rays. Positron/electron studies on POEMS will give key insights into solar modulation and galactic cosmic ray transport. In addition, Astromag will investigate the role of matter and antimatter in the universe. HNC will return the first high-resolution data on galactic cosmic ray composition beyond the iron peak. The successful implementation of these missions is a required precursor to the missions recommended in this study.

Decisive progress in addressing the scientific objectives outlined in section 2.3 will be achieved by launching fully instrumented missions to probe unexplored regions of space, and by missions featuring new measurements not possible until now. We outline briefly here some of the key science measurements that are required to achieve this progress.

Physical processes occurring on or near the Sun, including, for example, the acceleration and heating of the solar wind, and the acceleration of solar energetic particles, are blurred as the particle populations move to Earth, making it difficult or impossible to identify key mechanisms. The solar wind critical surface, for example, lies within about 20 solar radii, and only by probing that region of space can we decisively test competing models for the origin, acceleration, and transport of the solar wind. Definitive progress in this area requires measurements as close as possible to the Sun covering solar wind, fields, and energetic particles. Close-in measurements on the Solar Probe will also need supporting data from Earth orbit covering visible, EUV, and X-ray wavelengths, and magnetic fields.

Solar flare explosions routinely accelerate particles to high energies, which subsequently impact the solar surface releasing gamma rays and neutrons, and escape into interplanetary space where they can be studied directly. Solar particle events may be classified into two broad categories: large, gradual flare events, and small, impulsive flares. Large flares appear to sample coronal material which is accelerated by shock waves, while small flares sample hot regions enriched in heavy elements. The basic scenarios for particle acceleration and transport in flares remain largely unknown, however, due in large part to uncertainties which arise during particle transport to 1 AU. Close-in observations of solar flare particles, on the Solar Probe or a suitably instrumented Mercury Orbiter, would give decisive progress in this area. In addition, small microflares, whose fluxes are often obscured at 1 AU by shock events, could be studied for the first time on these missions. High-resolution gamma ray detectors in Earth orbit can measure the nuclear line spectra from the solar material impacted by energetic particles, giving unique insights into the solar composition, and details of the downward-moving accelerated particle population.

Because the solar wind prevents low-energy (< several hundred MeV/nucleon) cosmic rays from penetrating into the solar system, this region of the interstellar cosmic ray spectrum is completely unknown. Likewise, the local interstellar medium can only be sampled outside the heliosphere, away from the influence of solar UV and the solar wind plasma. Measurements made outside the heliosphere on an Interstellar Probe would revolutionize our knowledge and understanding of a broad range of questions. For example, the cosmic ray energy density is a key component of galactic dynamics, and only by measuring the local low-energy cosmic ray spectrum directly can we determine this quantity. Similarly, questions of the magnitude of the local interstellar magnetic field, the composition of the local interstellar gas, the role of cosmic rays in ionizing the local interstellar medium, details of the local rate of supernovae in the galaxy, and aspects of galactic evolution and dynamics can all be probed with *in-situ* measurements. Since the Interstellar Probe would also penetrate the solar wind termination shock and heliopause, it will give *in-situ* measurements of a hierarchy of interactions between the solar wind and the interstellar medium, including processes that apparently accelerate the anomalous cosmic rays and may also accelerate other species. In order to take full advantage of this exploratory mission, the Interstellar Probe will carry a complete complement of state-of-the-art particles and fields instrumentation.

The Interstellar Probe, along with the Pioneer and Voyager probes, will provide a relatively complete survey of the heliosphere in the ecliptic plane and low latitudes. The polar regions, however, have distinct properties because the interplanetary magnetic field is not wound up by solar rotation in these regions. The large-scale structure over the poles is unique, and reconnaissance is necessary to probe the special properties beyond the 1.5 AU distance to be studied by Ulysses, thereby completing this first exploration of the heliosphere. The Polar Heliosphere Probe will survey the region out to at least 10 AU, and in conjunction with the other deep-space probes will provide truly global insights into the physical processes operating in the heliosphere.

Galactic cosmic rays are known to originate in association with supernovae in the Galaxy. Yet it is an open question whether the accelerated material is the freshly synthesized matter from the supernovae or a sample of the local interstellar medium swept up by the supernova shock. This and other questions can be addressed with statistically accurate measurements of ultraheavy ($Z>30$) cosmic rays, which, because of their rarity, require very large-area detectors. Thus, for example, accurate measurements of U and Th can be used to date the nucleosynthesis of cosmic ray source material, with a low U value indicating old (interstellar medium) material. By extending isotope measurements of solar and galactic cosmic rays into the trans-Fe region, it will be possible to answer key questions concerning the importance of rapid and slow neutron capture processes in the synthesis of solar system and local galactic material. Measurements of the elemental and isotopic composition of solar energetic particles and the solar wind are also important to supplement spectroscopic and meteoritic abundance studies. These studies will give new insights into the origin of the solar system and the evolution of the galaxy. Studies of this type can be carried out at 1 AU on spacecraft of moderate size.

At very high energies ($>10^{15}$ eV), the spectrum and composition of cosmic rays is of special interest because of the change of slope or "knee" in the all-particle spectrum near 10^{16} eV, suggesting that higher-energy nuclei may have a fundamentally different origin. Direct measurements of the spectrum and composition at these energies will require a calorimeter several radiation lengths thick with a collecting power of ~ 100 m^{2}sr or more. The Moon may be the only place where such a large calorimeter can be constructed in space.

2.4.1 The Current Cosmic and Heliospheric Physics Program

The current NASA Cosmic and Heliospheric Physics Program is centered around extended exploration of the heliosphere, monitoring of the Sun, and continuing studies of particles and fields in the interplanetary medium and cosmic rays from the Galaxy using the existing fleet of operating spacecraft, as follows:

- Pioneer 10 & 11.
- IMP-8.
- Voyager 1 & 2.
- Pioneer/Venus Orbiter.
- ICE.
- Galileo.

During the coming years, major efforts will be devoted to the development, launch, and data analysis of the following approved missions:

- ***Ulysses.*** A NASA/ESA mission to be launched in 1990 to perform exploratory studies of particles and fields above the ecliptic plane and over the solar poles.
- ***SAMPEX.*** A Small Explorer mission in low polar orbit that uses the geomagnetic field in studies of anomalous cosmic rays, solar energetic particles, relativistic precipitating electrons, and low-energy cosmic rays.
- ***Wind.*** An ISTP program spacecraft at the Sunward Lagrangian point that will carry out comprehensive studies of interplanetary fields and particles, as well as low-energy solar particles and galactic cosmic rays.
- ***ACE.*** An Advanced Composition Explorer to measure the elemental and isotopic composition of H to Ni nuclei over six decades in energy/nucleon, from solar wind to galactic cosmic ray energies.

Frontier Probes to Explore the Global Heliosphere and Interstellar Space
- A Solar Probe to make *in-situ* measurements of the Sun's corona.
- An Interstellar Probe to the heliospheric boundary and interstellar medium.
- A Polar Heliosphere Probe to 10–20 AU above the ecliptic plane.

Missions to Investigate Particle Acceleration and the Evolution of Matter
- An Ultraheavy Element Spectrometer for $30 \leq Z \leq 100$ cosmic ray nuclei.
- An Explorer for Ultraheavy ($Z \geq 28$) Solar/Galactic Isotopes.
- A Solar Wind Turbulence/Particle Acceleration and Transport Explorer.
- A Matter/Antimatter Explorer for antiprotons, positrons, electrons, and antinuclei.

Space Exploration Initiative
- A Lunar-Based Calorimeter to measure cosmic ray composition to $\sim 10^{16}$ eV.

Space Station Payloads
- Second Generation Astromag Experiments (high-energy isotopes, antimatter, and plasma investigations).

Measurements of Opportunity
- Flight of the Cosmic Ray Nuclei (CRN) Experiment on Mir.
- A Heavy Nuclei Collector (HNC) for Mir.
- Solar Wind Sample Return Experiment.
- Instruments on Interplanetary Spacecraft.

Collaboration on Missions with other Disciplines
- Mercury Orbiter.
- Solar Polar Orbiter.
- Solar Flare Monitoring with a 1-AU Network.
- Coronal Imager Small Explorer.
- Solar γ-ray/Neutron Small Explorer.

Table 2.5–1 Proposed new cosmic and heliospheric missions for the years 1995 to 2010

- ***Astromag.*** A superconducting magnetic spectrometer facility for the Space Station, including powerful instruments that will extend particle and anti-particle spectroscopy into the GeV and TeV energy ranges.
- ***HNC.*** A Heavy Nuclei Collector for the Space Station that will measure the abundances of the heaviest elements in the periodic table.
- ***POEMS.*** A Positron Electron Magnetic Spectrometer for the Earth Observing System that will measure electrons and positrons from the Galaxy and the Sun, and also solar g-rays and neutrons.

In addition, the continuing program includes the following: energetic particle instruments to be carried on CRRES and NOAA-I and a solar wind instrument on SOHO; a vigorous balloon-flight program to develop and test new instrumentation and to initiate new investigations of cosmic ray elements, isotopes, antiprotons, and positrons; an accelerator-based program for testing and calibrating new detectors and for measuring critical nuclear cross-sections; and an extensive theoretical program to study heliospheric plasma, energetic particles, and fields.

2.5 Mission Concepts

We describe below the various mission concepts designed to carry out the proposed Cosmic and Heliospheric Program for the years 1995 to 2010. A summary appears in Table 2.5–1.

2.5.1 Large Missions

2.5.1.1 Solar Probe

The general problem of the origin of the solar wind has been a focus of observational and theoretical activity since the original theoretical work of E.N. Parker. Direct measurements of the solar wind plasma, the interplanetary magnetic field, energetic-particle populations, and associated wave-particle interactions are available, but only at distances greater than the 0.3 AU perihelion distances of Helios 1 and 2. From the solar surface out to a distance of about 60 solar radii, we must rely on indirect observations and theoretical extrapolations. We recommend a Solar Probe mission whose primary objective is to carry out the first *in-situ* observations of the solar wind plasma and fields (electric and magnetic) near the source of the wind in the solar atmosphere. Included will be a detailed study of energetic particles which will yield important diagnostic data on particle acceleration processes and coronal structure.

The spacecraft must be placed in an orbit that will bring it as close to the Sun as possible and still survive to provide useful data near closest approach. We anticipate a perihelion distance of 4 solar radii, where we expect the local wind speed to be about 50 to 200 km/s, the electron and ion plasma temperatures to be about 10^6 K, and the plasma density and magnetic field strength to be less than 10^6 electrons/cm^3 and 10^5 gamma, respectively. Figures 2.5–1 and 2.5–2 illustrate the proposed Solar Probe trajectory, which includes a Jupiter swingby. Note that the radial range beyond 4 solar radii includes most of the Sun's principal coronal features (see Fig. 2.5–3).

Theories of solar wind origin place the transition region from subsonic plasma flow to supersonic flow somewhere between 1 and 10 solar radii. Radio scattering experiments on Viking during superior conjunction suggest a critical point closer to 10 solar radii. *In-situ* measurements should clarify this issue.

The location of the critical point and the plasma properties (speed and temperature) of the supersonic wind will depend greatly on the physical processes that heat the corona. Theoretical studies suggest that the proton temperature profile is very sensitive to these heating processes. It is not clear whether the corona contains an extended region of heating (out to as far as 20 solar radii) or has principal heating occurring near the solar surface. Plasma velocity distribution data and observations of the wave types and amplitudes should lead to the identification of the important heating and acceleration mechanisms.

Many other important problems can be studied with the Solar Probe, including a detailed characterization of coronal streamers, the place of origin and the boundaries of high- and low-speed flows close to the Sun, the extent of heavy element fractionation and elemental abundance variations, and the

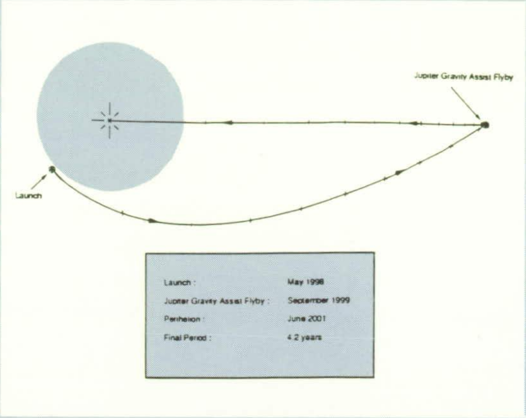

Figure 2.5–1. Solar Probe Jupiter gravity-assist trajectory

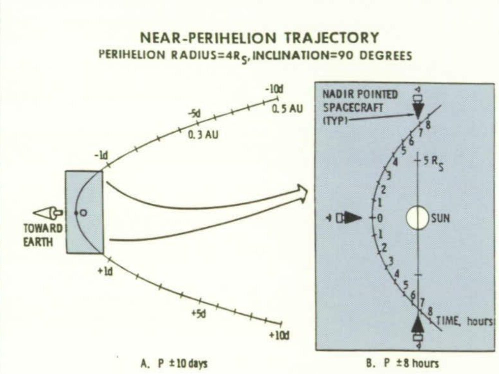

Figure 2.5–2. Solar Probe near-perihelion trajectory

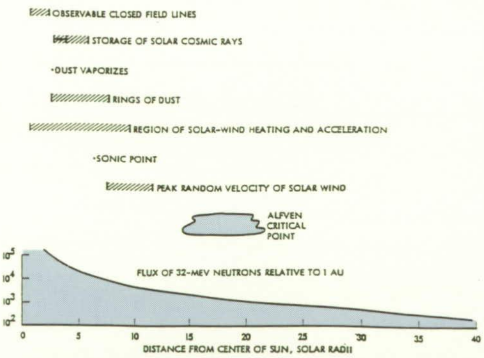

Figure 2.5–3 . The Sun's principal coronal features

scale sizes of inhomogeneities and the development of the magnetohydrodynamic turbulence that characterizes the solar wind near 1 AU and beyond. The Solar Probe mission can also study the solar spin-down rate through measurements of solar wind/angular momentum flux.

The Solar Probe mission proposed here was strongly recommended by the 1985 NAS/NRC study entitled *An Implementation Plan for Priorities in Solar-System Space Physics.* It has recently been studied in detail by a Solar Probe Science Study Team, as reported in the document *Solar Probe* (JPL D-6797, 1989). In previous studies on the concept of a solar probe, several other investigations were also included in the potential payload, *e.g.*, imaging, a drag-free experiment for studying relativistic effects, and measurement of the solar gravitational quadrupole moment. While these investigations undoubtedly have important scientific objectives, the primary objective of the mission proposed here is the study of the solar wind acceleration region, consistent with the above-mentioned report.

2.5.1.2 Interstellar Probe

We propose a dedicated Interstellar Probe that would explore the outer heliosphere, cross the solar wind termination shock and heliopause, and make a significant penetration into interstellar space, thereby providing the first *in situ* measurements of the particles and fields in nearby regions of the Galaxy. This probe would be targeted to travel as fast as possible in the direction of the nose of the heliosphere, carrying a complement of state-of-the-art particles and fields instruments to an eventual distance of at least several hundred AU. Such a mission was recommended by both the Solar and Space Physics and the Astronomy and Astrophysics panels of the 1988 study entitled *Space Science in the Twenty-First Century.*

The particles and fields of the local interstellar medium are excluded from the heliosphere by the solar wind, thereby shielding the inner heliosphere from any direct knowledge of the composition, spectrum, and energy density of energetic particles in interstellar space below several hundred MeV/

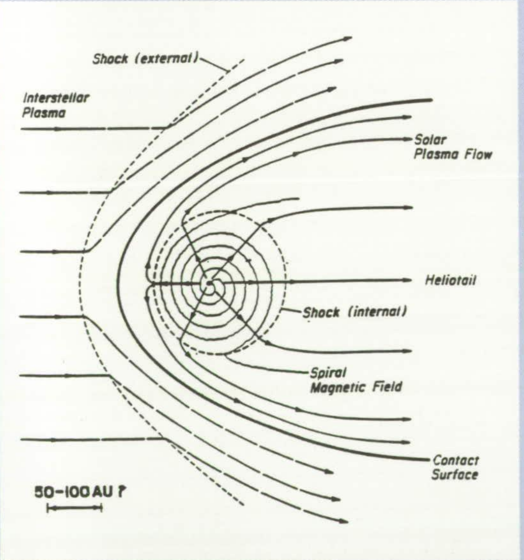

Figure 2.5–4. Large-scale structure of the heliosphere

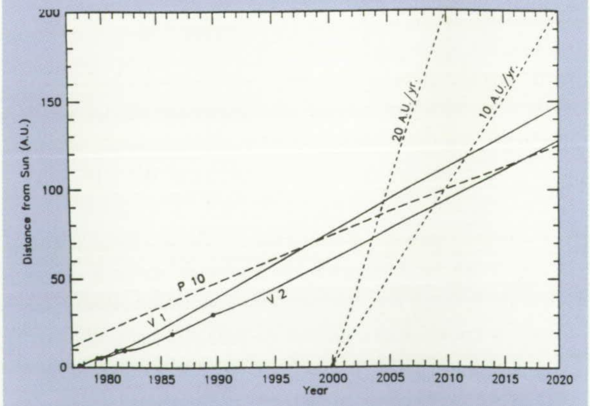

Figure 2.5–5. The radial distances of Pioneer 10 and the Voyagers are shown as a function of time along with two examples of Interstellar Probe trajectories. Pioneer 10 is expected to stop operating sometime in the 1990s; the Voyagers may last to ~2015.

nucleon. To observe interstellar plasma and interstellar cosmic rays with energies less than ~300 MeV/nucleon, one must get outside the heliopause.

Present estimates place the solar wind termination shock at ~60 to 120 AU, with the heliopause somewhat further beyond (see Fig. 2.5–4). One or more of the Pioneer or Voyager spacecraft may well cross the termination shock within their lifetimes, but it is much less likely that the heliopause is within reach of Voyager's potential range of ~130 AU, to be reached in the year 2015. Although these spacecraft may locate the termination shock and return unique exploratory data, detailed studies will require modern instrumentation designed to comprehensively observe the boundary of the heliosphere and the interstellar medium itself. As a reasonable goal, an Interstellar Probe could be accelerated to a velocity of ~10 AU/year or more, thereby overtaking the Voyagers within a few years, reaching a distance of 200 AU within ~20 years, and then possibly continuing beyond in an extended mission (see Fig. 2.5–5).

To accomplish this, we suggest that the Interstellar Probe take advantage of Solar Probe technology, as illustrated in Fig. 2.5–6. Following a Jupiter gravity assist, the Interstellar Probe would do a solar swingby to ~4 solar radii where a rocket burn at perihelion would result in the required escape velocity of 10–20 AU/yr. There are clearly a number of trade-offs to be studied on how to optimize such a maneuver, but it appears that the Solar Probe and Interstellar Probe may share a number of common issues and technologies.

The instrumentation for such a mission should be a combination of standard particles and fields sensors, along with a complement of high-resolution spectrometers to measure the elemental, isotopic, and charge-state composition of the plasma and energetic particles over a broad energy range from thermal energies to several hundred MeV/nucleon. Such state-of-the-art spectrometers are required to take full advantage of this unique opportunity. For studies of the structure of the outer heliosphere, it would be especially helpful to have coordinated observations from Interstellar Probe and Voyager.

An Interstellar Probe to the nearby interstellar medium could make a wide range of exploratory studies, including the following:

- Exploration of the nature of the solar wind termination shock and the heliopause.
- *In-situ* study of the acceleration of the "anomalous" cosmic rays and other species at the termination shock.
- Measurement of the unmodulated interstellar spectra of galactic cosmic rays, including their contribution to the ionization, heating, and energy density of the interstellar medium.
- *In-situ* measurement of the interstellar magnetic field, and of the temperature, density, and ionization states of the interstellar plasma.

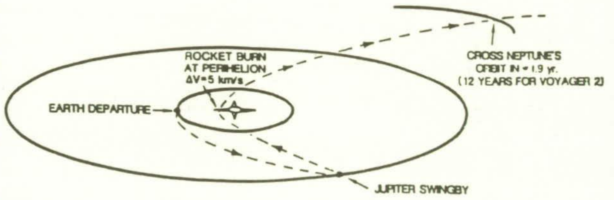

Figure 2.5–6. Illustration of how an Interstellar Probe could use a Jupiter gravity assist and a solar swingby to escape the solar system

- Measurements of the elemental and isotopic composition of the interstellar gas: essential quantities for studying galactic evolution and the origin of the solar system.
- Measurement of the elemental and isotopic composition of anomalous cosmic rays and low-energy interstellar cosmic rays.
- Direct measurement of interstellar cosmic-ray electrons and positrons that contribute to galactic gamma-ray production.
- Search for a possible heliospheric bow shock and associated particle acceleration.

In view of the fundamental importance of such measurements to a wide range of studies that include space plasma physics, nucleosynthesis, stellar and galactic evolution, and cosmology, it is important that NASA give serious consideration to this truly exploratory mission.

2.5.2 Moderate Missions

2.5.2.1 Polar Heliosphere Probe

The Polar Heliosphere Probe will be the first exploratory venture to the distant polar heliosphere. The mission will explore the region from 1 AU to ~20 AU above the ecliptic in the Sun's polar region. With the objective of understanding the global structure and dynamics of the heliosphere, the entry and exit of particles in the heliosphere, and basic plasma processes, the Polar Heliosphere Probe will make *in-situ* measurements of the electromagnetic fields, plasma, and energetic particle populations.

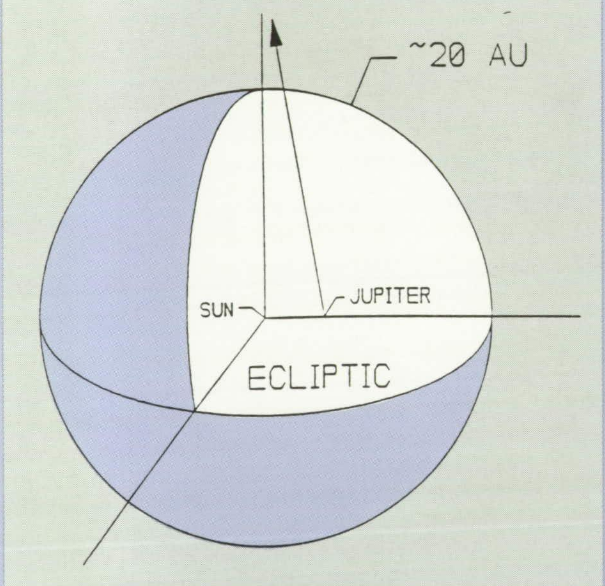

Figure 2.5–7. Polar Heliosphere Probe trajectory following Jupiter swingby

The distant polar heliosphere differs fundamentally from the distant heliosphere near the ecliptic because the effects of solar rotation are negligible in the polar regions while they are maximal near the ecliptic. A magnetic field line wraps around the Sun many times in a tight spiral in the ecliptic, whereas the magnetic field lines may be radial over the poles. Thus, in the polar regions, galactic cosmic rays may have direct access through the heliosphere, while solar energetic particles, the solar wind, and the solar wind heat flux have a direct exit path. Currently, there is disagreement over the structure and strength of the magnetic field in the polar regions. Corotating interaction regions and merged, corotating interaction regions, which are so important near the ecliptic, will be absent in the polar heliosphere.

The specific scientific objectives of the Polar Heliosphere Probe are as follows:

- Determine the dynamical characteristics of the plasma and magnetic field in the polar heliosphere.
- Determine the distribution and modulation of cosmic rays.
- Study the origin and propagation of the anomalous cosmic ray component.
- Investigate the propagation of solar energetic particles.
- Determine the distribution of interstellar neutral particles and pickup ions.
- Investigate the nature and origins of plasma waves.

Thus the Polar Heliosphere Probe will address several of the primary objectives of the Heliospheric Physics Program, including the large-scale structure and evolution of the solar wind, the acceleration and transport of energetic particles, the interaction of the solar wind with the interstellar medium, and fundamental plasma processes. The baseline payload should consist of a magnetometer, a solar wind analyzer, a suprathermal ions and electrons detector, solar energetic particle and galactic cosmic ray detectors, a low-energy ion composition instrument, a plasma wave experiment, and a UV photometer.

The suggested approach to achieving the required trajectory, illustrated in Fig. 2.5–7, is to use a gravity-assist from Jupiter to place the spacecraft in a trajectory which is nearly normal to the ecliptic so that it moves through the polar region of the heliosphere and toward the interstellar medium. This is a moderate class mission consisting of a spinning spacecraft similar to Pioneer 10/11. No technology development is required for the propulsion, the spacecraft, or the instruments.

2.5.2.2 An Ultraheavy Element Spectrometer for Cosmic Ray Nuclei with $30 \leq Z \leq 100$

Measurements of the abundances of cosmic rays beyond the iron peak are of special interest because of the information these "ultraheavy" (UH) nuclei carry about the neutron-capture nucleosynthesis processes that have forged the upper two-thirds of the periodic table, and because they include a number of radioactive species that can be used as "clocks," particularly among the "actinide" group of elements that includes Th, U, and possibly transuranic nuclei. Fig. 2.5–8 shows the expected relative abundance of these nuclei as a function of time after rapid neutron capture nucleosynthesis, such as is believed to occur in supernovae.

The relative abundances of the elements from H to U in cosmic rays are summarized in Fig. 2.5–9. Note the sudden drop in abundance that occurs above the "iron peak." For nuclei with $Z=30$ to $Z=60$ there are presently measurements of even-charged nuclei. Because of their rarity, elements with $Z>60$ have been measured only as element groups, and the combined HEAO-3 and Ariel-6 data identified only two nuclei in the Th-U region of the charge spectrum. Thus, it is clear that detectors with considerably larger collecting power are required. The Heavy Nucleus Collector (HNC) selected for Space Station Freedom will use passive track detectors with an area of 16 m^2 to measure UH nuclei with $Z>50$. A total of ~40 actinides (with a sizeable uncertainty) is expected for HNC in a four-year exposure.

The next step beyond HNC would be a detector with at least an order-of-magnitude increase in collecting power. Such a detector could provide accurate measurements of the clocks in the actinide region giving the age of the heaviest nuclei since nucleosynthesis. It could also provide a sensitive search for transuranic nuclei that would signify recent nucleosynthesis contributions to cosmic rays. This instrument should also be capable of providing fully resolved measurements of elements with $30 \leq Z \leq 82$ which will yield information on r- and s-process nucleosynthesis, and on the propagation history of these nuclei by studying the primarily "secondary" nuclei (those with $60 \leq Z \leq 75$, $41 \leq Z \leq 49$, and other odd-Z nuclei).

A large part of the required increase in collecting power can be achieved by placing this instrument in a high-inclination orbit, or outside the magnetosphere, possibly on a lunar base. There are two basic approaches, one utilizing electronic detectors and the other passive track detectors, which appear to be capable of achieving these high-resolution measurements. Passive track detectors require recovery for data analysis, and large electronic arrays may require assembly in orbit or possibly at a lunar base. Although further study is required to determine which approach is more easily implemented, it presently appears that a large array of electronic detector modules is the better approach for achieving the required collecting power, because of the recovery requirements for passive detectors. It is important that NASA study options for achieving the important objectives of this mission.

2.5.3 Small Missions

The Cosmic and Heliospheric panel believes strongly that there will be continuing requirements for small missions such as Explorers in the coming decades. Examples of such missions are given below.

2.5.3.1 Trans-Iron Solar and Galactic Isotope Explorer

The currently approved investigations of energetic heavy nuclei will explore in depth the nucleosynthesis of solar and galactic material for elements from hydrogen to nickel ($Z \leq 28$). The extension of isotopic composition studies to ultraheavy elements ($Z>30$) will make it possible to investigate the neutron-capture nucleosynthesis processes responsible for production of more than three-fourths of the stable nuclides. Galactic cosmic ray (GCR) measurements will provide the isotopic abundance of recently accelerated galactic

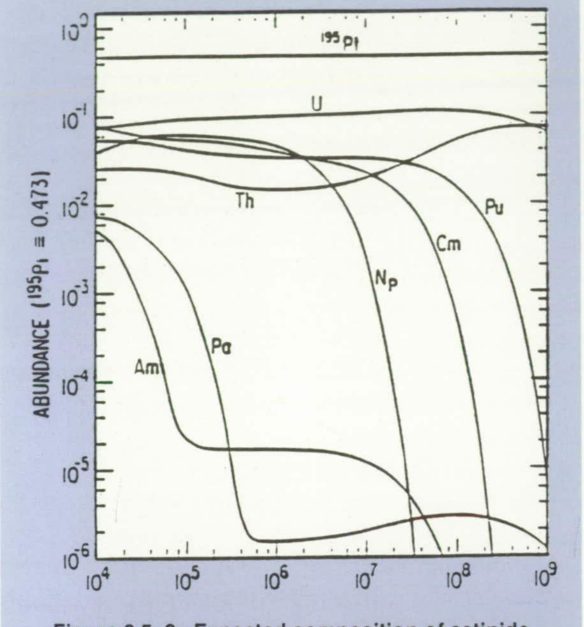

Figure 2.5–8. Expected composition of actinide nuclei as a function of time since r-process nucleosynthesis

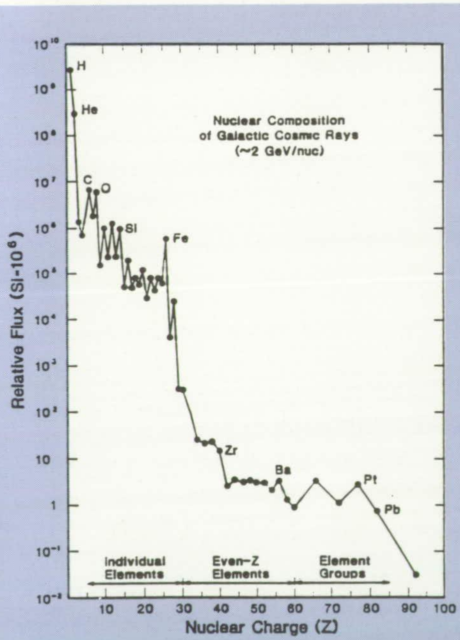

Figure 2.5–9. Nuclear composition of galactic cosmic rays

matter, while solar energetic particle (SEP) observations will give the solar system abundances at the time of formation of the solar system, 4.6x10^9 years ago, including volatile species (*e.g.*, rare gas nuclides) which are not well measured in either meteoritic or solar photospheric studies. ACE will provide definitive isotope measurements of nuclei up to Z=28, and exploratory studies extending to Z≈40, but the detailed study of isotopes with Z>30 will require new large-area instrumentation exposed outside the Earth's magnetosphere for a period of several years (see, *e.g.*, Fig. 2.5–8).

To address these objectives, we propose an Explorer-class mission dedicated to the measurement of the isotopic composition of ultraheavy elements in both solar energetic particles and galactic cosmic rays. Presently, the mass resolution needed for these measurements has been realized only for low-energy particles (<1 GeV/nucleon) which are prevented from reaching low-Earth orbit, except at high latitudes, by the geomagnetic field. To achieve the necessary exposure outside the magnetosphere, these measurements could be carried out in a circular or highly elliptical orbit with an apogee of >20 Earth radii. The use of a polar orbiting platform in low-Earth orbit (for which low-energy particles can be collected over ~30% of the orbit) is also possible but is less desirable since the time required to collect sufficient statistics is substantially increased.

The large-area sensor systems needed for ultraheavy isotope measurements can be realized as extensions of detectors now under development or planned for balloon experiments and for ACE. For galactic cosmic ray studies, options include measurements of dE/dx vs. total energy using ionization detectors (either solid-state or gas) and measurement of Cherenkov emission vs. range (or energy). For solar flare isotopes, time-of-flight in contrast with total-energy sensor systems should provide the needed resolution and statistics. Further study is required of the spacecraft requirements for accommodating large-area detector systems, and of the possible launch/spacecraft/orbit options for achieving the necessary exposure outside the magnetosphere.

2.5.3.2 Solar Wind Turbulence/Particle Acceleration and Transport Explorer

Hydromagnetic turbulence and energetic particle acceleration and transport are processes of fundamental importance to many areas of space physics and astrophysics. Because the scattering of energetic charged particles and cosmic rays is determined by the fluctuating magnetic field associated with the turbulence, they should be studied simultaneously on the same mission. The goals of the proposed Solar Wind Turbulence/Particle Acceleration and Transport Explorer mission would be the following:

- Measure the statistical properties (mean, variance, and two-point correlations) of the magnetic field vector, plasma density, and velocity vector to characterize the turbulence.
- Measure the particle distribution function (mean and anisotropic parts for protons, electrons, and alpha particles) from thermal energies up to 10 MeV.
- Study the acceleration of particles at shock waves which propagate past the spacecraft.

These observations must be carried out in the inner solar system (~1 AU) in a location free from the influence of any objects (Earth, Moon, *etc.*). Two or more identical spacecraft separated by variable distances of <0.1 AU are required. Because the relation between the turbulence parameters and particle acceleration and transport is complicated, this mission must incorporate theory as an integral part of the mission from beginning to end.

The mission discussed here addresses the goals of both the Plasma Turbulence Explorer previously studied by NASA in 1980, and the Energetic-Particle Acceleration Explorer discussed in *A Strategy for the Explorer Program for Solar and Space Physics.* For the small cost of adding appropriate instrumentation to the spacecraft required for the Plasma Turbulence Explorer, it is possible to obtain a much more powerful data set than could be expected from flying these two missions individually.

2.5.3.3 A Matter/Antimatter Explorer (MAX)

In recent years a great deal of attention has been focused on understanding the nature of the so-called "dark matter" that constitutes the non-luminous dynamical mass of the galaxies, galactic clusters, and perhaps the entire universe. Compelling arguments suggest that this matter is non-baryonic in nature and may constitute up to 98% of the total mass of the universe. Serious attempts to explain early balloon observations of large fluxes of low energy (<1 GeV) antiprotons have focused on supersymmetric (SUSY) particle models. Produced in the Big Bang, these particles would decay to the lightest SUSY particle which may now populate our galactic halo in great abundance and annihilate with one another to produce low-energy antiprotons.

Recent balloon experiments which have employed sophisticated particle identification techniques have set very low limits on the antiproton flux, prompting theorists to devise more realistic models to account for the new results. Fig. 2.5–10 illustrates presently available measurements of the antiproton to proton ratio in cosmic rays.

It now appears that a definitive experiment will require an exposure several orders of magnitude

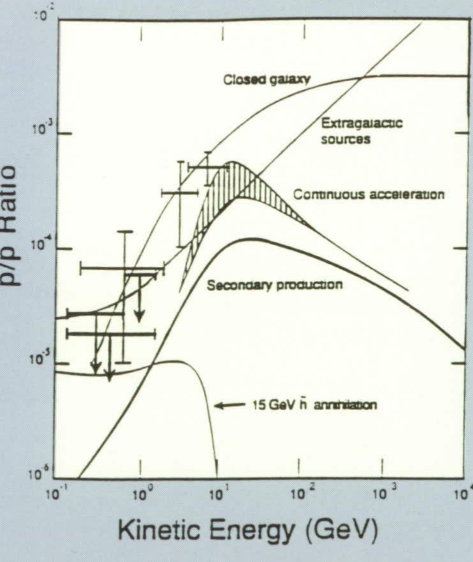

Figure 2.5–10: Measurements of the antiproton-to-proton ratio are compared to theoretical predictions.

greater than can be achieved on balloons. A Matter/Antimatter Explorer (MAX) would utilize technology already developed on balloons to achieve the required increase in sensitivity by placing an instrument outside the Earth's magnetosphere for five years. MAX would employ a precision drift tube array in conjunction with a high-field permanent magnet to measure magnetic rigidity in combination with high-resolution time-of-flight scintillators to measure velocity and charge. Particle mass can be obtained by combining these measurements, thus providing a powerful means of identifying potential backgrounds from electrons and locally produced mesons having negative charge. The goal of MAX would be to achieve a sensitivity of one part in 10^8 for the antiproton to proton ratio. At this level the signature of SUSY particle annihilation would begin to reveal itself against a rapidly rising spectrum of secondary antiprotons produced by the interaction of high-energy cosmic ray protons with the interstellar medium.

MAX would complement observations of antiprotons made at high energies on Astromag which cannot extend measurements below 2 GeV because of the geomagnetic cutoff in the Space Station Freedom orbit. Secondary objectives of MAX would include a sensitive search for primordial antihelium, and the measurement of positrons, electrons, and light isotopes in the energy region most sensitive to solar modulation.

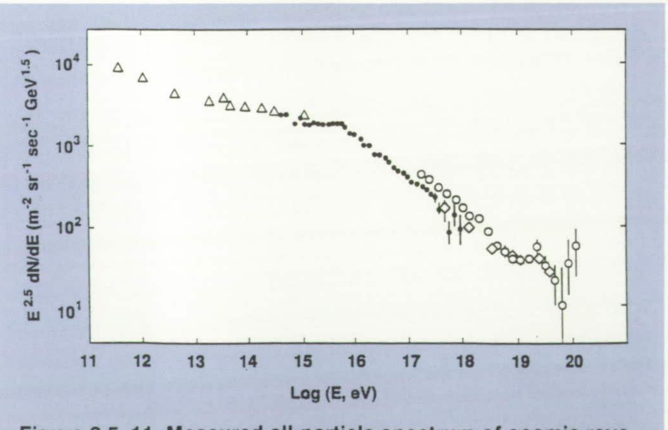

Figure 2.5–11. Measured all-particle spectrum of cosmic rays ($xE^{2.5}$) illustrating the "knee" in the spectrum at ~10^{16} eV

2.5.4 Space Station

2.5.4.1 Second-Generation Astromag Experiments

Astromag is a superconducting magnetic spectrometer facility for particle astrophysics that has been selected as a Space Station Freedom attached payload. Earlier, the Cosmic Ray Program Working Group recommended the development and flight of a large, high-field magnet for the mass spectroscopy of high-energy cosmic rays. To this end, the Astromag project was extensively studied and then named as a Space Station Facility. The three first-generation experiments selected for the first use of Astromag are Wizard, LISA, and SCIN/MAGIC.

Following the completion of the experiments selected for the initial use of Astromag, there are a number of second-generation experiments requiring continued use of this facility. These include higher energy isotope experiments and an advanced antimatter instrument. The facility and its large-volume, high-field magnetic field may also be used for other investigations in other disciplines such as plasma physics.

2.5.5 The Space Exploration Initiative

2.5.5.1 A Lunar-Based Calorimeter

The spectrum and composition of cosmic rays at energies above 10^{15} eV/nucleus is an area of intense interest. There is a distinct change in slope, or "knee," in the all-particle energy spectrum near 10^{16} eV (see Fig. 2.5–11), suggesting that at high energies, nuclei may have a fundamentally different origin and composition than at low energies. Because of the low fluxes, however, direct measurements of nuclei with 10^{15} to 10^{17} eV are very difficult. Current balloon- and space-based experiments are too small to provide good statistics in this region; at present, the only information comes from indirect Earth-based measurements of extensive air showers.

There are suggestions of very interesting astrophysics and particle physics at these high energies. It is presently thought that acceleration of particles to $>10^{16}$ eV would require larger-scale shocks than are presently thought to be possible in the galactic disk and in discrete sources. Cosmic rays may also escape more efficiently from the galaxy at these energies. In addition, balloon observations have given indications of a nuclear-matter phase change in the interactions of very high-energy cosmic ray nuclei, and ground-based measurements have suggested that the ratio of hadronic to electromagnetic interactions of photons may be rapidly increasing at these energies.

In order to measure the primary spectrum and composition at 10^{16} eV with reasonable statistical precision, a collecting power of ~100 m^2sr and an exposure time of ~5 years will be required. Calorimetric methods are the only approach available to accurately measure both the total kinetic energy and the composition of nuclei with these energies. However, the corresponding weight of such a calorimeter, if designed for space flight, would be ~200 tons. Since this is presumably too heavy to be flown in orbit, a lunar-based detector, fabricated primarily from lunar material, probably offers the only practical means for building the experiment. The bulk of the calorimeter material would be compressed lunar regolith; only relatively light plastic scintillators or drift tubes, electronics, and support structure would be carried up from Earth. Elements from protons through iron would be measured with good charge and energy resolution at energies up to and above the "knee" in the all-particle spectrum.

2.5.5.2 Cosmic Rays and Manned Space Missions

Manned exploration missions will require a better understanding of the effects of human exposure to galactic cosmic ray and solar energetic-particle events. This will involve questions of long-term exposures to galactic cosmic rays (for example, on a long-duration Mars mission or an extended tour of duty at a lunar base) and, probably more importantly, transient exposure to the particle fluxes from intense solar flares. Determination of realistic shielding requirements for extended missions demands accurate fluxes, spectra, and composition. It also depends on an accurate assessment of the attenuation of cosmic ray fluxes by shielding. Real-time and near-real-time measurements of these particles will be provided during the coming decade by CRRES, Wind, ACE, and the network of spacecraft to comprise the Global Heliosphere Initiative. Improved and updated measurements, together with an expansion of the existing program of interstellar and interplanetary propagation studies, will make possible significantly improved predictions of baseline flux levels, long-term variations over the solar cycle, and short-term variations due to heliospheric fluctuations. For early warning of flare events, a network of monitoring spacecraft will probably be necessary, including spacecraft able to observe directly flares on the far side of the Sun and capable of transmitting prompt warnings to astronauts on the moon, on Mars, or in transit.

If an accurate assessment of shielding efficiency requires improved knowledge of nuclear interaction cross-sections (particularly those for neutron production and those below a few hundred MeV/nucleon where present data are sparse), then the current program to measure the relevant heavy ion cross-sections at the Bevalac must be extended. Particle detection techniques developed in the cosmic ray discipline may also contribute to improving required dosimetry measurements and instrumentation.

2.5.5.3 Solar-Flare Warning and Monitoring

A critical element of the Space Exploration Initiative will be the safety of the astronauts. This may require multi-spacecraft missions specifically designed to monitor the radiation environment known to be present within the inner heliosphere, and to offer some predictive capability for the onset and magnitude of solar energetic-particle events. The primary goal of such missions would be to support SEI, and they should be fully funded by that program.

The need to monitor the transient solar ejecta expected throughout a single Mars mission requires that all longitudes be observable. This leads to a four spacecraft mission, spaced at 90° intervals around the Sun. Fewer spacecraft would be necessary for a lunar mission.

The instrument package for such missions should include energetic particle detectors, covering energies from a few MeV/nucleon up to ~1 GeV/nucleon and elements from H up through Fe; solar wind and magnetic field detectors for determining the impact of propagation conditions on radiation levels; and solar X-ray and coronograph instruments for determining the conditions that lead to the release of radiation from the Sun.

2.5.6 Collaborative Missions with Other Disciplines

2.5.6.1 Mercury Orbiter

The Mercury Orbiter (MeO) mission offers a unique opportunity for obtaining solar energetic-particle (SEP) observations that can answer long-standing, fundamental questions about the flare process and the solar corona itself. An MeO mission with complete solar energetic-particle instrumentation could make fundamental observations on the following two major types of solar flares: (1) large, solar energetic-particle events (LSEP), and (2) small, impulsive events which show enrichments in ^{3}He, heavy ions, electrons, and (sometimes) gamma rays. Since the energetic particles are scattered many times on their path to 1 AU, observations at Earth orbit cannot separate the effects of particle injections extended in time from particle scattering and storage near the Sun. MeO, located at 80 solar radii, would immediately resolve this fundamental question since the shocks would come near to, or even pass by, the spacecraft in the main acceleration phase. Small, impulsive flares which are often rich in gamma-rays, ^{3}He, and Fe, have very fast flux rise times at 0.4 AU, allowing the time of the particle injection at the Sun to be determined to within 1–2 minutes. This knowledge is critical for acceleration studies. MeO could also make unambiguous determinations of abundances and charge states from the flares which cannot be obtained at Earth orbit because of dilution with other classes of particles. The low frequency of LSEP events makes it likely that no such event would occur during the period when Solar Probe was closer than 0.4 AU to the Sun. MeO, which will spend years close to the Sun, is assured of observing many large and impulsive solar particle events. In addition, solar energetic-particle studies are important on MeO for comparison with the solar flare gamma-ray and neutron measurements that are planned.

2.5.6.2 Solar Polar Orbiter

The high-latitude heliosphere is expected to differ significantly from the equatorial heliosphere. The first observations of the solar wind, magnetic field, and energetic particles at polar latitudes will come from Ulysses, which is essentially a "solar polar flyby." The solar community has also discussed a Solar Polar Orbiter mission which would have as a principal objective remote sensing of the Sun from a polar line-of-sight. The orbit also provides an opportunity for an in-depth extended fields-and-particles observing program for the polar heliosphere in the vicinity of 1 AU, thus serving as a logical follow-on to Ulysses. Appropriate fields-and-particles instruments should therefore be included on this mission.

2.5.6.3 Coronal Imager

The solar corona is the source of the solar wind, which expands supersonically to form the heliosphere. Thus, it is the evolution of the solar corona on moderate to large spatial scales and on time scales of days to years that controls the evolution of the global structure of the heliosphere. Global, synoptic observations of the structure of the coronal density, velocity, and temperature will thus lay a basis for understanding the evolving three-dimensional heliospheric structure. Such global, synoptic coronal observations are currently available only through remote sensing using spectroscopic imaging in EUV, XUV, and white light. These observations can be readily obtained by a Scout-class Small Explorer launched into low-Earth orbit and operating over a number of years. A mission of this type will also improve our understanding of the transport and deposition of momentum and energy in the solar wind acceleration region and of the complex exchange of mass and energy between this region and the underlying transition region and chromosphere.

2.5.6.4 A Small Explorer for Solar Flare Gamma-Ray and Neutron Measurements in Conjunction with Energetic Particle Studies

The understanding of particle acceleration and transport is one of the major objectives of cosmic and heliospheric physics research. Details of acceleration processes at identifiable astrophysical sites other than the solar system can be obtained by photon observations. The solar system is unique in that it offers the only opportunity to simultaneously observe both energetic charged particle and neutral radiations (gamma-rays and neutrons) from a known source. Recent X-ray and gamma-ray results from SMM show that ions and relativistic electrons are routinely accelerated in impulsive solar flares. Correlated observations of gamma-ray line and continuum emission of the source, and of escaping energetic particles and neutrons from the source, would provide unique information about acceleration, fractionation, escape, and transport processes for energetic particles in both the solar atmosphere and the interplanetary medium. This is a necessary and important step toward better understanding of these processes in other astrophysical environments.

The necessary gamma ray and neutron measurements can be obtained by a Small Explorer-class experiment consisting of an array of four germanium detectors sensitive to gamma-ray line and continuum emission in the 25 keV to 10 MeV region, together with a BGO calorimeter to extend the energy range to 200 MeV. A ~600 km circular equatorial orbit would give longer detector life and high sensitivity, ~2 to 3 times superior to the GRS experiment on SMM. The instrument, with a maximum weight of ~90 kg, can be launched by a Scout-class vehicle. The correlated observational objectives require that the launch be in the 1997–1998 time frame when ACE, OSL, and possibly Wind are operating. With two Stirling-cycle coolers and no other expendables, the experiment could remain operational for up to a decade over the entire Cycle 23.

Note that these correlated observations, as well as others, could also be obtained by the High Energy Solar Physics (HESP) experiment, proposed by the Solar Physics panel, assuming that HESP is operational at the same time as ACE and OSL.

2.5.7 Measurements of Opportunity

2.5.7.1 Instruments on the Mir Space Station

Currently under discussion are joint US-Soviet flights of two cosmic ray experiments on the Soviet space station Mir that could take place within the next few years.

CRN, the Cosmic Ray Nuclei detector, was flown several years ago on Space Shuttle Challenger, where it successfully demonstrated its capabilities for determining the charge and energy spectra of very high-energy cosmic ray nuclei, albeit with limited statistics due to an exposure time of only a few days. CRN should be considered for a second, much longer deployment in space. A one year deployment would allow CRN's transition radiation detectors to realize their potential for determining the high-energy cosmic ray composition of nuclei from boron to iron up to energies of ~10 TeV/nucleon (corresponding to an energy of nearly 10^{15} eV for Fe nuclei).

Also under discussion for flight on Mir is a small version (1 to 3 m^2) of the glass detectors to be used in the Heavy Nucleus Collector (HNC) selected for flight on Freedom. For a two-year exposure in Mir's 51.6 degree inclination orbit, the yield of $Z>60$ ultraheavy nuclei for a 2 m^2 detector would be ~15% of that expected for a 5-year exposure of the full HNC detector in the 28.5 degree orbit planned for Freedom.

2.5.7.2 Solar Wind Sample Return

To meet the objectives of measuring the detailed elemental and isotopic composition of the solar wind, it is necessary to analyze minor or trace species as well as major components. One way to achieve the required sensitivity is to obtain a large product of (geometry factor *x* integration time) with solar-wind sample-return experiments. The strategy is to take advantage of planetary sample return missions (*e.g.*, SOCCER, Rosetta, and Mars sample returns) to expose meter-sized solar wind collectors during the cruise phases of these missions and to use sophisticated laboratory techniques to analyze the samples after return to Earth. Such measurements would be complementary to the real-time composition measurements made on other missions.

2.5.7.3 Small Instruments on Spacecraft Leaving 1 AU

Studies of the three-dimensional structure of the heliosphere and its 22-year temporal variations, as well as studies of particle propagation and transport processes, require an array of properly instrumented spacecraft continuously observing particles and fields at many different locations in the heliosphere. This can be accomplished by augmenting dedicated heliospheric missions with measurements made during the interplanetary cruise phases of planetary missions, or other missions leaving 1 AU. This proven, cost-effective approach achieves important objectives at minimal incremental costs to the mission. For planetary missions that are already launched or designed (*e.g.*, Galileo and CRAF), it is important to ensure adequate data return and funding for the analysis of interplanetary cruise data. It is also important to ensure that later planetary missions such as Cassini, Mars missions, and comet nucleus sample return (Rosetta) include the fields and particles instrumentation required for heliospheric measurements.

2.6 Other Program Elements

2.6.1 Infrastructure and Resources

The Cosmic and Heliospheric program, like all programs of space exploration, is focused towards a small number of missions, such as ACE, Astromag, or future Solar and Interstellar Probes. A significant fraction of the resources available at NASA must be dedicated to the support of such missions. However, each mission takes many years from inception to launch. These time scales present a serious problem for the participation of the scientific community, in particular at universities. Although a first-rate program requires contributions from innovative young scientists and students, such individuals often find themselves in a critical "publish or perish" phase of their career and may turn towards other fields unless a scientific infrastructure exists that permits creative work on a time scale shorter than that of the longer-term space missions. This work might include data analysis from previous space ventures, but it must also permit experimental activities that are at the cutting edge of technology.

It is therefore essential for the future of the field that opportunities and resources be available for the training of young scientists, for innovative detector development in the laboratory, for Guest Investigator programs on flight missions, for short turn-around observations in suborbital missions such as balloons, and for quick access to space as provided by Small Explorers or payloads attached to the Space Station.

A Space Physics Instrument Definition and Development Program (SPIDDP) is urgently needed to apply Advanced Technology Development resources to long-range development of detector techniques and instrument concepts. Only with such a long-range program will it be possible to provide the U.S. with the required up-to-date technological base needed to support future missions and to continue our leadership in space physics.

2.6.2 Theory

The scientific return of missions may be significantly enhanced by integrating data from two or more experiments together with theory. It is recommended that interdisciplinary and theory studies be an integral and accepted part of space science missions. Interdisciplinary science would also be enhanced by Guest Investigator programs.

From time to time, an important scientific problem becomes "ripe" in the sense that the accumulation of experimental data and theoretical ideas bring it to a threshold for major progress such as deciding between two competing theories. At such times it can be extremely valuable to conduct a series of several iterative workshops in which both experimenters (possibly from a variety of missions) and theorists participate. The sessions of each workshop need to be separated enough in time for the ideas of the earlier session to be developed and expanded to the point that a new session can catalyze novel thinking. Successful examples of this process are the Boulder workshops on coronal holes (1974) and on cosmic-ray modulation (1984–1985).

Particle astrophysics is a particular example of an area which has generated intense interest in the last decade among particle physicists, cosmologists, solar physicists, astrophysicists, and cosmic ray researchers. Ground-based measurements of solar neutrinos and searches for WIMP's and monopoles are connected to processes in the solar interior and the helioseismology measurements on SOHO; antiparticle searches such as those proposed for Astromag and MAX give information on cosmology and galaxy dynamics; and neutrinos and high-energy gamma rays studied by detectors on the Earth, on Astromag, and possibly on a lunar base will shed light on high-energy acceleration processes in discrete sources. Theoretical space science input into these frontier areas will be extremely important.

2.6.3 Coordinated Outer Heliospheric Observations (COHO)

During the 1990's an impressive array of spacecraft instrumented for cosmic ray investigations and related studies of heliospheric and solar phenomena will be in place. Pioneers 10&11 and Voyagers 1&2 will be exploring the regions beyond 50 AU from the Sun, with Pioneer 10 heading down the heliospheric tail and the others heading towards the solar apex, returning data from the mid-latitude regions above and below the ecliptic plane. In the inner heliosphere, the IMP-8 and ICE spacecraft will be monitoring the solar wind, cosmic ray, and solar particle intensity near 1 AU, close to the solar input that drives the dynamics of the heliosphere. These veteran spacecraft will soon be joined by others, including Ulysses, as it embarks on a solar latitude survey of the spectra and composition of a variety of particle species.

This network of spacecraft represents a uniquely powerful configuration for studying the large-scale structure and dynamical processes in the heliosphere and for locating and characterizing the heliospheric boundary. The opportunities which this network provides for simultaneous measurements at a variety of heliospheric radii and latitudes makes it possible to distinguish spatial and temporal variations in the observations.

The Coordinated Outer Heliospheric Observation program has as its objective coordinated global exploration of the heliosphere, including global solar wind structure and dynamics, interaction of solar wind and interstellar medium, global heliospheric behavior of galactic cosmic rays, solar energetic particles, and the anomalous component.

The program would appoint a NASA Program Scientist; and a Heliospheric Science Working Group, composed of relevant Project Scientists, who would serve as an executive committee to ensure coordination between projects, and establish scientific priorities with respect to data acquisition. To deal with the limited resource of DSN tracking, the program would have a representative to the DSN Joint Users Resource Allocation Planning System at JPL. The program would also implement a Guest Investigator program, promote workshops, and implement a common data pool available to all participants by remote access.

2.6.4 Tracking of Interplanetary Spacecraft

The Deep Space Network (DSN) is responsible for tracking a continuously growing armada of spacecraft, including a number of missions such as Pioneer and Voyager that are essential to the ongoing Cosmic and Heliospheric program. DSN coverage is presently woefully inadequate in many cases, and this tracking shortfall is expected to increase in the next few years as new spacecraft are launched, thereby seriously compromising the scientific integrity of a number of missions. It is therefore imperative that NASA provide for effective communication of OSSA tracking requirements, investigate possibilities for international cooperation in spacecraft tracking, and consider upgrading and adding to the DSN in order to maximize the science return from current and future missions.

2.6.5 The Balloon Program

This program remains an indispensable component of the cosmic ray program that provides significant scientific results in particle astrophysics in a very cost-effective manner. In addition, it supports the development of new experimental techniques and the test and verification of space instrumentation. Balloon-borne investigations play an irreplaceable role in the training and education of students and young scientists. They provide hands-on experience and the opportunity for quick responses to scientific questions. Their low cost, as compared to space vehicles, permits the taking of some risks that are inherent in truly innovative approaches. The following are examples of activities for which there is no practical alternative to the use of balloons:

- *Science goals.* As the load-carrying capability of balloons is quite substantial (~2–3 tons), and flight durations of days or perhaps even weeks are possible, a number of significant investigations can be pursued, including measurements of isotope abundances to ~1 GeV/nucleon; observations of electrons, positrons, and antiprotons over a fairly wide energy region; and measurements of the energy spectra of the more abundant particle species to ~100 GeV/nucleon.
- *Verification of space instrumentation.* Tests of the performance of magnet spectrometer systems and the resolution of trajectory measuring devices and time-of-flight systems within a near-space environment.
- *Experimental techniques.* Development of advanced particle detectors, such as aerogel and ring-imaging Cherenkov counters, scintillating fiber detectors, transition radiation detectors, precision drift tube arrays, and high-pressure gas ionization chambers. In some cases, such techniques are adapted from applications in the laboratory and at accelerators; in others, they are specifically developed for particle astrophysics applications.

An adequate level of support for the balloon program and enhanced funding for state-of-the-art detector developments are essential for the future of the discipline. At present, this activity is underfunded by a factor of at least two based on the needs for carrying out the highly rated science investigations on an appropriate time scale. A high science return can be expected from augmentations in this program.

2.6.6 Balloon Magnet Spectrometer Science Initiative

The stretch-out in the Space Station Freedom assembly will delay the launch of the Astromag facility. Already the schedule calls for a slip from 1997 to at least 1999, and further slips may be required as a result of the slow start in funding of attached payloads. A new Balloon Magnet Science Initiative is imperative to mitigate the impact of these delays on the Astromag scientific community. This initiative would support the development of new balloon payloads to take advantage of current ballooning capabilities. It would conduct high-priority investigations complementary to Astromag, while developing the basic infrastructure for supporting the timely development of Astromag techniques and instrumentation. Specific observations would include the abundance and energy spectra of light isotopes, antiprotons, positrons, and electrons. These measurements will complement those expected from Astromag data at high energies.

2.6.7 Accelerator-Based Studies

The Bevalac heavy ion accelerator at Lawrence Berkeley Laboratories has become an essential support facility for the field, providing the systematic and detailed measurements of nuclear cross-sections which are essential for the scientific interpretation of observed cosmic ray abundances and for the Space Exploration Initiative, and providing an essential facility to test and calibrate new instrumentation. The anticipated shutdown of the Bevalac in 1994–1995 will represent a serious loss to the field, and it is not clear how it will be replaced. The only comparable facility is the GSI (Darmstadt)-SIS facility, expected to come on-line in 1990. Whether NASA programs can obtain running time on this nuclear physics facility is unknown. It is therefore important that NASA work with the relevant agencies and governments to ensure that sufficient access to appropriate accelerator beams is available for instrument calibrations and cross-section measurements in the future.

3.0 Report of the Ionosphere-Thermosphere-Mesosphere Panel

N92-25323

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3.1 Summary

This report summarizes the deliberations of the Ionosphere-Thermosphere-Mesosphere Panel (ITMP) during Workshop 1 of the Strategy-Implementation Study (SIS) for NASA's Space Physics Division (SPD), held in Baltimore on 22–26 January 1990. The report presents the thematic scientific objectives and mission concepts that emerged from the Panel's discussions at the workshop itself and during two prior open meetings. The scientific objectives and, to some extent, the mission concepts were formulated in the light of the recommendations of the existing national strategy documents of the National Academy of Sciences and the specific goals defined in the *OSSA Strategic Plan of 1989.*

The report presents a considered, forward-looking program of research which focuses on the ionosphere-thermosphere-mesosphere (ITM) region as one of the least-studied yet most complex coupled domains within the near-Earth "geospace" environment. The approach addresses the need for a comprehensive experimental investigation of the physical, chemical, dynamic, radiative, and energetic processes that couple the ITM system both within itself and with the heliosphere and magnetosphere above and the stratosphere below. The mission concepts presented here build on the considerable successes of previous NASA missions that have delineated aspects of the ITM system with sufficient clarity to allow for the formulation of a set of definitive, critical, and substantive scientific questions for the future. These scientific questions relate to the temporal and spatial responses of the global and coupled ITM system to highly variable solar-terrestrial controls. They can be addressed aggressively over the next 15 years with a spacecraft program which combines existing and new technology.

The ITM community is poised to carry out the proposed ambitious program of specific missions. The community has the necessary previous experience with space platform investigations and has at hand a set of sophisticated numerical codes for various component parts of the ITM system that can be further developed and merged to provide the needed theoretical underpinnings for a comprehensive effort. The information yielded by the missions described in this document will provide a giant step forward in understanding the ITM system itself as well as its role in the transfer of energy, momentum, and mass within the solar-terrestrial environment. It will also open the possibility for the development of a predictive capability for changes in the ITM system due to natural and man-made controls.

This report summarizes the scientific rationale for the program elements, starting with the definition of an overarching scientific theme and subthemes, and then developing specific scientific and mission-related objectives. Five new-start missions are described in further detail, comprising one major and four moderate missions. The major mission, called the ITM Coupler (ITMC), is the centerpiece of the program and, as such, carries the highest priority. The four moderate missions are complementary to the ITMC and are responsive to a set of distinct scientific objectives. The Panel, however, also recognized the important need for smaller (SMEX and BEX) missions, and listed a set of specific mission candidates without prioritization. In all cases, the mission objectives are cast in the spirit of the overarching theme of the ITM discipline, and the instrument complement and orbital requirements are designed to answer specific scientific questions.

3.2 Introduction

This report describes the accomplishments and present status of the ITM discipline and presents the science objectives and mission concepts that have emerged from the Panel's discussions.

The science themes and mission concepts presented here are to be considered as *preliminary* findings of the ITM Panel; they will be modified and refined as appropriate during the next several months. The intention of this report, therefore, is to provide a *succinct interim summary* of a suggested ITMP strategic plan. As such, it will not go deeply into mission-implementation details.

Section 3.3 discusses the role of components of the ITM region within the solar-planetary system as a whole, and summarizes the accomplishments of the discipline. Section 3.4 presents the overarching scientific theme and sub-themes (or *foci)* as well as the motivation for the proposed program, including a discussion of societal benefits and connections to other disciplines. Section 3.4.4 presents the principal scientific objectives that are amenable to investigation within the defined *foci*. Section A.2 presents a sequence of mission concepts in priority order. These mission concepts, together with the relevant correlative and complementary support programs, are discussed individually in the light of overall SPD scientific objectives and ITM themes. The family of mission concepts includes major, moderate, and small missions. Section A.2.7 presents a short discussion of additional infrastructural requirements for theory, and the suborbital and ground-based complementary efforts.

3.3 The ITM and Its Role in Solar-Planetary Systems

3.3.1 Definitions and Overview of Objectives

The ITM domain is the region of the near-Earth space environment that includes neutral- and charged-particle populations in the altitude range from about 50 to 4000 km. For the purposes of this document, the "ionosphere" is roughly defined as the plasma domain that extends over the altitude region from 95 to 1000 km, while the "thermosphere" includes the neutral particles in the same altitude region. More traditional definitions of the ionosphere extend the lower boundary down to about 50 to 60 km, to include regions where positive and negative cluster ions play important roles and where collisions dominate the medium. At higher altitudes and mid-to-low latitudes, the ionosphere might also be considered to include the cold plasma of the plasmasphere, while at high latitudes, the definition might be extended to include the polar wind out to distances of several thousand kilometers. At the base of the ionosphere-thermosphere system is the mesosphere, in which a mixture of neutral atmospheric gases, free electrons, and ions of positive and negative charge all interact in a turbulent and unstable medium. The ITM system components are interactively coupled across their boundaries, reacting to electrical, collisional, and chemical controls in response to solar, heliospheric, and magnetospheric inputs from above, and tides, winds, and atmospheric waves from below.

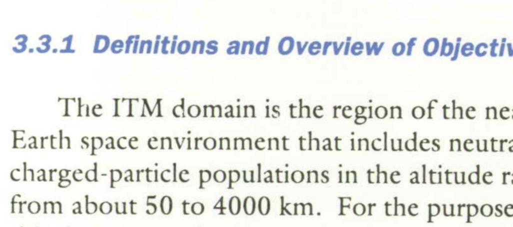

Figure 3.3-1. The solar-terrestrial interaction

The overall objective in the study of this geospace domain is the development of a self-consistent theoretical and empirical understanding and description of the ITM as a single, electrodynamic, chemically-active, and kinetically-reactive fluid. The understanding must be global, cover the full spectrum of solar-terrestrial conditions, deal with all internal and external coupling mechanisms, and encompass quiescent and dynamic conditions carried to the limit of highly irregular and unstable modes.

The ITM has a uniquely important role in the solar-terrestrial system, for it is the geospace domain that provides the interface between interplanetary and lower-atmospheric processes. It absorbs the bulk of the solar EUV/UV radiation and precipitating-particle energies, and supports, controls, and distributes currents and potentials ranging up to 10^6 amperes and 100's of kilovolts, respectively. It is the among the most complex, naturally-occurring, and weakly-ionized plasma domains accessible to *in-situ* diagnostics. It is a region with processes in the continuum, transitional, and free-molecular flow regimes. It involves positive and negative ion chemistry, global circulation, kinetics of neutral particle collisions, external and internal electric fields, and magnetically-induced anisotropies. It couples to the magnetosphere and heliosphere above, and the stratosphere below—responding to solar EUV/UV variations, coronal mass ejections, and high-speed streams from coronal holes on the one hand, and atmospheric tides, gravity waves, and lightning storms on the other. It is also believed by some to be the primary source for magnetospheric ions.

For these reasons, the ITM must be considered one of the most complex and significant domains for the study of solar-terrestrial relations. Its relative position in the transfer of energy and mass and the coupling and dynamics in the cascading of particles, fields, and waves in the solar-terrestrial environment is illustrated in the schematic diagram presented in Fig. 3.3–1.

3.3.2 Present Understanding

The topside ionosphere and thermosphere are the components of the system that are best understood, with respective levels of that understanding reflected schematically in Fig. 3.3–2. The topside ionosphere is known to be composed of atomic ions with the major constituents represented by O^+, N^+, He^+, and H^+ in distributions generally considered to reflect diffusive equilibrium. While qualitative information on total plasma densities and relative ion abundances is in hand, quantitative descriptions of horizontal and vertical profiles are not yet available because of the lack of information on particle redistributions due to electric fields and thermospheric winds, and undetermined protonospheric fluxes. These controls, coupled with uncertainties in the neutral composition of the thermosphere, stand in the way of a self-consistent description of ion and electron distributions, the height and dynamics of the F-region peak, and the energy coupling between large- and small-scale processes.

The lower region of the ionosphere/ thermosphere is the least understood, and the current quantitative descriptions of the F_1- and E-regions are grossly inaccurate. An evolving database from rocket investigations and a number of ground-based radar systems show that this region is regularly populated with intense intermediate layers that affect field-line-integrated conductivities and dynamo-driven electric fields. It is suspected that the structure of these layers reflects a unique balance among the various controls due to thermospheric wind-shear nodes, electric fields, and an inventory of metallic ions that is not consistent with known meteoric sources. The understanding of this region is fundamental to the understanding of ionospheric behavior at all altitudes, but for all practical purposes there is no information on the global distributions of electric fields, thermospheric winds, and ion composition upon which to build a self-consistent theoretical model.

Previous programs have either investigated the individual atmospheric regions in isolation, have not developed comprehensive databases, or have not given proper attention to internal and external coupling processes. We now know that a simplistic view that neglects dynamics and coupling among the various regions is not only incorrect, but

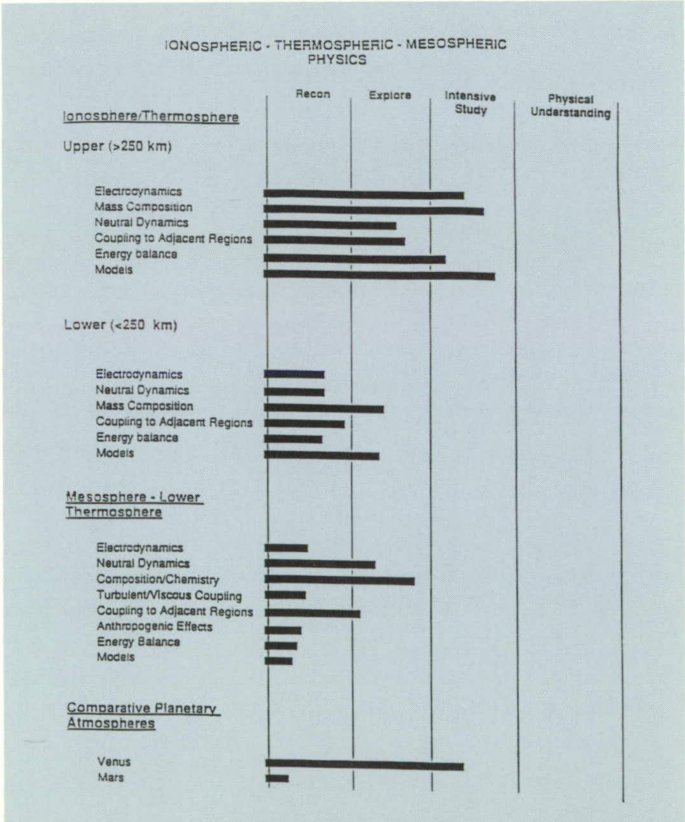

Figure 3.3–2 Ionospheric/mesospheric/thermospheric physics

misleading. The three most recent and very successful Explorer missions attest to this fact. For example, the Atmosphere Explorer program charted basic upper-thermospheric photochemistry without measuring dynamical interactions or couplings with other regions. Similarly the Solar Mesosphere Explorer measured trace-constituent abundances in the mesosphere but had no dynamical measurements to provide for a fully satisfactory interpretation. The Dynamics Explorer (DE) program, on the other hand, did provide a tantalizing glimpse of the richness and variety of dynamical processes in the upper-altitude and higher-latitude part of the ITM system and, in particular, the coupling with the magnetosphere. The coverage in space and time for DE was very limited, however, and did not extend below ~300 km in any effective way. Therefore the DE results raised far more questions than were answered. We still do not understand: (a) the effects of phases of the solar cycle and influences of various solar surface morphologies; (b) the UT/LT and latitude/longitude dependencies; (c) the effects of gravity waves and tides; (d) the roles of E- and F-region dynamos under static and dynamic conditions; and (e) the global impact of the neutral flywheel and fossil winds on ionospheric electric fields and their contributions to high- and equatorial-latitude irregularities.

In the previous study of our near-Earth space environment, the regions known as the mesosphere (~50–95 km) and the lower thermosphere/ionosphere (~95–200 km) have been neglected relative to the other, more accessible, higher-altitude regions. These regions are too high for balloon platforms and too low for *in-situ* measurements from long-lived satellites. In the mesosphere and lower thermosphere/ionosphere, therefore, the database is sparse and in many cases riddled with controversy. The basic state variables of wind, temperature, and composition have not been systematically measured in a global sense, though it is known that complex interactions among chemistry, dynamics, and radiation are responsible for controlling both the mean state and major departures from the mean. In the case of the mesosphere, it is likely that there will be anthropogenically-caused, first-order changes in its chemistry, composition, temperature, and dynamics within the next two to three decades due to the influence of increasing levels of methane and carbon dioxide. Methane, for example, is readily oxidized into water vapor. The consequent increases in mesospheric H_2O will drive stronger HO_x-family chemistry, with far-reaching effects on ozone and the absorption of energy within the mesosphere. These changes will project their influence upward into the thermosphere and ionosphere in undetermined ways.

Another outstanding question within this altitude region remains that of charged-particle distributions within the mesosphere. While it is generally agreed that the region is populated with free electrons and positive and negative cluster ions, reliable measurements and associated theoretical models are nonexistent. This lack of information exacerbates the related controversy involving mesospheric electric fields, known to span seven orders of magnitude, by generating unproven speculations on the existence of charged aerosols. These issues are fundamental to understanding mesospheric electric field distributions, current systems, and electrodynamic coupling to the ionosphere. Mesospheric unknowns also include the global distributions of winds, waves, and tides that couple upward into the thermosphere, establishing an important boundary condition on that domain, and ultimately of its interactions with the charged-particle population in the ionosphere.

There have been numerous approaches to theoretical modeling of various component parts of the ITM system during recent years. The modeling efforts include: (1) empirical models based on extensive world-wide data sets; (2) various specialized analytical and semi-empirical models; and (3) comprehensive, three-dimensional, time-dependent, general-circulation numerical models that require supercomputers (for the mesosphere, only two-dimensional, zonally averaged models currently exist). All these classes of models have serious limitations related to lack of experimental information. In particular, the numerical models use crude idealizations for important boundary conditions and may exclude major physical and chemical processes that are necessary to define the physical systems properly. To improve these models and thereby improve our understanding of ITM physics, new experimental programs are required that are designed from the outset to provide the comprehensive information essential for a study of complex nonlinear and dynamical-coupling processes.

3.3.3 Relationship of ITM Objectives and Missions to NAS Guidelines and OSSA Strategy

The ITM discipline and the objectives and missions presented in this report are fully consistent with NAS guidelines *(Space Science in the Twenty-First Century)* and the *OSSA Strategic Plan* of 1989. The NAS points to solar-terrestrial coupling as an important issue, with "emphasis on the response of the system to solar variability." The NAS also points out that to understand better the effects of the solar cycle, solar activity, and solar wind disturbances upon the Earth we need to accomplish the following objectives:

> Provide simultaneous measurements on many links in the chain of interactions coupling solar perturbations to their terrestrial response, and
>
> Create and test increasingly comprehensive quantitative models of these processes.

On several specific issues, the NAS points out the following:

> We still do not understand the basic processes that drive and control the behavior of the global electric circuit [and the model of] the ionosphere as a highly conducting equipotential upper boundary is incorrect.
>
> The Earth's mesosphere and lower thermosphere/ionosphere are the least explored regions in the Earth's near space.... [Its] overall structure and dynamic responses to magnetospheric substorms, solar flares and stratospheric warmings, and even the basic controlling physical and chemical processes of these effects are not understood. To study this system, the NAS suggests a multi-spacecraft mission with supporting diagnostics on tethers, rocket payloads, and ground-based systems.

The objectives of the ITM discipline are also in accord with the OSSA strategy which, according to the NAS, are as follows:

> Look to quantitatively describe the physical behavior of the geospace environment and the effects of solar processes on the Earth.
>
> Establish a set of platforms to study the Earth's system on a global scale... and develop the capability to model the system to predict changes that might occur either naturally or as a result of human activity.

The strategy-implementation plan developed within this document supports and responds to the NAS and OSSA positions with a theoretical and experimental approach to the global ITM system, its internal coupling processes, and reactions and feedbacks to its neighboring regions in the solar-terrestrial network. In the following sections, we present the ITM theme and specific objectives. Mission descriptions which in concert have been developed to satisfy the overall ITM objectives are included in Appendix A.2 to the *Report from Workshop #1* as a whole.

3.4 Overarching Scientific Theme and Motivation for the Proposed Program

3.4.1 Overarching Theme and Sub-Themes

Previous studies of the individual components of the ITM system have clearly indicated that dynamical processes are responsible for the strong couplings that bind the various regions as an interactive whole. Successful previous spaceborne and ground-based programs have delineated and, in some cases, quantified many of the important physical and chemical processes at play in individual regions. *We now need to build on the results of* *previous efforts and design an experimental thrust that recognizes the dynamical and coupled nature of the ionosphere-thermosphere-mesosphere system, including the important connections to the magnetosphere above and to the stratosphere below.*

In the light of the above considerations, and following a detailed review of the status of the discipline by the ITMP, the following overarching scientific theme has been suggested as a unifying principle for future NASA ITM missions.

3.4.2 Overarching Scientific Theme

> *Investigation of the Ionosphere-Thermosphere-Mesosphere (our Near-Earth Space Environment) as a Global, Dynamic, and Coupled System.*

Since this theme is very broad, the ITMP decided to limit the scope of its mission plan by establishing two specific sub-themes. These *foci* represent the *most critical* areas for study within the overarching theme and are given below.

3.4.3 ITMP Sub-Themes (Foci)

> 1. *Explore and Understand the Mesosphere and Lower Thermosphere/Ionosphere.*
>
> 2. *Investigate the Coupling and Dynamics within the ITM System itself and its coupling to the Magnetosphere above and to the Lower Atmosphere Below.*

3.4.4 Overall Scientific Objectives

The ultimate goal of the ITMP program, developed within the overarching theme and sub-themes described above, is the development of a self-consistent empirical and theoretical understanding of the ITM region as a single electrodynamic, chemically-active, and kinetically-reactive fluid that couples to the heliosphere and magnetosphere above, and to the stratosphere below. This objective requires that the understanding be global in scope, cover the full spectrum of solar-terrestrial conditions and associated coupling mechanisms, and encompass quiescent and dynamic conditions, carried to the limit of highly irregular and unstable modes. Within the framework of this ultimate ITMP goal and the themes developed above, we present a subset of scientific objectives which work toward the development of a unified description of the ITM system, associated internal and external coupling processes, and its interface role in the transfer of mass, energy, and momentum in the overall solar-terrestrial system. The objectives are numbered for later reference but are not in priority order.

The specific ITMP science objectives may be listed as follows:

1. Understand the consequences of transitions between turbulent and laminar flow and collisional and collisionless media.
2. Understand the response of the ITM medium to change in external energy sources.
3. Understand the mesospheric/thermospheric coupling due to gravity-wave, tidal, and trace-constituent transport processes at various scales to determine their role in the coupling processes.
4. Understand the electrodynamical coupling between the thermosphere/ionosphere and magnetosphere with adequate sensitivity and resolution to evaluate both the forward and backward generators.
5. Understand the coupling processes between large- and small-scale plasma structures.
6. Understand the long-term trends in the state of the ITM induced by solar-cycle changes and anthropogenic activity.
7. Understand ozone photochemistry and HO_x, NO_x, and ClO_x catalysis.
8. Understand auroral NO production and transport downward through the mesosphere.
9. Understand the basic chemistry, dynamics, physics, and radiation of the mesosphere/lower-thermosphere/ionosphere transition region.
10. Determine the real-time evolution of the global ionosphere electric field in response to solar wind/magnetosphere coupling.
11. Determine the physics and the impact of mesoscale electrodynamic perturbations on the energy transport and on the coupling between regions.

3.5 Relevance of ITMP Program to the Infrastructure of Fundamental Space Physics and Applications Research

The ambitious ITMP program described below has been developed in accordance with the overarching theme and the two scientific subthemes. It has been designed to be *scientifically focused* and *achievable*. Not only scientific but also societal and practical benefits would accrue from such a program, and some of the more significant ones are discussed briefly below.

3.5.1 Anthropogenic Changes in the Mesosphere: A Harbinger of Global Change?

The mesosphere, lying between about 50 and 95 km altitude, is an atmospheric region with complex dynamics and photochemistry that is highly susceptible to changes in solar UV radiation. Furthermore, the increasing levels of methane and CO_2 in the mesosphere will undoubtedly profoundly influence the delicate chemical and dynamical balances known to exist there. *The mesosphere is therefore an important test bed for studies of global change because of its high susceptibility to changes induced by varying abundances of trace constituents such as CO_2 and methane.* There is an urgent need to establish the current mean state of the mesosphere so that we can investigate future anthropogenically-caused perturbations to that state.

3.5.2 Satellite Drag and Shuttle Re-Entry

The drag on space vehicles is directly proportional to the total density encountered along the orbital path. Previous studies have shown that the density structure of the mesosphere and thermosphere is highly structured in space and time, with changes in density of up to an order of magnitude or more occurring in association with geomagnetic storms or solar-cycle variations. These density changes are driven by a complicated mixture of radiative and dynamic forcings. Previous, and sometimes painful, experience has also shown the importance of a detailed understanding of these changes for mission planning purposes and budgeting. Important satellites have re-entered well ahead of schedule, and complex systems, such as the Hubble Space Telescope, need expensive periodic re-boosting. Clearly, we need to understand how, where, and why density variations occur in the mesosphere and thermosphere in order to improve NASA's ability to model and predict satellite lifetimes and to design re-entry procedures.

3.5.3 Energy Cascading, Plasma Instabilities, and Communications and Radar Imaging Effects

Plasma instability processes are ubiquitous in the Earth's ionosphere at all altitudes and all latitudes. This is especially true in the nighttime equatorial region and in the auroral zone. These irregularities have broad scale-size distributions covering structures from tens of kilometers to fractions of a meter. These distributions are related to important energy-transfer processes that involve poorly understood and improperly diagnosed instability mechanisms, and they represent source regions for major perturbations of electromagnetic wave propagation systems operating over the frequency range from the HF to the EHF. ITMP studies of these cascading processes will result in a definitive understanding of the hierarchy of active plasma instability processes, and a formalism and predictive scheme vital for the development of future communication system architectures.

3.5.4 Aerobraking in a Planetary Atmosphere

Aerobraking in the Earth's atmosphere is an issue for the National Aerospace Plane (NASP) system, STS re-entry, and other programs. *In order to perform engineering designs properly, improved models of middle- and upper-atmosphere density structures and variability are needed.* Also, the human safety considerations for a manned mission to Mars imply a requirement for aerobraking to be employed prior to landing on the Martian surface. For aerobraking to be safe on Earth or on Mars, it is critical to have a reliable description of the mean state and the possible variability of the density structure in the mesosphere and lower thermosphere.

3.5.5 Exploration and Investigation of Fundamental Boundary or Transition Regions in Near-Earth Space—Keys to The Coupled System

Certain specific and identifiable regions of space often act as *transition regions* where important and rapidly changing physical, radiative, chemical, and dynamic processes force the entire system to change rapidly from one state into another. It is in these transition regions that critical non-linear physical mechanisms act to control the entire domain. In the discipline of ITM physics, the obvious and critical transition region where the various chemical, radiative, dynamical, and thermal processes undergo rapid change is the mesosphere/lower thermosphere (MLT) region between about 70 and 200 km. Unfortunately, this region is not only the least understood, as might perhaps be expected, but it is also the least amenable to experimental investigation and hence the region about which we know the least. Thus *the MLT region is the* critical transition region for the ITM system *and represents the key to our understanding of the energization of the ITM system from EUV radiation and magnetospheric and mesospheric coupling. It represents the* current frontier *in our attempts to complete our understanding of the ionosphere and thermosphere.*

3.5.6 Imaging the Evolution of Dynamical Processes in the Ionosphere, Thermosphere, and Mesosphere

The processes that couple the ITM system are not local but global in scale, with large-scale vertical and horizontal wind systems acting to redistribute energy, mass, and momentum. To unravel these global-scale processes, we will need to "picture" critical parameters on suitable time scales in order to develop two-dimensional, time-dependent descriptions of the temporal and spatial evolution of the thermosphere, ionosphere, and mesosphere. Thus, imaging systems of various types, with high temporal and spatial resolution, will be needed to map parameters such as electric fields, neutral winds, constituent abundances, currents, wave forms, and temperatures. *The nature of the challenge faced by the ITM community will require the deployment of such imaging systems so that measurements are made not of local phenomenology but of global-scale systematic structures that* evolve in space and time.

3.5.7 Technological Challenges and Innovative Geophysical Research

The scientific themes discussed above call for innovative techniques and measurement programs. It is clear that simply *repeating* the earlier missions with updated instrumentation will not provide the key information necessary to study the ITM system as a coupled whole. Therefore, *the suggested ITM program involves innovative technology and mission concepts.*

3.5.8 Comparative Planetary Atmospheres

Planets other than the Earth have analogous ITM systems of their own. Obviously, much less is known about these other planetary atmospheres and ionospheres. In particular, Mars is a planet about whose atmosphere and ionosphere we know very little, yet it may be the most important body in the solar system for humankind other than the Earth itself. We need to understand the upper atmosphere of Mars, both because of its intrinsic interest and because of the need to use aerobraking on potential future manned missions to the red planet. *A full comparative experimental study of Earth, Mars, and Venus will be necessary to complete our understanding of terrestrial planetary aeronomical processes.*

3.5.9 The Upper Atmosphere and Ionosphere as a Natural Laboratory for Atomic and Molecular Collision Physics and Chemistry

The upper atmosphere contains many trace constituents that are difficult, if not impossible, to study in the laboratory due to their extreme reactivity or rarity. Many atomic and molecular cross sections, branching ratios, and chemical rate constants have been measured using direct atmospheric observations. *Much basic atomic and molecular collision physics and chemistry is yet to be done with improved techniques and more comprehensive coverage in parameter space.*

3.5.10 Predictability of Ionospheric, Thermospheric, and Mesospheric Processes

Predictability of ITM processes represents a long-term goal for the discipline. The ability to predict the climatology and weather of a complicated system such as the upper atmosphere and ionosphere correctly requires a complete knowledge and understanding of the important physics processes and mechanisms. *A predictive capability for ITM "weather" is not outside the bounds of possibility, and should represent a natural end-goal for the research program discussed here.*

3.5.11 A Balanced Program

The experimental and theoretical study of the ITM system has always been performed by scientists or "generalists" able to use scientific tools from a wide variety of disciplines. The tools needed within ITM physics include, for example, atomic and molecular collision physics, thermodynamics, fluid dynamics, gas kinetics, spectroscopy, chemical kinetics, plasma physics, radiative transfer, photochemistry, gas-surface interaction physics, etc. Also, as discussed above, the ITM physical system is both complex and strongly dynamical and interactive. Because of the intrinsic nature of the domain of study and because of the nature of the scientific tools needed to make progress, there is a special need for any national program within ITM physics to have the appropriate balance. Regions cannot be investigated in isolation; couplings to and from the magnetosphere and stratosphere are of importance; different diagnostic tools (rockets, satellites, radar, etc.) view the region with differing temporal and spatial resolutions and can access different regions of parameter space. Thus the ITM mission concepts, *by the very nature of the discipline itself,* are responsive to the need for the appropriate programmatic balance, both in scale and type of mission concepts, and in the connectivity and interrelationship with the other SPD disciplines.

3.5.12 Connectivity to other Disciplines and Agency Programs

The last scientific and programmatic theme discussed here is a very important one, namely the connectivity of the ITM discipline to other discipline areas and NASA programs. Within the SPD there is a particularly strong connection to the magnetospheric physics and solar physics communities. In many respects, the ionosphere may be considered to be a critical part of the magnetosphere, providing a major source of ions and mechanisms for current closure and energy dissipation. Occurring within the ionosphere and thermosphere are the important auroral processes that are the signatures of magnetospheric processes. A complete investigation of magnetospheric physics therefore necessarily involves high-latitude ionospheric physics. The coupling with the magnetosphere goes in both directions. The magnetosphere provides an important source of energy and momentum to the ionosphere, the thermosphere, and even the mesosphere. In return, the ITM system provides a large, possibly dominant, source of magnetospheric plasma, and couples strongly with the magnetospheric current system, distorting and modifying field-aligned current structures. The connection to the solar community is also obvious: the thermosphere and ionosphere respond directly to the energetic solar flux which is created in the chromosphere and corona. *It is quite clear that ITM missions are synergistically associated with the magnetospheric physics and solar physics programs.*

The need to consider the ITM system as a dynamically coupled one with internal and external linkages has been recognized by the U.S. scientific community. This recognition has led to the development of extensive, coordinated, ground-based measurement and theory programs dedicated to unraveling and quantifying the important processes. One such national program is entitled CEDAR—Coupling, Energetics, and Dynamics of Atmospheric Regions. It is obvious to all, however, that the study of the global ITM system cannot be accomplished by ground-based techniques alone, and there is an urgent need for NASA to provide leadership in this area with the definition of an effective spaceborne and suborbital program in ITM physics.

4.0 Report of the Magnetospheric Physics Panel

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4.1 Science Accomplishments

Almost a nonexistent discipline before 1958, magnetospheric physics has grown explosively in the three decades of the space age. We have come from the initial recognition of the existence of the Earth's magnetosphere to a considerable understanding of most of its global properties. As our knowledge of the terrestrial magnetosphere grew, planetary missions also gave us our first, tantalizingly incomplete glimpses of the magnetospheres of other planets, and it became possible to situate the study of the Earth's magnetosphere within a broader, comparative context. With the continued evolution and maturation of the discipline of magnetospheric physics, we can look forward not only to developing a more complete and detailed understanding of the magnetospheres of bodies in our own solar system but also to expanding the context of our comparative investigations even further to include the magnetospheres of stars, pulsars, and galaxies.

Although the scope of our discipline encompasses the magnetospheres of the planets and other solar system bodies (and indeed, of other astrophysical bodies as well), it is the terrestrial magnetosphere that has been the object of the most intense study and that is best understood. The principal magnetospheric domains have now been identified, and numerous plasma physical processes have been characterized in considerable detail. It is now understood that the solar wind, magnetosphere, and upper atmosphere and ionosphere of Earth constitute a single, intimately coupled system, and that energy flows in from the solar wind to be stored in part in various magnetospheric domains as well as released quasi-continuously in the aurora and explosively in substorms. However, despite great advances in the understanding of individual magnetospheric domains and of many of the processes coupling them, it has not yet been possible to synthesize the whole: it is not known how various magnetospheric domains fit together as parts of an interacting system, coupled to each other as well as to the solar wind and ionosphere.

From many spacecraft in diverse orbits at different times, we have obtained a general picture of the average morphology of the Earth's magnetosphere and its various distinct regions, including the ring current and the radiation belts, the magnetopause, the bow shock, the plasmasphere, the plasma sheet, the polar cap and cusp, as well as various boundary layers. Past spacecraft missions have also demonstrated that the magnetosphere is a very complex and dynamic system, with strong couplings occurring on a very wide range of spatial and temporal scales. Based on our past theoretical and observational work, we have identified a number of dynamical processes of importance in magnetospheric physics, such as magnetic reconnection, radial diffusion, wave-particle interactions, and the like. We have learned that the solar wind is the dominant source of energy for the terrestrial magnetosphere but that the ionosphere plays an exceedingly important role in the coupling and transport of that energy through the system. Moreover, the ionosphere is now known to be a significant, at times dominant, source of magnetospheric plasma. Past missions have additionally provided ample testimony to the rich variety of microscopic collisionless plasma processes that affect the macroscopic dynamics. The missions we have flown have also proved the value, indeed necessity, of making simultaneous multipoint measurements to distinguish spatial from temporal variations. Further, they have demonstrated the importance of obtaining a global overview of the system, as with auroral imaging.

Important coupling of magnetospheric domains to each other and to the solar wind and the ionosphere occurs in thin transition and boundary regions, across which stresses are exerted, particles can be transported, and fields can penetrate. These flows of momentum, mass, and energy across the boundaries are mediated by both large- and small-scale processes, including magnetic reconnection, Kelvin-Helmholtz instabilities, wave-particle interactions, and particle drifts. The interrelationship of such small- and large-scale processes is an important unsolved problem. Coupling between the magnetosphere and the ionosphere is mediated by field-aligned currents and modified by field-aligned precipitation. The auroral zone contains further examples of thin transition layers across which particles can be energized to excite auroral emissions and plasma can be injected into the magnetosphere. There are other important coupling processes that are not confined near transition regions but pervade the 3-D magnetosphere domains; these include plasma wave-induced precipitation of energetic particles, which also excites auroras, and the flows of electric currents along and across field lines to balance plasma stresses and transmit them to other domains.

The present program of magnetospheric research takes us from the exploratory stage into a stage of more focused study. The centerpiece of our present research efforts is the International Solar-Terrestrial Physics (ISTP) program, which is supported by several smaller missions, by theoretical effort, and by ongoing analysis of existing data sets. In particular, now that we realize that the energy flow occurs through a complex set of interacting processes, we are establishing a network of spacecraft in key regions of the magnetosphere to trace the flow through these various steps. In addition to the global picture to be provided by these widely spaced, simultaneous measurements (Wind, Polar, and Geotail), the closely spaced multiple measurements to be made by Cluster will greatly improve our understanding of some of the microscopic and mid-scale processes which underlie magnetospheric physics. A very important additional feature of ISTP will be much improved global auroral imaging.

In contrast to the study of the Earth's magnetosphere, our study of planetary magnetospheres still remains in its exploratory stage, but could potentially evolve much more rapidly. To date, we have had an orbital investigation only of Venus, while brief fly-throughs have been made of all the other planetary magnetospheres except Pluto's. Nonetheless, we have determined that planetary ionospheres, satellites, and rings can be the dominant plasma sources within magnetospheres, just as we have recently concluded that the Earth's ionosphere might be the dominant source of plasma and energetic particles for the terrestrial magnetosphere. We have seen cases where planetary rotation is the dominant source of particle energization, while at Earth it is negligible; and we have observed auroras that may be powered by this rotation and not by substorm phenomena as at Earth. On the other hand, substorms may well occur at many planets, particularly Mercury and Uranus, but the flybys simply could not confirm their presence, or absence for that matter.

4.1.1 Magnetospheric Research After ISTP, Galileo, and CRAF/ Cassini

As we now stand at the threshold of ISTP and as Galileo begins its six-year journey to Jupiter, our ongoing analysis of existing data sets, coupled with rapidly developing observational and theoretical tools, enables us to look beyond ISTP to new and promising approaches to our goals, to previously unrecognized aspects of the physics, and to previously recognized aspects that cannot be directly addressed by the ISTP mission. The program we envisage for magnetospheric research during the next two decades is a coherent approach designed to expand and deepen our understanding of the fundamental problems listed above by answering the challenging scientific questions that will not be addressed by ISTP or planetary missions that are presently approved or underway. Answers to these questions are ultimately vital to a comprehensive understanding of the magnetospheres of the Earth and other planets.

In formulating scientific objectives to be pursued during the next two decades and designing the missions best suited to address these objectives, it is useful to think of a magnetosphere and the various regions within it as cellular structures separated by thin transition or boundary regions. (Hannes Alfvén has stressed the ubiquity of such cellular plasma structures in the universe, which range in scale from current filaments on the order of a few ion Larmor radii in diameter to stellar magnetospheres embedded in the interstellar medium.) The bulk of the mass, energy, and momentum reside in the large-volume cells and constitute the magnetosphere as a macroscopic physical object. However, it is in the transitional regions where the driving physical processes occur, transporting mass, momentum, and energy between cells and simultaneously propagating signals along the boundaries to remote parts of the magnetosphere. The determining physics of a magnetosphere, in other words, happens in the microscopic transition regions, while the response of the magnetosphere as a system is manifested in the macroscopic cells.

This fundamental characterization of the magnetosphere as a macroscopic cellular structure within which smaller-scale plasma cells are embedded helps identify the right exploratory strategy. With this understanding, the right strategy for successful exploration is obvious. "Microscopes" are the necessary tools for the transition regions, and "telescopes" are required for the cells, so the optimum strategy is to use the right mix of "microscopes" and "telescopes." The ISTP project is an initial attempt to implement such a strategy with multiple spacecraft and auroral imaging to provide at least a sketchy global perspective, and the Cluster satellites to examine sharp gradients. But technological advances now seem to present the possibility of imaging the whole magnetosphere, including some large portion of the tail. If such imaging is indeed possible, then combined with internal magnetosphere measurements by sets of satellite "clusters," it would constitute an order-of-magnitude improvement over the capabilities of ISTP. As in ISTP, our "microscopes" are clusters of spacecraft with the instrumental resolution in space-time sufficient to resolve the plasma physics of the transition regions, placed in orbits that will maximize their encounters with the domains of interest (regions left unexplored or underexplored by ISTP). Our "telescopes" are in fact imagers—detectors of UV, EUV, X rays, and energetic neutral atoms—placed in orbits that optimize their views of all the cells (and their boundaries) that make up the extended magnetosphere. The full realization of the potential of this strategy will come with the deployment of clusters of clusters, and multipoint imagers, so that the microphysics and macrophysics of the entire magnetosphere (and its coupling to the ionosphere and interplanetary medium) will be revealed by simultaneous and coordinated observations.

Ultimately, a strategy appropriate for the Earth's magnetosphere will, when suitably modified, be close to ideal for any one of the other magnetospheres we know about. While each mission to another planetary magnetosphere will of necessity have several unique aspects, we will ideally use the imaging and cluster approaches in order to investigate the large- and small-scale plasma phenomena that characterize and control each magnetospheric system. What is needed is to go into each magnetosphere, identify its cellular structure, the important boundaries and transition regions, the major plasma sources and sinks, and the processes of momentum and energy transfer that control the magnetospheric environment. The flyby missions conducted to date have provided valuable snapshots of all of the planetary magnetospheres except Pluto's but have given us very little information about their dynamics. The orbiting missions, Pioneer Venus, Galileo, and CRAF/Cassini, represent the next logical step in identifying how the magnetospheres interact with the solar wind and with their own ionospheres and atmospheres. The next steps might be (1) to conduct an orbital investigation of Mercury, which possesses a small but significant intrinsic magnetic field and a conducting, sodium-emitting surface, and (2) to go into a polar orbit at Jupiter to search for the existence of high-latitude plasma sources and acceleration and to image the Jovian particle environment as we will be able to do at Saturn with Cassini.

4.1.2 Goals of Magnetospheric Research

The history of magnetospheric research has proven to be one of remarkable discoveries and leaps of theoretical comprehension made as spacecraft missions have become more sophisticated and have extended our reach farther into the solar system. Through this evolution and growth in knowledge, the fundamental goals of magnetospheric research have endured. They now encompass questions of considerably more complexity and specificity and can be addressed much more confidently with techniques that can and should achieve them. These goals are:

- To understand the structure and large-scale dynamics of the Earth's magnetosphere and the magnetospheres of the planets.
- To understand the plasma physical processes

operating within the various magnetospheres.

- To understand the sources of magnetospheric plasmas and the causes of variations in their source strengths.
- To understand how mass, momentum, and energy are transmitted from the solar wind and from an ionosphere into a magnetosphere.
- To understand how energy is transported, exchanged, and transformed within magnetospheres.
- To understand quantitatively the coupling between magnetospheres and their ionospheres.
- To understand magnetospheric current systems and their role in the solar/magnetosphere coupling.
- To understand the magnetospheric mechanisms which accelerate particles to high energies, as well as the ultimate fate of those particles.
- To understand the range of variability in the structure, processes, and dynamics possible for a wide range of magnetospheres, both planetary and astrophysical.

4.2 New Frontiers and Enabling Technologies

Although the overarching goals of magnetospheric physics have not changed substantially in the last ten years, new tools, techniques, and vantage points accessible to our field have created new opportunities for measurements to reach those goals. Like the field of medicine which is undergoing a revolution by using new macro-techniques (such as magnetic resonance imaging) and new micro-techniques (such as chromosomal analysis), the development of new macro- and micro-techniques in magnetospheric physics heralds a revolution in our understanding of the magnetosphere. Like a physician who uses diagnostics of all types to put together an integrated view of his or her patient, we are developing a comprehensive, coordinated program of diagnosis for magnetospheric physics into the next century. The themes which thread our efforts will be (1) new frontiers, (2) new experimental techniques, and (3) new analysis techniques. Together they will allow us to develop for the first time a true global perspective of the coupled magnetospheric system and a strong drive towards a quantitative comparative magnetospheres program.

4.2.1 New Frontiers

Most of the Earth's magnetosphere has been explored and is understood at a basic phenomenological level; nevertheless, important regions remain underexplored. In addition, the magnetospheres of other planets, though briefly visited by earlier planetary probes, have yet to be explored. Thus, exciting new frontiers of magnetospheric physics still exist and will be a hallmark of our program. The unexplored or underexplored regions that will still exist in 1995 include the subsolar magnetopause, the polar magnetopause at distances tailward of the Earth, the magnetosphere of Mercury, the polar magnetosphere of Jupiter, the inner magnetosphere of Mars, and the possible magnetosphere at Pluto. With a cluster of spacecraft lingering in the boundary layers, we will be able to resolve the still active controversy of the nature of flux transfer events (FTE's) and the stability of magnetic merging. The life cycles of magnetospheric substorms have also eluded our unambiguous understanding, with the substorm injection front a region of hot controversy (is the plasma accelerated *in situ* or convected quickly inward from the magnetospheric tail?). Again, a cluster of equatorial spacecraft should finally settle that controversy. In addition, some of the regions of physical space, although we have visited them with previous missions, have been left with important segments of velocity space unmeasured. And lastly, although Dynamics Explorer confirmed by a dual spacecraft mission that auroral electrons are accelerated by an magnetically-aligned electric field, the inability of single or widely-spaced measurements to resolve space-time ambiguities in that incredibly dynamic region points up our fundamental lack of coverage in the combined space-time domain. Thus physical space, velocity space, and space-time are new exciting frontiers.

4.2.2 New Experimental Techniques

Analogous to the medical advancements that resulted from the development of the X-ray machine, which made it possible to *look* inside the body and not merely *probe* inside it, our potential capability to progress from single-point *in-situ* measurements to global two-dimensional imaging, not only of the Earth's aurora but also of various magnetospheric plasma regimes, could lead to comparable advances in diagnosing the major features of the magnetosphere. The ability to image the magnetosphere does not eliminate the need to continue probing it, but serves to place the probes in perspective to the whole. And as the revolution in medicine has progressed to three-dimensional imaging by means of CAT scans and Magnetic Resonance Imaging, so are we poised to attempt the next step to construct a true, nearly instantaneous, three-dimensional view of space plasmas by stereoscopic imaging coupled with "space truth" from a fleet of carefully chosen spacecraft. Our progress so far has shown us that a static model built up over time from single-point measurements cannot come close to describing adequately the complexity of the system we are trying to understand. Only by getting a nearly instantaneous global view can we make significant new progress in understanding the magnetosphere as a system of interacting plasma domains and processes.

At the other end of the spatial and temporal scale, a closely-spaced suite of spacecraft will allow us to eliminate the temporal and spatial ambiguity which is endemic to single-spacecraft or even dual-spacecraft observations. Like a microtome, it will allow us to peel off separately each layer in the temporal and spatial domains and to evaluate their interconnections, and to measure unambiguously the electric currents which are the major ties between spatial regimes, particularly between the "generators" and the "loads."

Finally, we propose to try a variety of less expensive but effective experimental techniques to supply more pieces of our puzzle. These include, but are not limited to, using active experiments to map magnetic field-line topology; using magnets in space as analogs of magnetospheres with differing parameter regimes; and using radio sounding of the magnetopause and boundary layer from a lunar base.

4.2.3 New Analysis Techniques

Just as MRI and CAT require new analysis techniques as well as new experimental techniques, so our ways of analyzing data and creating models will need to evolve in the next two decades as well. Our models have typically concentrated on a single aspect of the problem and considered the rest of the coupled system as a boundary condition. In the next two decades we will be forced to make the models truly interact in an integrated way. The key challenge is to integrate different spatial regimes as well as different temporal regimes. Our analyses, theories, and data systems must evolve in a way which, in synergism with our new measurements, leads us to a comprehensive view of our coupled system. The ultimate goal is a view that is so well integrated that we will be able to make predictions about magnetospheric behavior.

Certainly it is not likely that in 2010 all our questions about the magnetosphere will be resolved; but, like the physician, we should at least have a good selection of tools in hand to aid in the attempt.

4.3 Science Measurements

Progress in magnetospheric physics is predicated upon an adequate supply of two types of data: (1) global or synoptic observations of the entire system, and (2) small-scale length/high time-resolution measurements of micro-plasma processes. The former allow the distribution of plasma throughout the magnetosphere to be tracked as a function of time; the latter will make possible the characterization of microphysical processes, such as x-lines, double-layers, slow shocks, and waves. The critical issue for the magnetospheric discipline is determining the optimal mix of macroscopic and microscopic techniques.

4.3.1 Macroscopic Techniques

Two techniques are available which together provide a comprehensive view of the magnetosphere: (1) widely spaced multipoint *in-situ* measurements and (2) remote imaging using energetic neutral atoms and UV and EUV detectors, as well as radio wave techniques. The multipoint approach utilizes a constellation of spacecraft at various locations within the magnetosphere to build up an image of its global state. This technique has the advantage of using well-developed spacecraft/ instrument technology, such as that employed by ISTP, and providing high-resolution measurements at the location of each spacecraft. The main disadvantage of the multipoint technique is that with a small number of spacecraft the granularity of the global measurements is very poor. Furthermore, the image is significantly blurred by dynamical effects.

Remote sensing techniques involving energetic neutral atoms (ENA) generated by charge exchange between exospheric or interplanetary hydrogen atoms and energetic magnetospheric ions have been demonstrated previously and are now under intensive study. The possibility of sensing magnetospheric plasma via resonant scatter of solar UV lines from singly ionized helium and oxygen atoms has been known for some time. Technological issues, such as sensitivity, background (S/N), field-of-view, and temporal resolution are still being evaluated, but hold significant promise for extending remote imaging to greater altitudes than is possible for ENA.

In addition to the above two remote-sensing techniques, barium shaped charges producing fluorescent plasma can be used to trace magnetic field lines directly. With the release of barium particles at an altitude of 25,000 km in the nightside magnetosphere, it may be possible to illuminate the magnetic flux tube for a distance of about 100,000 km and for as long as about 1 hour. Such a flux tube might connect the auroral ionosphere to the ring-current region or the tail plasma sheet.

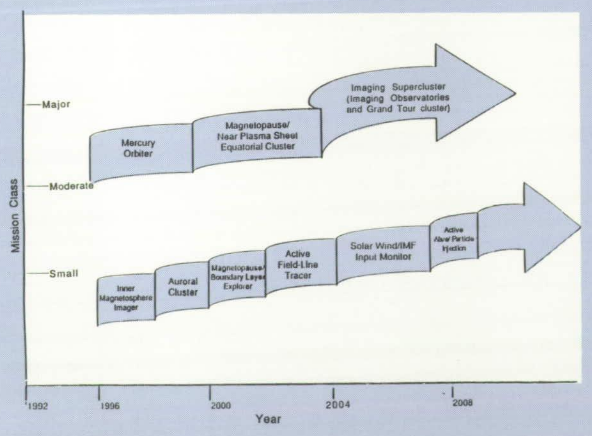

Figure 4.4-1. Proposed magnetospheric physics missions

4.3.2 Microscopic Techniques

The aforementioned techniques would provide a macroscopic view of the magnetosphere and the various domains within it, and of the mesoscale and macroscale dynamics of the system. However, we have learned that the various magnetospheric domains are separated by thin transitional or boundary regions in which most of the driving physical processes occur on a microscale, transporting mass, momentum, and energy between domains. In order to study these microscale processes, rather closely-spaced arrays or clusters of spacecraft are needed in order to probe the structure and dynamics of the transitional layers on appropriate spatial and temporal scales. These spacecraft clusters represent the "microscopes" that we need to complete the comprehensive view of the magnetosphere that is required.

The choice of an optimum mix among these techniques is determined by the particular aspect of magnetospheric dynamics or structure under investigation. In the mission concepts discussed in this report, multipoint missions are proposed to attack more narrowly focused objectives such as reconnection at the dayside magnetopause, the injection of hot plasma into the nightside magnetosphere during substorms, and auroral electrodynamics. Stereoscopic remote imaging missions will be needed when the coupling of mass and energy between different regions of the magnetosphere are considered. Ultimately, however, both macroscopic and microscopic techniques must be simultaneously employed.

4.4 Mission Concepts

Future magnetospheric missions that satisfy the defined science objectives are made up of four separate and complementary components: (1) global imaging, (2) *in-situ* clustered spacecraft (2–4 spacecraft), (3) active experiments, and (4) planetary missions. Missions of all four types are included in the recommended program for magnetospheric physics described below.

Figure 4.4–1 shows two bands of progressive mission development in the magnetospheric study. The upper arrow shows the sequence of recommended moderate and major missions throughout the study period. The lower arrow shows the recommended sequence of possible small missions that will accomplish critical, focused science objectives.

4.4.1 A Statement on Small Missions

During the course of our deliberations on appropriate new missions in magnetospheric physics, it became clear that a remarkably broad range of scientific objectives could be served by a steady sequence of explorers and smaller explorer-class spacecraft. The scientific payoff of a greater number of small-spacecraft launches is also attested to by the large number of outstanding proposals received as a result of recent Scout- and Delta-class explorer AOs. We have found that virtually every aspect of magnetospheric research—auroral studies, boundary exploration, particle acceleration, *etc.*—would profit from focused research with small missions. These low-cost, fast-turnaround missions are particularly important for the training of students and post-doctoral scientists in our field. We also note that explorer missions remain critical as platforms on which to test technologies and concepts that feed into our moderate and major missions. Therefore, we strongly urge that a separate explorer-class line be established as soon as possible within Code SS to meet this critical, unmet need.

4.4.2 Proposed Missions

The proposed magnetospheric physics program consists of two major missions, two moderate missions, and a variety of small missions, as illustrated in Figure 4.4–1 and Table 4.4–1. We will discuss each of these proposed missions in the following sections. Detailed mission fact sheets can be found in Appendix A.3.

Major
- Imaging Super Cluster (two imaging observatories with magnetosphere grand tour cluster)
- Jupiter Polar Orbiter (JPO)

Moderate
- Mercury Orbiter
- Magnetopause/Near-Plasma Sheet Cluster

Small
- Ring Current, Auroral Zone, Plasmasphere Imager—$200M
- Auroral Cluster—$200M
- Magnetopause/Boundary Layer Explorer—$150M
- Active Field-Line Tracing—$30M
- Solar Wind/IMF Input Monitor—$150M
- Active Wave/Particle Injection—$100M
- Artificial Magnetosphere (Astromag)—$50M

Table 4.4–1 Magnetospheric physics proposed programs

4.4.2.1 Major Missions

A. Imaging Super Cluster. The Imaging Super Cluster (ISC) consists of two imaging spacecraft in highly elliptical (10–30 R_E apogee) polar and equatorial orbits and a four-spacecraft super cluster in an elliptical magnetotail orbit with apogee that ranges from ~6 R_E to 200 R_E with variable inclination. This mission provides:

- Global images of the auroral region, the three-dimensional topology of the magnetosphere and the plasmasphere, their boundaries, and their dynamics.
- A measure of magnetotail boundaries, current systems, and their relation to inner magnetosphere/ionosphere boundaries and current systems.
- A measure of how major macroscale regions of the magnetosphere interact on a global scale.

- A measure of the relation and interplay between local processes and global dynamics.

The two imagers are positioned to provide stereoscopic images of magnetospheric charged particle populations using photon, energetic neutral atom, and radio-wave imaging techniques. These images will provide high-sensitivity observations of magnetospheric regions below ~15 to 20 R_E and a more limited perspective of tail regions from 15 to 20 R_E.

In addition, there are several missions in the moderate and small science segments of our proposed program (see Figure 4.4–1) which will probably still be operating during the ISC mission and can, therefore, provide the *in-situ* multipoint measurements in the auroral zone and near-tail regions for comparison with the stereoscopic images.

The super cluster will provide *in-situ* magnetotail observations that allow three-dimensional determinations of boundaries and current systems throughout the magnetotail, with the other magnetospheric regions being observed by the imagers. The tail cluster configuration will separate spatial and temporal effects; the cluster will use a variable satellite spacing (from a fraction of an R_E to ~10 R_E) and will be capable of observations out of the plane of the nominal cluster orbit.

The ISC mission will represent a major advance in our goal of understanding both the global behavior of the magnetosphere and the role of local processes in determining the observed global features. It builds upon and is a natural extension of the ISTP program, which is studying the mass, momentum, and energy flow through the magnetospheric system. An understanding of this flow will provide a basis on which to interpret and test the ISC results concerning global dynamics and their relation to local processes.

B. Jupiter Polar Orbiter. Two spacecraft in complementary high- and low-perijove polar orbits (or a single hybrid spacecraft capable of modifying its orbital regime) will focus on questions that Galileo, because of its orbital parameters, will leave unanswered. Principal among these are the time variations of the Io plasma torus, as viewed *in situ*, and torus/magnetosphere coupling with the Jovian ionosphere as manifested by Birkeland currents, pitch angle scattering, and the Jovian aurora, and the identity of the particles (heavy ions or electrons?) that are primarily associated with these phenomena.

Required observations include magnetic field measurements, ion and electron distribution functions, ion composition, and measurements of the torus and auroral spectra. The following instruments constitute a strawman payload: electron and ion mass spectrometers, neutral mass spectrometer, electron temperature probe, plasma waves instrument, magnetometer, IR mapping spectrometer, EUV/UV spectrometer, auroral imagers, CCD imager, gravity gradiometer, and radio science. Radiation-resistant sensor and electronic components must be developed to withstand the harsh radiation environment at Jupiter.

This mission utilizes the DVEGA trajectory technique to obtain sufficient mass from the Titan IV/Centaur launcher. Upon Jupiter approach, each spacecraft is separately targeted to polar elliptical orbit: one at very low perijove and the other at Io-distance perijove. Low-perijove orbit optimizes aeronomy and *in-situ* auroral investigations, while high-perijove orbit investigation of Io and the torus provides high-altitude transpolar views of Jupiter's auroral regions. An alternate concept would be a single spacecraft with sufficient propulsive capability to change orbital regimes.

4.4.2.2 Moderate Missions

C. Mercury Orbiter. Mariner 10's encounter with Mercury revealed an Earth-like magnetosphere in miniature, with dynamical processes occurring on time scales of minutes compared with time scales of hours and days at the Earth. Scientifically, Mercury presents us with a unique laboratory for making a self-contained magnetospheric study of plasma convection and particle acceleration in a setting where the effects of planetary rotation are: suppressed and the boundary conditions, *e.g.*, a conducting surface and very little atmosphere, are radically different from those prevailing in the Earth's magnetosphere. The primary magnetospheric physics objectives for the dual Mercury mission are: (1) to map, in three dimensions, the magnetic structure and plasma environment of the planet's "miniature" magnetosphere; (2) to determine the principal processes taking place during magnetospheric substorms with an emphasis on differences from terrestrial substorms due to Mercury's lack of an ionosphere; (3) to assess the role of interplanetary conditions in determining the rate at which Mercury's magnetosphere draws energy from the solar wind and the manner in which it is later dissipated; and (4) to exploit Mercury's relative lack of internal plasma sources and measure quantitatively the transfer rate of solar wind plasma into the magnetosphere.

Within the past few years it has become apparent that a moderate-cost mission to Mercury can provide the particle-and-fields measurements and planetological observations necessary to yield major advances in our understanding of Mercury and its magnetosphere. A Mercury Orbiter Science Working Team (MeO SWT), appointed in 1988 under the auspices of the Space Physics (SS) and Planetary Exploration (SL) Divisions of NASA Headquarters, conducted three workshops in 1988–89 and was supported by spacecraft engineering and mission design studies at the Jet Propulsion Laboratory. The findings of the engineering team indicate that a pair of spin-stabilized spacecraft carrying comprehensive particle-and-fields experiments and some planetology instruments in highly elliptical orbits can survive and function in Mercury orbit without costly Sun shields and active cooling systems. The MeO SWT identified a ten-instrument strawman payload to meet the science objectives stated above: magnetometer, electric-field analyzer, plasma wave analyzer, energetic-particle detector, fast-plasma analyzer, ion-composition analyzer, solar-wind plasma analyzer, solar neutron detector, line-scan imager, and gamma/X-ray spectrometer. All of these instruments are based on mature technologies.

The single-launch-vehicle, dual-spacecraft baseline contained in the JPL mission design meets the fundamental magnetospheric science requirements for the simultaneous multipoint measurements and provides critical redundancy in the event of spacecraft failure. The coordinated orbit scenarios for the two spacecraft will provide unique particle-and-fields measurements which are unobtainable elsewhere due to the constraints of orbital mechanics and to the large dimensions of other magnetospheres relative to their planetary bodies. In conjunction with the Earth-orbiting GGS and Cluster missions to be flown in the 1990's, the MeO mission will provide the essential data necessary to formulate the next generation of theories and models for terrestrial-type magnetospheric structure and dynamics. This mission will also return critical measurements necessary for the understanding not just of the surface history and internal structure of Mercury, but of the formation and chemical differentiation of the solar system as a whole.

D. Magnetopause/Near-Plasma Sheet Equatorial Cluster. The magnetopause is the site of mass, energy, and momentum transfer between the solar wind and the magnetosphere. We are currently faced with a bewildering array of possible steady and transient interaction mechanisms. Each predicts a specific pattern of magnetic field, electric field, plasma, and energetic particle signatures as functions of position on the magnetopause surface. The subsolar or equatorial magnetopause is believed to be the dominant site of solar wind-magnetosphere interaction; prolonged observations are essential in this region. To date there has been no comprehensive survey of processes occurring at very low latitude, and the contemporary data cannot uniquely distinguish among the possible processes nor their relative importance. The inner edge of the plasma sheet and the near-magnetotail is the region where the substorm process may be initiated. In this region, the magnetic field makes the transition from dipole-like to tail-like and substorm plasma injection occurs. Although the region near geosynchronous orbit has been well explored, the region from ~7 to 12 R_E is very much underexplored. This area must be surveyed in order to understand the processes that produce particle injections, the disruption of the cross-tail current, the change in field topology, and the mapping of field-aligned currents.

To understand the important physical processes operating both at the magnetopause and in the near-tail, a cluster of four properly instrumented spacecraft is required. Utilizing variable separations between spacecraft, the cluster will make it possible to separate spatial from temporal variations and to determine the spatial morphology of the structures of interest. This mission will investigate the coupling of magnetospheric domains and, in particular, will focus on domain boundaries and coupling across spatial and temporal regimes.

Some specific objectives of the mission are as follows:

- Study in detail magnetopause structure and processes (FTE's, pressure pulses, surface waves, impulsive entry, steady-state or enhanced merging).
- Examine solar wind and IMF control of each of these processes.
- Resolve space-time ambiguities by lingering in the equatorial magnetopause region with a high-time-resolution, variably spaced cluster.
- Perform a detailed investigation at all local times on the dayside.
- Examine the near-tail region with cuts through the transition region from dipolar to tail-like geometry.
- Determine the processes involved in substorm particle injection.
- Study the process of current sheet interruption.

To address these science objectives, measurements of the following are needed: DC and AC electric and magnetic fields, 3-D ion composition and electrons (few eV to 50 kev), cold electron density and temperature and density fluctuations, and energetic ion composition (up to few MeV/nucleon) and electrons (to 1 MeV). An upstream monitor of the solar wind is required. The scientific return will be enhanced if the Inner Magnetosphere Imager and the Magnetopause/Boundary Layer Explorer are operational during part of this mission.

4.4.2.3 Small Missions

E. Inner Magnetosphere Imager (IMI). A dramatic advance in our understanding of the global magnetosphere and its dynamics can be obtained through the use of recently developed techniques of imaging the charged-particle populations of the magnetosphere. The Inner Magnetosphere Imager will apply these techniques to provide the following:

- Images of the global ring current and its dynamics.
- Images of the plasmasphere and its dynamics.
- Images of the inner edges ($<15\ R_E$) of the plasma sheet and its dynamics.
- Images of the auroral regions and their dynamics.
- Global mapping from low altitude to the equatorial regions.
- A measure of the global interactions among the macroscale regions listed above.
- Global images of substorm injections and a measure of the injection boundary.
- A measure of the magnetic field/electric field configuration within $\sim 15\ R_E$.

The IMI mission will incorporate energetic neutral-atom, photon, and radio-wave imaging techniques to obtain global images of various magnetospheric regions. Instrumentation that has already been developed includes X-ray, UV, and visible auroral imaging, energetic neutral atom cameras, and EUV plasmasphere imaging using 30.4 nm He^+ resonantly scattered radiation. Instrumentation to be developed includes imaging using the 64 nm O^+ resonantly scattered line and radio-wave imaging. The IMI will be placed in a high-inclination elliptical orbit (apogee altitude in the 5 to 20 R_E range).

Results from the IMI will provide an entirely new perspective of the magnetosphere on a global basis and will allow an initial assessment of how local processes determine the global dynamics of the system. Such perspectives have not been available in the past and will mark the first time that an astrophysical plasma system can be observed and studied on both global and local scales. Both the science and technology results of the IMI mission will be applied directly to the Imaging Super Cluster mission, the next major magnetospheric mission. The science return of this mission will be strongly enhanced if the magnetopause/near-plasma sheet equatorial cluster mission is operational during the same time period.

F. Auroral Cluster. The auroral acceleration region is one of the key regions of energy transformation in the magnetosphere. It is the region through which energy stored in the outer magnetosphere is coupled to the ionosphere. There are many fundamental, but not well understood, micro- and meso-scale plasma processes involved in this coupling.

This region has been explored during the past two decades by several spacecraft including S3-3, DE, and Viking. These missions established the macro-parameters of this system and have identified the importance of the micro-scale physics involved, stimulating significant theoretical and modeling activity. However, the single- or dual-point measurements have been inadequate to separate spatial and temporal effects or to uniquely define both the wave frequency and wavelength.

The set of four auroral-cluster spacecraft will have the capability to separate temporal and spatial variations on scales ranging from 1 to 1000 km, with interspacecraft spacings varying from a few hundred meters to 100 km. The four spacecraft will be identically instrumented to measure electric fields (DC to 1 MHz), magnetic fields (DC to 10 KHz), 3-D electrons (~1 eV to 30 keV), 3-D ions with composition (~10 eV to 30 keV), and wave-particle correlations. The major technical challenges are the desired 1% knowledge of inter-spacecraft positions over the full range of separations and the 0.01° relative altitude determination knowledge.

The cluster of spacecraft would be launched into a 1,000 km by 12,000 km polar orbit and would initially be in a closely spaced configuration. The S/C would operate throughout the auroral zone but store data at a relatively low rate until the desired event signature was identified by one spacecraft. This would trigger very high rate (~10 MHz) data capture from all S/C for a fixed period surrounding the triggering event (similar to the FAST mission). The effects of dipole wobble and orbit precession would permit an altitude scan of the critical region of auroral acceleration mapped out by previous missions. A two-year mission would suffice to cover all local times and altitudes.

This mission would benefit from a continuous solar-wind monitor upstream from Earth and from fine-scale auroral imaging of the auroral zone. The mission is also synergistic with the Ionosphere-Thermosphere-Mesosphere (ITM) coupler mission.

G. Magnetopause/Boundary Layer Explorer. The Magnetopause/Boundary Layer Explorer (MPEX) consists of one or two polar-orbiting spacecraft intended to explore in depth three important boundary regions of the magnetosphere: the dayside magnetopause (at all latitudes and local times); the high-latitude magnetopause on the night side and the polar cusp; and the region near 10 R_E in the tail, which is the transition region between the near-Earth ring current and the tail plasma sheet. The orbit would initially be a 10 R_E circular polar orbit, with a local time of the orbit plane at about 1500 to 0300 hrs. At this distance and local time, the spacecraft would spend about 15 hours skimming the dayside magnetopause from the southern to northern cusp every two days, crossing over the pole and then traversing the tail from north to south and returning to the day side. The orbit, virtually inertially stable, would decrease in local time by two hours per month, reaching 0900 to 2100 MLT after three months. At this point, the dayside apogee could be gradually increased to match the flare of the dawnside magnetopause, becoming a 10 x 15 R_E orbit when it reaches the dawn-dusk meridian. At this time the dawnside portion of the orbit would be skimming the magnetopause while the duskside portion would remain in the low-latitude boundary layer, investigating particle entry mechanisms. Propulsion could also be used to tilt the line of apsides up out of the ecliptic plane, reaching perhaps 35° and an apogee of 30 R_E by one half-year past launch. Now the dayside (perigee) portion would spend about a day skimming the dayside magnetopause from pole to pole (being slightly inside the average magnetopause location in the southern hemisphere and outside of it in the northern hemisphere), and the nightside portion would cross the magnetopause considerably down the tail, once every 5.6 days. In this way, momentum transfer (and supposed northward IMF reconnection) could be investigated in a near-skimming trajectory. The spacecraft would spend about three months traversing the tail in this manner, and then would swing back around to the dayside, investigating the high-latitude bow shock as well.

This mission would be highly synergistic with the Magnetopause/Near-Plasma Sheet Equatorial Cluster (MNPSEC), which would remain in the near-Earth equatorial plane (perhaps a 2 x 12 R_E orbit) while the MPEX cuts through the magnetotail from north to south. Whenever the MPEX was out in the solar wind at apogee (about half of the time for half of the year), it could serve as a high-quality solar-wind monitor for other magnetospheric missions, much closer to the magnetopause than, say, a Wind orbit. If, for example, the two missions are at apogee at the same local time, then when MNPSEC was on the dayside nearly skimming the equatorial magnetopause, the MPEX could be its nearby solar-wind monitor.

The mission breaks new territory by being the first mission to skim the dayside magnetopause and the turbulent exterior cusp. It will be the first to cross the polar magnetopause at distances tailward of $x \sim -10\ R_E$, crossing it at 20 R_E or more. In this way it would be the first to explore the magnetopause cross-section at high latitudes behind the Earth. Does the magnetopause continue to flare at high latitudes or does its polar cross-section reach some maximum value and decrease again? Does the IMF y-component gain access at high latitudes through the merging process or through turbulent diffusion in the equatorial plane?

Dayside magnetopause skimming orbits will make it possible to follow the development of plasma which is injected either by FTE's, spatially and/or temporally varying dayside merging, or quasi-diffusive processes.

In the near tail, the mission can monitor the fate of the plasma mantle: does the plasma mantle eventually reach the tail neutral sheet and return as the plasma sheet, or does its supersonic flow never return? In addition, the mission can trace the fate of ionospheric plasma fountains emitted from the dayside cusp and nightside auroral zone, testing where they convect back to the neutral sheet and providing quantitative tests of the relative importance of mantle plasma versus low-latitude boundary layer and ionospheric plasma in supplying the plasma sheet.

For substorm processes, the MPEX mission will provide an out-of-ecliptic monitor to check the size and motion of plasmoids. It can also, for the first time, allow measurements of the vertical dimension and field strength in the lobes to measure total magnetic flux changes during growth phases and expansion phases of substorms.

The polar magnetosheath will also be skimmed for part of the mission. At this part of the trajectory, one can monitor solar wind deceleration by current dynamo processes, and perhaps watch bursts of magnetospheric plasma, which will be most easily observed in the magnetosheath just outside the magnetopause. The MPEX will spend about 1 day in its 5.6-day orbit out in that region, being engulfed periodically by the magnetopause as it "breathes" and/or flaps.

H. Active Field Line Tracing. A serious problem in magnetospheric research is our lack of detailed understanding about the geometry of magnetic field lines within the magnetosphere. Actually, it is rather surprising that such a fundamental property is still highly uncertain despite the fact that virtually every magnetospheric satellite has carried a magnetometer. The difficulty is that satellite observations are essentially point measurements, and even with data from several satellites, the spatial coverage is vastly inadequate. Although a large number of magnetospheric models have been developed, there have been no definitive observations to confirm how each plasma regime can be projected along the magnetic field lines to another region within the magnetosphere and to the ionosphere. This is a serious uncertainty in magnetospheric physics. Unfortunately, all past efforts to remove this uncertainty have been indirect and therefore cannot be decisive.

An understanding of how the various regions of the magnetosphere and the ionosphere are connected by the geomagnetic field is essential to our understanding of the physical processes in the magnetosphere. Over the last decade a number of tracing techniques have been developed or proposed: chemical tracers, electron accelerators, and positrons. For tracing over large distances, the barium-shaped charge technique appears very promising. A barium-shaped charge will create a highly directed neutral beam which will ionize when exposed to sunlight; the resulting ions will subsequently follow the ambient magnetic field. Since barium ions have resonance lines in the visible portion of the EUV spectrum, the ions can be observed optically. In a dual release, with charges currently used in rocket-based auroral research, but released at high altitude and in opposite directions, up to 100,000 km of magnetic field lines can be illuminated. This distance is sufficient to illuminate an auroral magnetic flux tube from the ionosphere to past its equatorial crossing. It is possible that larger charges will make it possible to trace field lines even farther.

An essential goal of this mission is to increase our understanding of the magnetic configuration of the magnetosphere and how it changes in response to the solar wind and to auroral activity. Therefore a number of tracing experiments will be carried out under different conditions. Although the barium-shaped charge technique is a proven field-tracing technique, it has only been used in experiments carried out from rockets in the near-Earth magnetosphere. The estimated 100,000-km tracing possible with releases at higher altitude is based on the rocket experiments. For tracing field lines in the more distant magnetosphere, the release must be made at higher altitudes where the magnetic field strength is much smaller. This may affect the distance over which we can trace. Before engaging in a large program with many tracing releases, it is prudent to have a number of test releases for proof of concept. It is also strongly urged that other field-line tracer techniques be studied and that funding be made available for such studies.

I. Analog Magnetospheric Plasma Laboratory. The Analog Magnetospheric Plasma Laboratory (AMPL) provides an experimental laboratory for comparative magnetospheric physics studies in conjunction with the Astromag cosmic ray facility for the Space Station. It falls into the category of an active experiment, since an anthropogenic disturbance of the natural environment is exploited for these studies. It will: (1) test space physics theory of fundamental processes under new conditions, (2) add a new member to the set of magnetospheres accessible to study, and (3) provide a reproducible experimental system which may be imaged, freely sampled, and altered or perturbed in a deliberate and controlled way. A deployable, maneuverable plasma diagnostic probe is used to study the interaction between Astromag and the ambient ionosphere. Various embellishments of the basic concept may be developed as experience is gained. Preliminary studies should include theoretical predictions of Astromag's behavior, and a proof of concept by study of the orbital decay and optical emission of a permanent magnet placed in low-Earth orbit by a Scout class vehicle.

J. Solar Wind/IMF Input Monitor. Magnetospheric physics has matured to the point that there is now little doubt that the solar wind is the primary energy and momentum input that drives and controls magnetospheric processes. Thus, nearly continuous monitoring of the solar wind and interplanetary magnetic field (IMF) immediately upstream of the Earth is a requirement of essentially all future magnetospheric missions. The ideal monitoring location is from a double lunar swing-by orbit similar to that of the Wind mission. This avoids the problems of aberration which can occur from L_1. A simple explorer spacecraft providing basic solar wind plasma and IMF measurements would replace the Wind spacecraft after it is no longer operable.

K. Energetic Injection Plasma Laboratory (EIPL). Operation of an injection payload comprising both energetic particle accelerators and intense wave transmitters will enable plasma physics studies and remote sensing of ambient plasma structures, including (1) particle beam-plasma interactions and beam echoes from auroral potential structures, (2) wave-particle interactions of emitted waves across the VLF frequency spectrum, and (3) remote sensing of plasma structures by wave echoes. A deployable, maneuverable plasma diagnostic probe will be used to study the interaction between injected beams or waves and the ambient ionosphere. Various embellishments of the basic concept may be developed as experience is gained in the operation of the injectors. The heritage of this type of experiment consists of several sounding rocket and shuttle payload projects: notably seven

Echo experiments, the E-parallel-B rocket, the SEPAC investigation on Spacelab 1 and Atlas, and the FPEG/VCAP experiment on STS 3 and Spacelab 2, which made use of the Plasma Diagnostic Probe.

4.4.3 Space Exploration Initiative

If the Space Exploration Initiative (SEI) proceeds as expected, it could provide a significantly enhanced capability for magnetospheric studies. The Moon could be used as a base for large imaging instruments and for remote probing of the Earth's magnetosphere with radio waves. The numerous planned missions to Mars, beginning with the Mars Aeronomy Observer (MAO), could provide opportunities for the detailed study of the Mars plasma environment.

The program discussed herein might, therefore, have the potential of being expanded to include the following experimental capabilities:

- A lunar-based imaging observatory employing EUV, ENA, and radio-wave imaging for macroscopic studies of the Earth's magnetosphere.
- A "lunar magnetosonde" for remote mapping of the Earth's downstream magnetopause, boundary layers, and downstream plasmoids from the lunar base.
- *In-situ* studies of the interaction of lunar magcons with the solar wind and magnetotail plasmas.
- *In-situ* and remote sensing of the plasma and magnetic-field environment within the Mars/Phobos system.

4.5 Theory and Modeling

Until recently, progress in magnetospheric physics has been led by the many new experimental results that were being obtained rapidly, with theory and modeling efforts mainly attempting to explain the observations. With the present capabilities for large-scale computer modeling and simulation, it is becoming more possible and appropriate to make detailed predictions of what new spacecraft missions might observe, thereby providing specific testable hypotheses for the various models that have been proposed. For example, it should be possible to predict what sequence of measurements would result from impulsive plasma penetration across the dayside magnetopause and from reconnection at the dayside magnetopause. With appropriate imagers and clusters, the space-time confusion can be minimized, so that the success of an experiment in either proving or falsifying a particular hypothesis will depend primarily on achievement of the necessary sensitivity and resolution of the data obtained. The missions proposed for the future must be based on such predictive modeling and the necessary scope and resolution of the data must not be allowed to be compromised.

The present generation of global magnetosphere models is fairly successful in describing the large-scale structure of the terrestrial magnetosphere beyond a few Earth radii. At the same time, microphysical and mesoscale models of many dynamical processes have been able to enhance our understanding of a wide range of magnetospheric phenomena. However, the information presently available is inadequate to support a significant further development of magnetospheric models (and consequently, a better understanding of magnetospheric phenomena).

Future missions will provide an unprecedented data base concerning the dynamics of a wide range of global, mesoscale, and microphysical magnetospheric phenomena. A new generation of models must play a dual role in this new phase of exploring and understanding our space environment. These models will provide guidance during the design phases of the missions, and then they will synthesize the new knowledge gained by global imagers and clusters of spacecraft. The major challenges the new models must meet include:

- Integration of microphysical processes into macroscopic transport models. For instance, anomalous processes due to waves excited by wave-particle interaction must be incorporated into macroscopic transport coefficients.
- Incorporation of the cellular structure of the magnetosphere into a global model. This problem is especially complex because of the wide range of cell scale sizes. For example, the permeability of the largest scale cell boundary, the magnetopause, needs to be understood.
- A more accurate treatment of boundary

conditions. Of particular importance is the manner in which the ionosphere acts both as a major plasma source and an electrodynamic boundary.

- Incorporation of the fact that most of the magnetospheric plasma is a collisionless magnetized multi-species medium, which cannot always be described by classical MHD treatments. A typical example is the need to use complicated non-Maxwellian distributions which are often observed by satellites but not described by MHD equations.
- Inclusion of neutral atmospheric effects in global magnetospheric models. This requires a connection to global thermospheric models, which in turn must be properly linked to the lower atmosphere.
- Incorporation of appropriate data on particles and waves for study of macroscopic processes with particle simulations.

4.6 Supporting Research and Technology

The future of space plasma physics depends on a balanced program which develops the human and material resources necessary to carry out the diverse and often complex missions required to further our understanding. Such a program must include mechanisms for stimulating the analysis of previously acquired data, as well as the training of individuals who will build and manage future instruments and data analysis programs. Consequently, the following programs should be initiated and supported by the Space Physics Division:

- Advanced Instrument Development Initiative.
- Space Physics Data Initiative.
- Magnetospheric Mapping Initiative.

These initiatives should be supported as additions to the current Research and Analysis base of the Division and not be regarded as redirections of effort within that base.

4.6.1 Advanced Instrument Development Initiative

The objectives of this initiative are to:

- Develop new instrument concepts to the "brassboard" level, sufficient to demonstrate the concepts and to provide refined cost estimates and spacecraft resource requirements leading to a higher level of confidence in mission cost estimates.
- Fund parallel systems research in support of the implementation of missions. The goal would be to reduce hardware costs by identifying cost/benefit payoffs of present methodologies with the elimination of non-beneficial elements.
- Correlate instrument development possibilities with theory and modeling programs to establish key regions and parameters to be targeted for verification and for refinement in models and theory.

We recommend that this program be funded through an identified line item within the Space Physics Division budget to stress its fundamental importance.

4.6.2 Space Physics Data Initiative

The strength of the U.S. space science program lies in its many successfully completed spacecraft missions and the development of data base management and handling techniques which exploit and challenge the leading edge of such technologies. Advances in computing technologies have been spectacular in the short-term past and provide a compelling reason to re-address existing and future data bases with the following goals:

- Obtain unique science.
- Improve the Space Physics data archives.
- Build discipline infrastructure in support of future missions.
- Establish archiving practices which facilitate correlative science studies.

The implementation of this program includes the initiation of pilot studies, examination of techniques, media, and approaches, and the acquisition of tools and resources in a manner analogous to that implemented by the Planetary Division Data System.

We recommend that the Space Physics Division provide a "new start" for a pilot data system with support for data analyst and theorist participation in the development of new archival, analysis, and visualization technologies. This may be provided as an extension of smaller past efforts such as the

CDAW's. This program will play a critical role in support of future spaceflight programs involving multiple data sources and requirements for global synthesis of results.

4.6.3 Magnetospheric Mapping Initiative

Synthesizing a global view of magnetospheres as systems will require a means of interrelating the diverse measurements and images to be obtained throughout at least the terrestrial magnetosphere. This task will be greatly facilitated by the development of an empirically-based quantitative map of the magnetosphere. Such a map would be based to a large extent upon a quantitative empirical model of the geomagnetic field suitable for comparison with information concerning the interconnections among magnetospheric "cells" or regions. Efforts to develop such a magnetic-field model have been refined over the years until at present we do indeed have such a map. However, further refinements are still needed, especially in the detailed mapping of auroral zone and boundary layer field lines. These refinements may be obtained by means of active tracer experiments.

In addition, there is a need to develop complementary maps of other characteristics of the magnetosphere, particularly such plasma parameters as density, composition, temperature, flow velocity, and heat flow. The rudiments of a "specification model" of magnetospheric plasma can already be identified in the literature, and future missions will both make use of such a model for planning purposes, and ultimately add much new information to the map so obtained.

The effort required at this time is in the organization of an assimilative effort that would ingest all of the available information and generate a model of magnetospheric plasma which would be accessible to the community for comparison with individual measurements or as initial states for numerical modeling efforts. We recommend that the Space Physics Division support such an effort in developing a comprehensive map of the terrestrial magnetosphere, based on existing data sets. Interested researchers should be convened to plan the course of action in more detail. Funds must be identified to carry out the assimilation effort until a preliminary map can be made available to the user community through the National Space Science Data Center.

4.7 Magnetospheric Science on the Threshold of a New Age

Among the notable accomplishments of magnetospheric physics are the discovery and exploration of virtually every major region of the Earth's magnetosphere, and the discovery and initial reconnaissance of the magnetospheres of all the planets except Pluto. The elements that have made possible these achievements in magnetospheric physics are: (1) a talented, critical-mass community of scientists; (2) the advanced spacecraft and state-of-the-art instruments needed to make the required measurements; (3) the theoretical models and methods to assimilate data and synthesize ideas; (4) the computational tools to process data and visualize the results of analyses; and (5) the engineers, technicians, and support personnel to carry out effectively and efficiently the critical elements of the space program.

We are now entering a new stage in our investigation of solar system magnetospheres. Galileo is on its way to an orbital rendezvous with Jupiter, CRAF has received a new start, and proposals for Cassini have been submitted. The ISTP/GGS program, which will allow us to detail the flow of mass and energy throughout the Earth's space environment, is building to its active operation phase. The magnetospheric community is growing in size and interactivity, and will be well-poised to address whole new classes of problems. We are gaining new appreciation for the role of the magnetosphere in the linked solar-terrestrial system, and we are developing a genuine global predictive capability. Remarkable new tools are being developed for data/theory closure and data assimilation.

The combination of new theoretical insights, advanced spacecraft designs, modern instrumentation approaches, and unprecedented data analysis methodology puts us on the threshold of a modern, golden age of magnetospheric science. We see a future in which, for the first time, the global connections of the entire solar-terrestrial system can be concurrently examined while the fastest microphysical fluctuations are revealed in all their complexity and significance. And yet, we see this microphysical scale tied logically and integrally to the largest global-scale variation on the coupled solar-magnetospheric-ionospheric system. This bridging of temporal and spatial scales makes magnetospheric physics the one astrophysical discipline in which we can finally see both the forest *and* the trees.

4.8 Addendum: Active Experiments

As space physics has progressed, its exploratory emphasis has evolved toward a more quantitative understanding of the systems and phenomena which have been discovered, leading in the direction of a predictive capability. During the course of this evolution, the increasing potential role of active experimentation in space has been widely recognized, but only partially realized in practice. In such experiments, by definition, the ambient or natural space environment is altered in a premeditated way, such as by the introduction of visible materials so as to reveal the motions of the medium or trace the path of magnetic field lines. Alternatively, processes are initiated which are analogous to natural processes; for example, beam-plasma or wave-particle interactions driven by artificially generated beams of particles or waves, or critical ionization velocity processes driven by high-velocity gas jets.

More recently, capabilities are in development which enable new experiments to be performed. The Space Transportation System orbiters have proved to emit large volumes of gases which lead to a comet-like interaction with the ionospheric flow past the orbiter, including the production of pickup ion populations which are much hotter than the ambient plasma and distributed as rings in velocity space. The development of a Tethered Satellite System will soon lead to the operation of an MHD dynamo powered by the motion of the long conducting tether through the conducting ionospheric plasma. Since the ionosphere itself will serve as an electrodynamic component of the resulting circuit, much stands to be learned about the way in which the ionosphere carries currents, and this new knowledge should carry over to our understanding of natural electrodynamic phenomena.

It has also been suggested that the orbital motion of a strong magnet in low-Earth orbit would lead to an interesting experiment which would support the general theme of comparative magnetospheres by adding a new member to the set of magnetospheres which are accessible to our study. Moreover, such an experimental magnetosphere would provide a reproducible capability to vary magnetospheric parameters, enhancing the opportunities for rapid interaction between space physics theory and observation. Now it appears that independent requirements will lead to the deployment of a strong magnet in low-Earth orbit in connection with the Astromag cosmic ray facility planned to fly on the U.S. Space Station. With suitable advance studies, and in conjunction with an appropriate plasma diagnostic probe, such a facility would serve the magnetospheric physics community as well as the cosmic ray community synergistically.

4.8.1 Supporting Services and Technical Requirements

Orbiting Magnet Assemblies. Both the cosmic ray and magnetospheric physics communities have developed needs for very strong magnets in low Earth orbit. Astromag in particular has developed relatively complete technical requirements for a pair of superconducting ring magnets to be mounted in a "bucking" configuration so as to cancel dipole moments. Such a facility would serve both as a highly effective spectrometer for cosmic radiation and as a basis for an extremely interesting artificial magnetosphere for the simulation of certain well-known magnetospheric processes.

Deployable Plasma Diagnostic Probe. There is a continuing need for a deployable, maneuverable plasma diagnostic probe with capabilities similar to that of the PDP flown from the Spacelab 1 and 2 shuttle missions. Such a facility would serve well in the role of providing diagnostic measurements of the disturbed environment near the STS orbiter or the Space Station, particularly in conjunction with the comparative magnetospheric study opportunity presented by the presence of Astromag aboard the Space Station.

4.8.2 Active Experiment Accomplishments

Though active experimentation is a relatively recent development in space physics, it has already contributed in many ways to our understanding of natural phenomena. Chemical releases at low velocities have been used to create optically visible clouds which act as tracers of convective motions of magnetospheric plasmas. In some experiments, evidence supporting the concept of magnetic field-aligned electric fields has been obtained. A release in the solar wind has provided an artificial comet which yielded insights into the interaction of real cometary gases with the solar wind. Energetic releases of gas have provided some confirmation of and insight into the critical velocity ionization effect of Alfvén waves. Accelerated beams of ions or electrons have provided insights into the energetics of wave instabilities in the auroral ionosphere, including the role of strong wave turbulence in impeding the flow of auroral field aligned currents, and in heating the ambient plasma.

Among the most notable active experiments are the flights of the Space Transportation System orbiters themselves. They have proved to emit large volumes of gases which lead to a comet-like interaction with the ionospheric flow past the orbiter, including the production of pickup-ion populations which are much hotter than the ambient plasma and distributed as rings in velocity space. The development of a Tethered Satellite System will soon lead to the operation of an MHD dynamo powered by the motion of the long conducting tether through the conducting ionospheric plasma. Since the ionosphere itself will serve as an electrodynamic component of the resulting circuit, much stands to be learned about the way in which the ionosphere carries currents, and this new knowledge should carry over to our understanding of natural electrodynamic phenomena.

Despite this record of initial accomplishments and the demonstration of considerable promise, budgetary pressures and the Challenger disaster have in recent years led to the cancellation of the Spacelab mission known as Space Plasma Laboratory, which was to have been the centerpiece of the active experimentation effort. As NASA recovers from Challenger, and prepares for the Space Station, it is time for a reassessment of active experimentation as a contributor to the goals of magnetospheric physics and space plasma physics. In particular, the flight of a strong magnet on the Space Station for the Astromag cosmic ray spectrometer facility will lead to an important experiment of opportunity for the refinement of space plasma theory in the area of comparative magnetospheres.

5.0 Report of the Solar Physics Panel

5.1 Science Accomplishments

Recent accomplishments in solar physics can be grouped by the three regions of the Sun: the solar interior, the surface, and the exterior.

5.1.1 Interior

Observational work on the structure and dynamics of the solar interior began with the neutrino observations of R. Davis. The measured, smaller-than-predicted neutrino flux has led to rethinking about the physics of stellar interiors and the fundamental physics of neutrino interactions with ordinary matter. More recently, the development of "helioseismology" has provided a capability for probing the solar interior.

Among the major discoveries thus far, we find the following:

> The location of the base of the convection zone has been determined empirically.
>
> The solar rotation has been mapped out, demonstrating that the bulk of the interior mass rotates essentially at the surface rate.
>
> The differential rotation in latitude penetrates unchanged radially inward, in conflict with the predictions of large-scale hydrodynamic simulations.
>
> Sunspots (or their buried magnetic roots) absorb p-mode energy, offering us the possibility of mapping out these condensations of magnetic flux below the photosphere "tomographically," and thence learning about the physics of the magnetic flux concentrations causing the solar activity.

5.1.2 Surface

The photosphere-chromosphere region is the interface between the interior processes and those of the outer atmosphere and solar wind. The photosphere is the site of the solar luminosity. It is the presumed locus of much of the physics involved in magnetic activity, from the flux concentrations of the facular network and of sunspots to the large-scale distortions of the coronal field that produce the remarkable phenomena of the solar corona, including flares and coronal mass ejections. This region must be observed at high angular resolution as one of the most fundamental observational goals of solar physics.

Among the recent major discoveries in studies of the photosphere and chromosphere, we can list the following:

> The discovery that, at high resolution, the facular granules underlie bright CaII emission features of the plage. These tiny regions of the solar atmosphere thus resemble early-type stellar atmospheres, just as cool sunspots resemble late-type atmospheres.
>
> The discovery, again at high resolution, that the solar granulation does not resemble classical Benard convection, instead following an "exploding granule" pattern.
>
> The measurement of subtle horizontal flows (*e.g.*, that of the differential rotation) and the apparent diffusive dissipation of magnetic flux, together with the order imposed by the ill-understood interior dynamo, around the surface of the Sun over solar-cycle time scales.
>
> The discovery, using vector magnetography, that regions of strong magnetic shear tend to coincide with the sites of flaring energy release.

5.1.3 Exterior

The external region of the Sun—the corona—and its outward extension—the heliosphere—contains the most dramatic evidences of solar variability. This can be observed in virtually every spectral band and via thermal plasma (the solar wind) and high-energy particle species, even including neutrons. The phenomena range from the explosive energy releases of solar flares to the steady expansion of the solar wind. The corona is an astrophysical plasma laboratory, amenable to study by both *in-situ* and remote-sensing measurements. The coronal luminosity varies most strongly at the extremes of wavelength, with flares producing intense high-energy emissions in the hard X-ray and gamma-ray bands (as well as broad-band radio emissions) as a result of powerful and little-understood particle accelerations.

A short list of recent discoveries in this regime includes the following:

> The discovery that solar flares can accelerate ions to GeV (cosmic ray) energies on short time scales (a few sec), and produce a rich gamma-ray emission-line spectrum.
>
> The elucidation of mechanisms for enhanced mass loss (*i.e.,* the ablation of the chromosphere during flares).
>
> The discovery of field-aligned current systems in coronal magnetic structures.
>
> The discovery of microflares in hard X-ray, UV, and EUV observations.
>
> The development of multi-layer mirror technology, and the first successful applications to XUV and soft X-ray coronal imaging.

5.2 Future Science Problems/Science Themes

During the coming decades, solar research will explore the limits of what can be observed. At one extreme, beginning with OSL, we expect to explore the smallest physical scales at which the fundamental solar processes take place. At the other extreme, we increasingly realize that the Sun can only be understood from a global viewpoint; *i.e.,* when considered and observed at a wide range of spatial, temporal, and spectral scales from multiple locations. Determination of structure must take place in three dimensions, using time series which have a length of a considerable fraction of the magnetic activity cycle period, and simultaneous viewing of the solar surface.

Three major themes have been identified which are consistent with the recognition of the global viewpoint as an essential element of an integrated research strategy for the Space Physics Division. The themes are as follows:

> Identification of the variable nature of the Sun as key in the modulation of the volume of the solar system and the heliosphere. The Sun is the causal factor in the structuring of the three-dimensional volume of these regions, and its activity drives the modulation of this volume.
>
> Investigation of the shorter-term variations associated with the evolution of the magnetic activity cycle. Flares, active regions, coronal holes, and their associated high-speed wind structures are all shorter-term consequences of the activity cycle which directly influence the solar neighborhood.
>
> Investigation of the magnitude and significance of longer-period solar variability and its influence on various component elements of the solar system and heliosphere. These elements range from the changes which are observed over fractions of a day to those which occur over the range of the magnetic activity cycle, and include the determination of the interior structure and variation of the star as well as the forcing of physical processes in the magnetospheres and atmospheres of planets.

The following series of scientific questions immediately presents itself based on the global perspective of the Sun as the magnetic variable star located at the center of the solar system:

> ***Interior of the Sun.*** What is the nature of that portion of the Sun which lies below the photosphere? What are the dominant structures and physical processes of the interior, and how do these evolve over the time scales of interest?
>
> ***Generation of the Magnetic Activity Cycle.*** What are the physical processes which determine the generation of a magnetic variation in the star? Of what significance is this variation in the modulation of other objects and structures in the solar system?

Energy Storage and Release. How is non-potential magnetic energy stored in the Sun, and how is this magnetic energy converted into other kinetic and thermal forms of energy? How are the energetic particles accelerated to high velocities as the active regions evolve and change?

Solar Activity. What are the physical processes which govern the nature of the plasma structures found in the solar atmosphere in active regions? How are dynamic processes initiated and maintained in the upper layers of the Sun and out into the heliosphere?

Solar Wind and Solar Interaction. What physical mechanisms couple the variability of the Sun to the other elements of the solar system; such elements as the magnetospheres and atmospheres of planets, the modulation of cosmic rays, and the structure of the plasma flowing away from the Sun in the form of solar wind?

Multiple perspectives and improved instruments, observing over long intervals from space-observing systems, offer unique opportunities for developing an increased understanding of the solar mechanisms which couple the Sun to the heliosphere, planetary magnetospheres, and our own Earth.

5.3 Science Measurements Required

The scientific themes and objectives discussed in the previous section require a large variety of solar measurements, some fundamentally new and others substantially improved over the present state-of-the-art. They may be grouped into three broad categories, as follows:

Simultaneous measurements of the Sun from new vantage points, including the solar poles, multiple azimuths in the ecliptic, and near the Sun.

The quest for higher spatial resolution in all temperature regimes of the solar atmosphere.

The long-term measurement of solar radiative and particle outputs which affects plasma and atmospheric processes throughout the solar system.

An exhaustive list of scientific problems and specific measurements has been compiled in the document entitled *Solar-Terrestrial Sciences: Report from the Science Strategy Workshop* (ed. P. Banks *et al.*, September 1988; see Table 5-2). In addition, a vigorous program of imaginative small experiments must be supported. This will permit the development of new measurement techniques and wavelength windows, the importance of which cannot be fully anticipated today.

5.3.1 New Vantage Points—Global Observations

Measurements using familiar techniques from new vantage points will provide fundamental new data for understanding the structure of the quiet and magnetic Sun and the activity cycle. The types of measurements include coronal morphology; UV/EUV/WL disk and coronal spectra/spectroheliograms for temperatures, densities, flow velocities, and chemical abundances; EUV/soft X-ray imagery, showing magnetic loop structure in the low corona and coronal holes; vector magnetic fields and Doppler velocities in the low chromosphere and photosphere; full-disk irradiance and velocity for helioseismology and luminosity variability studies; and zodiacal light photometry for following solar wind plasma into the heliosphere.

The polar view of the Sun will allow accurate measurements of the polar magnetic field, differential rotation, and meridional flow free from the extreme projection effect of viewing from Earth. The downward view of coronal streamers and mass ejections will show their acceleration and time evolution faithfully for the first time. The development and decay of active regions without interruption by rotation will be possible. Helioseismological probing of the interior will be free from the rotational splitting of the low-order modes.

Imaging of a portion of the solar surface or corona from multiple aspect angles can free our observations from both projection effects and line-of-sight averaging. Using two or more views from polar and ecliptic spacecraft, X-ray coronal images and longitudinal magnetic and velocity maps can be converted to full vector measurements in the photosphere and corona. With a full network of ecliptic spacecraft at 1 AU, we can combine these observations to measure the detailed evolution of coronal field connectivity and energy content during the life-cycles of active regions. The three-dimensional geometry of coronal structures can be reconstructed from multiple projections. The low-order global oscillations can be measured without the ambiguity caused by seeing only one solar hemisphere.

5.3.2 New Vantage Points—Simultaneous Close-in and Remote Sites

A combination of remote-sensing optical measurements and *in-situ* measurements of the solar wind acceleration region can provide unique information on physical conditions in this important region of the solar atmosphere/heliosphere. Remote-sensing imaging and spectroscopic measurements made from Earth orbit while a spacecraft or probe flies close to the Sun are required for provision of critical data on the lower atmospheric sources of the outflowing plasma sampled *in situ* by instruments on the probe. The physical conditions and processes in the lower atmosphere determine the structure and conditions to be found in the higher layers. The bulk of the plasma heating appears to occur within several solar radii of the Sun. In addition, the plasma changes from a collision-dominated plasma to a collisionless plasma; the ionization states "freeze in"; the coronal structure changes from predominantly closed (magnetically) to open; and the solar wind is believed to be accelerated to near supersonic speeds within a few solar radii of the Sun. *In-situ* particle-and-field measurements made close to the Sun can provide critical "ground truth" information for interpretation of remote-sensing data acquired in the same region. This is important because the latter types of data can be acquired over much longer periods of time and in a much larger number of structures than *in-situ* measurements made during brief near-Sun "fly-bys" of a solar probe. Finally, remote-sensing observations can observe coronal mass ejections from their low coronal origins out to large distances from the Sun.

5.3.3 High Spatial Resolution Over a Wide Temperature Range

High spatial resolution, coupled with the appropriate spectroscopic diagnostics required to measure basic plasma parameters (temperatures, densities, velocities, magnetic fields, and chemical abundances), is required to probe the structure of the solar atmosphere and acquire the basic data needed to provide empirical constraints and insights concerning the fundamental physical processes responsible for plasma heating and the transport of mass and energy at, and between, different levels of the solar atmosphere.

The OSL mission will provide long-awaited measurements of physical properties from the photosphere to the low corona with 100 to 500 km resolution. It is essential to complement this mission with high-resolution imaging and spectroscopy of high-energy radiations during the maximum of Cycle 23. The impulsive phase of a solar flare, for example, can energize both protons and electrons to relativistic energies in a short time, in flare kernels whose size has never been resolved. Sub-arc-second imaging and high-resolution gamma ray spectroscopy ($R>1000$) are needed, along with simultaneous photospheric and coronal imaging (from OSL if possible), to provide the context of the flare.

OSL will have enough resolution to see the individual flux tubes in the photosphere (where the dimensions are about 100 km) and in the chromosphere and corona (where the diameters should be about 1000 km). OSL will reveal the advection, shaking, and shuffling of these elementary flux tubes. This will be a tremendous advance for understanding the physics of solar magnetic activity.

The subsequent step, to clearly resolve structure and activity within and between these flux tubes, requires another advance in resolution into the realm of 10 km. Resolution of this order will reveal the following:

The current sheath that bounds each flux tube in the photosphere.

Twist within a tube.

Field shear (current sheets) between tubes.

Waves excited within tubes by the photospheric and subphotospheric forcing (turbulent convection and oscillations).

Location and form of microflaring activity within and between tubes.

These features are expected to have enough optical depth or emission measure to be seen, at least when viewed edge-on. Such observations at 10 km resolution will certainly be needed to pursue the physics of the fine-scale magnetic phenomena discovered and characterized at 100 km resolution by OSL.

5.3.4 Solar Outputs and Solar Variability

The output of the Sun, viewed as a star, must be measured continuously so that the effects of its variability on the Earth and on space plasmas can be studied. These measurements must include the solar constant and the spectral irradiance for all wavelengths from soft X-ray to the visible. In addition, spectral images for some wavelength bands must be collected over the same time base, so that the solar mechanisms which cause the variability can be determined and eventually predicted. (High-resolution observations, see sections 5.3.1–5.3.3 above, are particularly critical for the latter.) Measurements of the output of low-energy (solar wind) and high-energy solar particles must include data on the both the particles and the magnetic fields.

5.4 Mission Concepts (Overview)

5.4.1 High Energy Solar Physics (HESP)

5.4.1.1 HESP Mission Description

The high-energy neutral radiations (hard X rays, gamma-rays, and neutrons) contain direct information about the acceleration of non-thermal particles in flares and other forms of solar magnetic activity. The impulsive phase of a solar flare, for example, can energize both protons and electrons to relativistic energies, in some cases within tens of seconds. The accelerated particles contain an appreciable or even major fraction of the total flare energy. Observations of bremsstrahlung from the electrons, and of nuclear radiations of several types from the high-energy ions, can reveal the propagation of these particles in the solar atmosphere, showing us the actual site of their acceleration. With HESP observations, we will accomplish the following:

Identify particle acceleration mechanisms in solar flares and coronal disturbances.

Study the flow of the energy represented in the high-energy particles.

Study the plasma physics of non-thermal particle propagation, trapping, and release from the Sun.

The technology now exists for high-resolution imaging (< arc second) and spectroscopy (R>1000 in the nuclear line region) of these radiations, even including the neutrons. The HESP mission proposed here will exploit this technology in an Explorer-class mission (*i.e.,* small to moderate in scope). Related imaging technology has been implemented at low energies and relatively low resolution on the Solar Maximum Mission and Hinotori satellites, and will be flown at 7 arc seconds resolution (FWHM) on the Solar-A (to be launched in 1991). The HESP mission will give us a first opportunity to combine such imaging technology with sensitive high-energy gamma-ray spectroscopy. The maximum science return from such observations requires a suite of simultaneous measurements at wavelengths capable of defining the photospheric and chromospheric dynamics of the flare environment; vector magnetic-field measurement is one of the essential elements in this suite. Section 5.4.1.3 describes a strawman instrument complement.

5.4.1.2 Implementation Strategies

We can identify two different strategies for deploying HESP on a free-flying spacecraft. Both require an equatorial low-Earth orbit because of the high background radiation found at high inclinations. We note that the HESP science overlaps with that of the Pinhole/Occulter Facility (P/OF), currently under study as an attached payload for the Space Station Freedom (see section 5.4.6). The key to the implementation strategy is to begin observations by 1998, in time for the onset of flare activity in the next solar maximum. The HESP science would complement that of the ACE, especially in terms of abundance variability. The mission lifetime of HESP should cover at least three years, with an extension over the entire solar maximum and into the succeeding minimum strongly desired.

The two different strategies are the following:

> A self-standing mission with the full instrument complement listed, HESP would be capable of all of the observations needed to characterize high-energy phenomena in solar flares, at resolutions high enough to study the fundamental physics of energy build-up, release, and particle acceleration.
>
> If HESP were treated as an adjunct to other missions, such as the Orbiting Solar Laboratory, the instrument complement (and payload weight) could be significantly reduced. It would be absolutely required that observations from HESP and the missions it would complement be simultaneous. HESP in this case could consist of a single instrument, *i.e.,* a combined imager/spectrometer for hard X-rays and gamma-rays.

5.4.1.3 HESP Strawman Payload

The strawman payload for HESP is as follows:

Spectral Imager for Hard Radiations

High-energy detector	Germanium
Energy range	10 keV–10 MeV
Energy resolution	<1 keV
Angular resolution	<0.5 arc second
Field of view	Whole Sun
Time resolution	1 sec

Anticoincidence Shield Response

Radiation type	Gamma-rays, neutrons
Energy range	10–100 MeV
Time resolution	1 msec

EUV Spectrograph/Imager

Aperture	30 cm
Angular resolution	<0.5 arc second
Spectral resolution	TBD

White-light Telescope

Aperture	30 cm
Angular resolution	<1 arc second
Field of view	Whole Sun

5.4.2 Global Solar Mission

5.4.2.1 Themes

Themes are as follows:

> Observe the entire Sun from different vantage points simultaneously, to study global magnetic, thermal, rotation, circulation, and oscillation properties never observable before.
>
> Combine these fundamental new observations with a mission-oriented theoretical program, to understand the origin of the solar magnetic cycle.

Obtain stereoscopic views of solar structures and events, revealing their true three-dimensional geometry for the first time.

Provide the platforms for a flare warning system for the Space Exploration Initiative, if necessary.

5.4.2.2 Specific Scientific Goals

5.4.2.2.1 Polar Orbiting Spacecraft

Baseline solar instruments include the following: UV/WL coronagraph, EUV/X-ray imager, longitudinal magnetograph/dopplergraph, low-resolution helioseismometer, radiometer, solar-wind photometer, and particles-and fields experiments. Objectives are as follows:

Measure the polar magnetic field accurately, during the time of polar field reversal near the peak of Cycle 24.

Measure the high-latitude differential rotation profile.

Detect the hypothesized meridional flow by both Doppler and tracer techniques.

Investigate for pole-equator temperature differences.

Observe coronal streamers continuously in time, with constant viewing geometry from above, to deduce the acceleration profile from the spiral shape.

Observe active regions continuously with constant viewing geometry.

Observe coronal mass ejections aimed toward the Earth to correlate the coronal instability with evolution of structures on the disk.

Observe the solar wind throughout the entire inner solar system from above with a Helios-type photometer.

Measure the solar wind *in situ* as a function of solar latitude.

Perform radio science experiments concerning gravity, the solar wind, and the corona during occultations.

Measure p-modes free of rotational splitting from the pole.

5.4.2.2.2 Ecliptic Stereoscopic Spacecraft (2–4, Depending Upon SEI)

Baseline solar instruments are as follows: UV/WL coronagraph, EUV/X-ray imager, longitudinal magnetograph/dopplergraph, low-resolution helioseismometer, radiometer, and particle-and-field experiments. Goals for these instruments are as follows:

Determine three-dimensional geometry of specific coronal structures and events, including CME's, by reconstruction from multiple projections.

Observe magnetic topology of coronal magnetic fields from multiple projections seen in soft X-rays.

Observe vector magnetic field in the photosphere from longitudinal fields with multiple lines of sight.

Combine these two observations to study the detailed evolution of coronal field connectivity and energy content during the entire life cycle of active regions.

Measure low-order global p-modes free from the ambiguity introduced by observing less than half the solar surface.

Measure solar-cycle effects on the convection zone via helioseismology.

Search for g-modes by measuring the vector velocity in the photosphere, allowing cleaner suppression of solar noise sources from the predominantly horizontal velocities of the modes.

Measure global solar constant by integrating over multiple lines of sight.

Conduct definitive studies of periodicities of solar activity, such as active longitudes, sunspot "nests," and the 155-day flare periodicity.

Provide warning of large active regions rotating onto the Earthward hemisphere for flare alerts.

5.4.3 The Space Exploration Initiative

The Space Exploration Initiative (SEI) may make it possible to do unique kinds of science in many fields, including solar physics. We discuss here several aspects of this endeavor. The key to this application of solar physics will be the deployment of networks of solar observation satellites, initially for data-gathering and research, and ultimately as an operational warning system.

5.4.3.1 Protecting the Astronauts

Hard photons and "solar cosmic rays" present a substantial health hazard for astronauts. The long voyage to Mars, in particular, would expose astronauts to solar hard radiation as a result of solar flares. Our knowledge of flare occurrence patterns is not deep enough, either empirically or physically, to permit our predicting times and intensities with sufficient accuracy to afford much confidence to space travelers. For this reason, we feel that a concerted effort leading to much better knowledge of flare occurrence must be made well in advance of manned missions into deep space.

Warning of a solar flare, as far as possible in advance, would be extremely helpful. If such a warning could define windows of safe travel opportunity, that would be even better. We propose a two-pronged approach for this warning: empirical and physical.

5.4.3.1.1 Steps Toward Empirical Definition of Flare Occurrence

Solar activity and flare occurrence are known to be highly organized in time and space, in the sense that occurrence patterns are far from random. The quantitative details of this non-random behavior are not known well because of the incompleteness and inappropriateness of solar-flare data, especially as gathered at ground-based observatories. For example, the H-alpha importance of a flare in and of itself can err by many factors of ten as a predictor of the hard radiation associated with the event. Indeed, the classical manifestations of a solar flare may not have much to do with the intense, long-lived particle acceleration responsible for most of the risk.

Therefore, the first goal of an observational program dedicated to astronaut safety would be the simple collection of relevant data, as abundantly and extensively as possible, in order to define the nature of the problem statistically. The observations needed would include the following:

Particle fluence measurement. These measure ments should be defined by the need to determine the dose experienced by astronauts, *i.e.,* should have as much fidelity as possible.

Flare occurrence data. The location and timing of the flare should be determined unambiguously.

Flare physical parameters. The data should define enough of the physical parameters of a flare (*e.g.,* soft X-ray fluence, "superhot" temperatures, gamma-ray line intensity, chromospheric morphology, sunspot configuration, microwave or other radio manifestations, or other features to be decided after appropriate study).

Photospheric flows and magnetism. A relatively simple set of observations, analogous to those of the SOUP experiment on Spacelab-2, could provide information on the distribution of shear (or $v \times B$) of key physical significance (see the next section).

Armed with data of this type, collected from a network of spacecraft able to view the entire solar surface at all times (at least in the active latitudes), a proper empirical basis for flare occurrence could be constructed for the first time. In view of the major engineering decisions that should await this kind of knowledge, the establishment of even preliminary forms of this network should take place on a crash program basis, with the first elements in place as soon as 1993. This initial network should grow to a total of three spacecraft, at one AU and dispersed in helio-longitude, for full coverage of the solar disk.

5.4.3.1.2 Prediction Based Upon the Physics of Flares

At the same time, and on some of the same vehicles, a series of observations devoted to a physical understanding of flare occurrence should take place, again with highest urgency. The linchpin of these observations would be the Orbiting Solar Laboratory, which will provide extraordinary improvements in our knowledge of physical conditions in the photospheric and chromospheric regions of solar flares, including especially the active regions and their environments preceding the eruption of magnetic fields. Such a simple observation as the horizontal flow patterns of the photosphere ($v \times B$) may well provide the physical key to flare energy build-up and thus imminent flare danger.

The high-energy radiations from solar flares are likely to be directly related to the particles emitted into interplanetary space, based upon existing information about particle spectra and event morphology. Thus we should tackle these observations as rapidly and effectively as possible. A new and advanced "solar maximum mission," the HESP Mission defined for the first time here (section 5.4.1), or the Pinhole/Occulter Facility (sections 5.4.5.2 and 5.4.6), should be deployed well in advance of the solar maximum, ideally by 1998 at the latest. One of the key objectives of such observations will be to clarify and extend the remarkable 155-day periodicity in the most energetic solar flares, noted first during the maximum of 1980; such observations can, therefore, help to clarify flare occurrence patterns as well as to define physical conditions of the most relevant types.

5.4.3.1.3 A Note on Infrastructure

The interplanetary network of observatories described above carry instrumentation producing imaging data with relatively high resolution (in arc seconds) and temporal sampling (tens of sec average interval). The data requirements are, therefore, extreme, at least for deep-space missions, on the order of 100 kbps on a continuous basis. NASA will need to make allowance for this requirement, since uninterrupted data is an important attribute of an ideal data set.

5.4.3.2 A Warning System

The interplanetary network of solar and heliospheric observatories, described above, should evolve into a warning system to be used operationally during astronaut excursions. Especially during voyages to Mars or other distant locations, the warning system must be capable of direct communication with the astronauts (*i.e.*, bypassing the long time delays required for links to and from the Earth). We would hope that in one decade's time, the flare warning system can be virtually autonomous, based upon the data gathered in the intervening years and upon modern information science techniques (artificial intelligence, neural networks, expert systems, etc.).

5.4.3.3 Science en Route

Solar science obviously will benefit tremendously from the data gathered in this program, even though its motivation is for a practical application and not entirely for research objectives. The OSL and HESP programs, of course, are planned research-quality tools, and indeed the operational and research objectives coincide in the need to develop precise knowledge of flare prediction—such knowledge would be most soundly based upon comprehensive knowledge of the physics of flares, their necessary conditions, and the causes of their eruption.

The infrastructure developed during human transportation to the planets can be of great use for still more advanced solar observations. In noting this, we recognize that the information gained over the next decade will not suffice completely to solve the flare problem, and will instead provide partial solutions and stimulating new questions in similar measure. Interesting research usually works this way.

Observatories in space have many advantages for sophisticated observation; for example, in permitting unrestricted access to the whole spectrum of waves and particles. In addition free space has certain engineering advantages: no gravitational stresses (little limit on experiment volume or geometry), stable thermal environment, uninterrupted sunlight, and minimal or zero interference from human nuisance. At the same time, the transportation nodes developed for interplanetary travel will probably confer the benefits of frequent access and material transportation, and human presence when needed for repair, adjustment, or deployment. As an important by-product, then, the Space Exploration Initiative may make it possible to obtain solar observations fully as revolutionary as those of the Apollo Telescope Mount in 1973–1974.

5.4.3.4 Science Using the Lunar Surface

Although most advanced solar observations that we can speculate about for the 21st century should probably be done from free space (if not from the Earth's surface) for reasons of economy and efficiency, there are nevertheless several items for which the lunar surface offers some interesting advantages. We discuss some of these, not necessarily in priority order, in the following paragraphs:

> ***A lunar radio interferometer.*** The lunar surface offers vast real estate and a stable platform, which could be used for a set of autonomous radio antennae. These would comprise the elements of a large interferometer, perhaps spread over hundreds of kilometers of the lunar surface. Each unit could have a high degree of autonomy, with its own solar energy supply and communications link to a central "phasing node." The phasing node for a large array would ideally be a lunar satellite, or set of satellites, capable of interrogating each element and correlating the data to obtain visibility functions. Such an approach would work best at low frequencies, 10 kHz–10 MHz, and would permit unprecedented angular resolution for every astronomical target, not excluding "the Earth as a star." The Earth's magnetosphere is known to be very bright as a result of auroral particle activity, and remote sensing from the distance of the Moon would be about right for a comprehensive view.
>
> ***Large gamma-ray observatories.*** The lunar material itself can serve as a massive absorber for background reduction. Proposals for the use of the water supply of a lunar colony as a potable detector (analogous to the present I.M.B. and Kamiokande observatories) exist.
>
> ***Advanced Pinhole/Occulter Facility.*** An extension of the Pinhole/Occulter concept could make it possible to obtain 0.01 arc second images of hard X rays and gamma-rays from solar and celestial sources.
>
> ***Large optical instruments.*** The low-gravity continuous sunlight during the lunar day, and frequent (biweekly) eclipses of the Sun at lunar dawn and lunar night, can provide unique opportunities for operation of large optical instruments capable of acquiring very high-resolution solar measurements.

5.4.4 Solar Probe Mission Context

The proposed Solar Probe will acquire uniquely detailed measurements of particles and fields along its flight path which is expected to come to within four solar radii of the Sun. It is vital that these highly unique, critical data be placed in context of the larger-scale time-varying structure of the solar atmosphere. As indicated in section 5.3.2, remote-sensing imaging and spectroscopic measurements made from Earth orbit while the Solar Probe flies close to the Sun are required for provision of critical data on the lower atmospheric sources of the outflowing plasma sampled *in situ* by instruments on the Probe. The physical conditions and processes in the lower atmosphere determine the structure and conditions to be found in the higher layers. The bulk of the plasma heating appears to occur within several solar radii of the Sun. In addition, the plasma changes from a collision-dominated plasma to a collisionless plasma; the ionization states "freeze in"; the coronal structure changes from predominantly closed (magnetically) to open; and the solar wind is believed to be accelerated to near supersonic speeds within a few solar radii of the Sun. *In-situ* particles-and-fields measurements made close to the Sun can provide critical "ground truth" information for interpretation of remote-sensing data acquired in the same region. This is important because the latter types of data can be acquired over much longer periods of time and in a much larger number of structures than *in-situ* measurements made during brief near-Sun "fly-bys" of the Solar Probe. Finally, remote-sensing observations can observe coronal mass ejections from their low coronal origins out to large distances from the Sun.

UV/EUV/white-light coronagraphic instrumentation is required to image the white-light corona from the solar surface out to several tens of solar radii and to acquire detailed spectroscopic measurements of coronal densities, temperatures, velocities, chemical abundances, and ion states out to 5 to 10 solar radii (distances beyond the closest approach of the Probe). A low-coronal imaging instrument is required to image the low coronal structure on the disk (EUV/XUV and/or soft X-ray instrument). The Pinhole/Occulter Facility proposed for the Space Station Freedom (see section 5.4.5.2) could provide the desired capability. A second alternative is to add or upgrade the appropriate instrumentation on the Earth-orbiting spacecraft of the Global Solar Mission (see section 5.4.2). A third possibility would be a small or low-end moderate mission in Earth orbit. The instruments should be at least SOHO-class, preferably larger (for the coronagraphic instrumentation) in order to permit detailed spectroscopic measurements to be acquired as far from the Sun as is feasible.

5.4.5 Solar Physics on Space Station Freedom

The Space Station Freedom will carry instrumentation for solar physics in three categories, as defined below. Although at the time of writing, the decisions regarding scientific uses of the Space Station are incomplete, we regard its advertised capabilities with high interest and urge the development of a scientific observing program if and when this becomes possible.

5.4.5.1 Early Attached Payload Element

A suite of solar XUV telescopes has been selected for early deployment on the Space Station. This telescope array, known as the Ultra High Resolution Extreme Ultraviolet Spectroheliograph, will carry out multi-wavelength observations with innovative technology based upon synthetic multilayer normal-incidence mirrors.

5.4.5.2 Second-Generation Attached Payload Element

The Pinhole/Occulter Facility will contain state-of-the-art coronal and high-energy instruments, with innovative use of an external occulter at the tip of a 50-meter deployable boom (see section 5.4.6). These instruments, if deployed in time for the solar maximum of 1999, can play the role of a solar maximum observatory in place of the HESP free flyer.

5.4.5.3 Small Attached Payloads

A capability for small attached payloads, on a fixed and simple interface, could serve an analogous role on Space Station Freedom as is presently served on the Space Shuttle by GAS, Hitchhiker, and other "quick" and small payloads. Such a facility would be of extreme attractiveness for innovative instrument development, student involvement, and other uses now reserved for the suborbital programs.

5.4.6 Pinhole/Occulter Facility

The Pinhole/Occulter Facility is being studied as a second-generation attached payload for the Space Station Freedom (see section 5.4.5.2). It could also be flown as a free-flyer. An advanced version could be operated from the lunar surface. The facility uses large-aperture optics for high-resolution imaging and spectroscopy in X rays through gamma-rays (pinhole component) and in the UV/EUV/visible coronal radiations (occulter component).

The scientific objectives are as follows:

Solar Physics

The impulsive phase of flares.

Characterize the conversion of magnetic energy into material heating and motions.

Determine the mechanism responsible for this energy dissipation.

Solar Activity

Measure the dynamic events in the "quiet" Sun that cause unexpected brightenings, flows, quiescent prominences, and other manifestations of non-thermal and geometrically complicated structure.

The Corona and Transients

Study the temporal variability of the classical corona over a wide range of spatial scales (from jets of chromospheric material, heating in magnetic loops, through coronal transients).

Quantify the generation of high-energy particles in the corona.

Determine the mechanisms for storage of magnetic energy, energy release, transport, and dissipation; and the driving mass ejections and acceleration of high-energy particles.

X-ray and Gamma-ray Astronomy

Provide large-area and high-angular imaging of a variety of galactic sources.

Map extended sources (*e.g.*, synchrotron nebulae, clusters of galaxies, jets and lobes, and SN1987a).

Resolve confused regions (*e.g.*, the galactic center, M31 and other normal galaxies, globular clusters, and the extragalactic sky).

Provide spectroscopy, at energies >10 keV, of a variety of galactic sources including investigating the following:

The origin of hard X-ray and gamma-ray emission from active galactic nuclei.

The origin of annihilation and nuclear gamma-ray lines.

Spectral features in galactic sources.

Predicted, but unobserved, spectral features.

5.4.7 Solar Variability Explorer

The solar output at ultraviolet and X-ray wavelengths has profound effects on the upper atmosphere of the Earth. The chemistry of the atmosphere, the energy budget, and perhaps the dynamics of the stratosphere and lower mesosphere, are solely determined by the incoming UV radiation in the 120 nm<λ<300 nm band, while XUV radiation at 15<λ<100 nm determines the energy budget of the thermosphere. X rays are absorbed or scattered in many layers. The solar-cycle variations of the thermosphere are governed by the strongly variable solar XUV radiation. Ozone concentration in the stratosphere is dependent on the solar UV radiation between 180 and 300 nm. It has been estimated that a decrease of 5% of the solar radiation at 250 nm results in an ozone column density change of approximately 2.5%. Solar-cycle-induced ozone column-density variations are therefore comparable to long periodic variations caused by chemicals released from the surface of the Earth. It is impossible to distinguish between the two effects as long as no precise knowledge exists of the Sun's 11-year variability at the critical UV wavelengths. The list below shows the required precision and accuracy of the solar UV spectral irradiance over a solar cycle, a solar rotation, and short intervals such as flare-induced variations.

Short-term solar UV variability (days to months) is caused in first-order approximation by excess radiation of plages (UV intensity is modulated by the evolution of the plages, and by their passage across the solar disk as a result of the solar rotation). However, there are strong indications that a so-called third component may significantly contribute to the 11-year cycle variation. This third component may consist of small, isolated chromospheric brightenings distributed over the whole solar disk, or a uniform variability of chromospheric temperature. It is obvious that total solar irradiance measurements cannot distinguish between the two- or three-component model; however, the understanding of the solar cycle and its underlying magnetic variations requires a resolution of this problem.

Therefore, a need exists for synoptic observations of the Sun over a solar cycle at all UV wavelengths with good spatial resolution (1 arc second) and appropriate time resolution (1 day).

5.4.8 Janus

5.4.8.1 Mission Description

The Janus mission is conceived as a simultaneous attack on solar and terrestrial physics in relationship to variability, including global change. The solar scientific interest in this centers on the characterization and physical understanding of the solar luminosity. Known forms of solar variability extend over the presently-known range of time scales (up to about a decade), and proxy data suggest strongly that longer time scales of variability exist and are important for the understanding of the solar interior. The long-term observation of solar total and spectral irradiance variations, when coupled with well-calibrated images in key wavelengths, will provide a new and important channel for understanding basic physical processes in the solar interior. These include convection and other forms of energy transport, rotation, generation of magnetism, and the roots of solar activity.

The keys to the Janus solar observations are mission longevity and measurement precision. To determine the secular variation of total irradiance or luminosity by intercomparing two sunspot minima, for example, may require a level of systematic error better than one part in 100,000 over the eleven-year time scale. At this level of systematic error, known forms of variation due to solar surface features (sunspots, faculae, and the "active network") compete strongly; therefore Janus must include imaging instruments capable of helping to distinguish among these components, each of which in turn also contributes to our knowledge of solar interior dynamics.

	0.1.5–15 nm Soft X-rays		15–100 nm XUV		180–300 nm EUV	
Time	Prec.	Acc.	Prec.	Acc.	Prec.	Acc.
11 Years	10%	20%	5%	10%	<1%	<5%
25 Days	5%	20%	2.5%	10%	<0.5%	<5%
~ Minutes	5%	20%	2.5%	10%	<0.5%	<5%

5.4.8.2 Janus: The Other Disciplines

Other scientific disciplines interested in solar forcing would benefit from simultaneous observations: heliospheric physics, magnetospheric physics, and atmospheric science. These may require different or multiple platforms, most of which would be consistent with the solar observational requirements. Orbital locations that have been mentioned include the L_1 Lagrangian point, from which telescopes could study the Earth from a distance; polar geosynchronous orbit; the surface or vicinity of the Moon (perhaps superior for magnetospheric imaging), etc.

5.4.8.3 Solar Instrument Complement

The solar instrument complement for Janus is as follows:

- Active cavity radiometer.
- Spectral irradiance monitor.
- Full-sun visible imager.
- Full-sun chromospheric imager.
- Heliospheric imager.
- Soft X-ray telescope.

5.4.9 Small Missions

A number of small solar missions have been discussed in various forums. These are listed below. A subset of these are also described in Appendix A.4, "Mission Requirement Sheets."

HESP. High Energy Solar Physics (see section 5.4.1 above).

Solar Variability Explorer. Measure spectral irradiance from 150 to 4000 angstroms, (see section 5.4.7 above).

Solar Composition Explorer. Measure spatial variations in coronal chemical composition. Variable coronal composition using XUV-EUV spectroscopy.

Solar IR Explorer. Exploit advances in infrared technology for probing the photosphere/chromosphere interface.

Coronal Imager. Acquire full-sun synoptic data on the structure of the inner corona, synoptic maps of solar wind velocity at the coronal base for correlation with ACE, etc.

Solar EUV/XUV Explorer. Study dynamics, mass and energy flow in the chromosphere-corona, and small-scale variability over the temperature range 10^4–10^7 K.

Solar Luminosity Explorer. SMEX version of SVE.

Flare Radiation Budget Explorer. Measure radiation flux with good spectral resolution from 0 to 10 keV to determine the radiation spectrum produced during solar flares.

Tomographic Hectometric Explorer. Detection of 10 kHz to 10 MHz radiation from multiple spacecraft to perform interferometry of interplanetary radio events.

Flare Build-up Explorer. Measurement of the vector magnetic field, X-rays, and XUV with sub-arcsecond resolution to analyze pre-flare build-up of magnetic energy in active regions.

Soft X-Ray Spectroscopic Explorer. Very high-resolution soft X-ray spectroscopy to derive accurate temperatures and densities in coronal structures.

Hard Radiation Anisotropy Mission. Multi-spacecraft measurements of hard radiation photons to detect the presence of beamed radiation; also valuable for cosmic gamma-ray burst observations.

Heliospheric Tomography Mission. Stereoscopic 3-D detection of density enhancements in the interplanetary medium to trace the movement of coronal mass ejections from the Sun to 1 AU and beyond.

Ultra-High-Resolution EUV Explorer. Exploit multi-layer mirror technology to provide tenth arc-second imaging in UV and EUV with near diffraction-limited normal incidence optics, and active image stabilization to study the microphysics of the transition region and low corona.

Neutral Atomic Imager. Detection and imaging of neutral atoms emanating from the Sun, including imaging to reveal the solar or interplanetary sources of accelerated neutrals.

Gamma-ray Spectroscopy Mission. Gamma-ray spectroscopy of solar flares to understand acceleration processes, fractionation, and transport processes. Added benefits accrue, if coordinated with ACE and Wind.

5.5 Supporting Research and Technology

5.5.1 Enhancements to Supporting Research and Technology

The quality and quantity of science from future solar missions such as SOLAR-A, SOHO, and OSL depend on the vitality of the solar science community. Observational advances require development of new instrumental and observational techniques which exploit both existing and state-of-the-art technology. Past experience has demonstrated that suborbital programs have played a critical role in development of new instrumentation. Recent examples include advances in helioseismology (ground-based effort), the HRTS instrument, UV/EUV reflecting coronagraphic instrumentation, multi-layer mirror XUV, and soft X-ray instruments. The funding for individual sounding-rocket experimental teams has been eroded by inflation. Advances in balloon technology provide excellent potentials for developing and testing new instruments. Advances in computer technology and developments in two-dimensional detectors are providing new opportunities and challenges in developing techniques for handling large data bases. Because of these factors, we recommend a major augmentation to the funding for solar suborbital programs (including establishment of a solar balloon program) and for advanced technology development. We also recommend significantly increasing the level of support for the solar research and analysis program.

5.5.2 Educational and Programmatic Considerations

5.5.2.1 University Research and Education

The discipline of solar physics is currently poorly represented in universities, and is consequently hampered in the development of a strong theoretical and experimental personnel base for future research. Several initiatives would specifically address this problem. First, the NASA Graduate Student Research Fellowship program, which funds graduate students semi-independently of a primary advisor, should be greatly expanded. This very successful program has commendably increased its student enrollment beyond allocated levels by *ad hoc* additional funding supplied by various OSSA Divisions; but we urge that NASA instead consider simply increasing the scale of this program. Second, stronger connections between universities and national research centers should be encouraged. This could be done by establishing more cooperative research programs, expanding visitor programs (at both the postdoctoral and faculty level), and increasing the size of student visitor programs. The latter could be done through the NASA Graduate Student Research program, which at present funds students only at universities or NASA centers.

These remarks also apply to observational and instrumental solar physics.

5.5.2.2 Facilitating Solar Research

To facilitate solar research through minor restructuring of existing funding programs, NASA contracts/grants should have funding periods ranging from one year to five years, with the length of the funding period being determined by the quality and the requirements of the proposal.

5.5.2.3 Integrated Support of Solar Research

It is important that NASA take an integrated approach to the support of solar physics, particularly with regard to theoretical and observational research and to solar and related astrophysical research. Recommendations include the following:

> When possible, a balance of support of theoretical and observational research should be provided at a particular institution, but the two forms of support should remain independent so that "house theorists" and "house observers" are not created. At the same time, we strongly

urge NASA to improve its past and present record of funding minimal amounts of science in conjunction with instrument proposals. This has led to the unfortunate situation that theoreticians are recruited as co-investigators on instrument proposals, contribute to the credibility of the proposal during peer review, and then are not funded to provide substantive scientific input prior to launch.

NASA's Space Physics and Astrophysics Divisions should develop a jointly administered fund to support interdisciplinary solar/astrophysical research. Other agencies should consider establishing similar arrangements, as appropriate.

5.5.2.4 Computing

Computer requirements are as follows:

Supercomputers. A uniform capacity for transfer of large data sets between users and supercomputers should be provided for all users.

Workstations. Workstations are becoming essential tools for both experimentalists and theorists in the analysis of their "data." For this reason, we recommend that contracts and grants should provide for both the purchase and maintenance of such workstations.

5.5.2.5 Theory Initiatives

The NASA Solar-Terrestrial Theory Program (STTP) has made a commendable start in the support of theoretical work which is not directly mission-oriented. As a number of National Academy of Sciences reports have noted, provision of such support in addition to more mission-related theoretical studies is essential for the health of the space physics disciplines.

These reports also noted that theory needs to be supported on two distinct scales: first, at the individual investigator level; second, at the level of group efforts with significant "critical mass." The STTP program indeed was created initially with the specific intention of responding to this second need.

However, other concerns include the following:

The current typical grant size of the NASA STTP is well below what is desirable for support of "critical mass" theory groups at universities. This desired mean support level has been discussed by NASA, and projected at the roughly $300K level, but has never been implemented. We recommend augmentation of the current program in order to increase the mean grant size to the previously discussed support levels.

The bulk of current NASA theory grants to individuals is funded through the SR&T budget, in which there is substantial pressure to focus funding on directly mission-related work. This means that theoretical studies which are not directly mission-related are strongly discouraged, contrary to the recommendations of previous National Academy studies. We recommend that NASA modify the ground rules so that such grants can be funded, based on the peer reviews.

At present, there is no mechanism for maintaining balance between experimental programs, data analysis, and theory. We recommend that NASA establish a modest "tax" on the ongoing flight and data analysis programs which will maintain this balance.

5.5.3 New Technology Issues for Future Solar Missions

Several solar missions require high-resolution imaging from deep-space platforms in high-radiation environments. Two-dimensional image sensors with much greater radiation tolerance than present-generation detectors will be needed to acquire the data. Current charge-coupled device (CCD) arrays approach theoretically ideal sensors for imaging in visible light, and they are very competitive for many IR, UV, and soft X-ray instruments as well. However, their performance degrades steadily in a radiation environment, and permanent blemishes can accumulate. These problems are matters of serious concern now for Solar-A, SOHO, and OSL instruments, and they are potentially even more serious for long-duration, deep-space missions. Research is needed on methods to limit the radiation sensitivity without compromising the otherwise outstanding performance, leading to modified designs and space-qualified rad-hard sensors. If necessary, materials other than silicon, such as gallium arsenide, should be explored and space-qualified.

High-resolution imaging in deep space leads to another requirement for new technology. Since dynamic solar phenomena are being studied, we can safely assume that telemetry rates will never match the raw data-gathering capability of the instruments. Therefore, considerable on-board intelligence and computing power will be needed to reduce the bit-rate required without eliminating the scientific return, even when discovery-type data is being collected. On-board image processors will combine many raw images into one physical measurement, select subsets for transmission, and encode the results for optimum usage of the available bandwidth. New technology is needed for digital components (microprocessors and memories) which are space-qualified, have low power requirements, and are radiation-tolerant and/or fault-tolerant. Considerable scientific work will be needed to develop the algorithms for data selection and compression. The investigators must have confidence that discoveries will not be overlooked in the on-board selection process, and that reconstruction of the data from the compressed forms will be faithful.

Other technology issues for specific missions are given in Appendix A, "Mission Requirement Documents."

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6.0 Report of the Theory Panel

6.1 Introduction

The purpose of research in the discipline of space physics is to improve our understanding of the natural systems encompassed by this discipline, and their underlying physical processes. The ultimate goal of this research is to develop an understanding which is sufficiently comprehensive to allow realistic predictions of the behavior of the physical systems. Theory has a central role to play in the quest for this understanding.

Toward this end, theory must first develop a framework for interpreting observations of the various physical systems. Next, using this framework as a basis, quantitative analytic and numerical descriptions of model physical systems must be developed and refined through comparison with observations. Ultimately, the model physical systems must be sufficiently similar to the natural physical systems, and the numerical and/or analytic descriptions of these model systems must be sufficiently refined to provide a high level of predictability of the observed behavior of the natural systems.

Because of the communality of the physical processes occurring in different regions of the solar system, theoretical research often transcends the division of space science into different branches (ionosphere, magnetosphere, heliosphere, and solar). This interdisciplinary aspect of theory defines special needs and suggests solutions that have been the topics of discussion by the theory panel.

The level of theoretical description that provides what constitutes an adequate predictive capability depends, at any time, on three constraints all of which result from the inherent complexity of the subject matter: (1) the theoretical tools available, (2) the nature of the physical system being studied, and (3) the observational information that is available or is likely to become available in the foreseeable future. Examples of these three constraints are: (1) the fact that the available computing hardware may limit both the number and the size of physical processes the model system can describe, (2) the fact that a natural physical system may be inherently unsuited to anything more than a statistical description (*e.g.*, turbulent systems), and (3) the fact that a natural system may be observable only through remote sensing which is intrinsically limited by spatial resolution and line-of-sight integration.

This report is organized in seven sections, including this Introduction. Section 6.2 of this report describes the principal accomplishments in the various disciplines served by the Space Physics Division. Section 6.3 focuses on the key problem areas facing space physics theory in the coming decade. The following section discusses the importance of theory-data closure. Section 6.5 then presents a reasonable organizational plan for future theory efforts. The final sections 6.6 and 6.7 address important problem areas together with the Theory Panel's recommended solutions.

6.2 Representative Major Scientific Accomplishments

The ultimate test of accomplishment in theoretical research must be the degree to which closure is achieved between theory and experimental observations. On the one hand, theoretical investigations may be conducted with the goal of explaining physical phenomena that have been observed and measured. On the other hand, theoretical studies may be designed to lead to predictions testable in space physics missions. During the past decade, theoretical studies in space physics have made significant advances, both in enhancing our understanding of observations and in making predictions which have subsequently been verified by observations. Theoretical advances have been made by creative individuals using simple analytic tools. The best examples of this are Parker's derivation and solution of the equations describing the development of the solar wind, and other groups' use of analytic and numerical tools to solve complex systems of equations. These efforts included the development of global models and the numerical simulation of complex physical phenomena. Although we still lack a comprehensive theoretical understanding of many intriguing phenomena, significant progress has been made in many areas during the past decade. We mention a few of these in the following sections. Because of space limitations such a summary as this cannot be comprehensive, but represents only the types of problems on which notable advances in understanding have been made.

6.2.1 Cosmic and Heliospheric Physics

6.2.1.1 Diffusive Shock Acceleration

The acceleration of cosmic rays is a fundamental physical problem which has been significantly illuminated in the past dozen years. It now seems likely that diffusive shock acceleration (the acceleration of charged particles to high energies in the diffusive approximation at shock waves) causes many of the cosmic ray species observed. The process is very efficient, produces particles with a spectrum close to that observed in space, and has been observed ***in situ*** in the heliosphere.

Theoretical investigation of diffusive shock acceleration, which has involved both analytic and numerical tools, has shown that the scattering-caused diffusion results from waves generated by the particles themselves. These theoretical results have been confirmed by observations carried out in the solar wind.

6.2.1.2 Origin of Galactic Cosmic Rays at Supernova Shocks

It now seems reasonably certain that galactic cosmic rays below approximately 10^{16} eV energy originate from diffusive shock acceleration at supernova shocks. The efficiencies are adequate to provide the requisite number and energy density of cosmic rays. Moreover, the resulting energy spectrum is nearly independent of parameters such as shock speed, particle transport, and magnetic-field strength, and is in good agreement with observations.

6.2.1.3 Solar Modulation of Galactic Cosmic Rays: The Anomalous Component

The access of galactic cosmic rays to the heliosphere is impeded by the solar wind and the heliospheric magnetic field. This phenomenon can now be modeled realistically: to do so investigators have employed the same basic transport theory as that used in diffusive shock acceleration (the termination shock of the solar wind fits naturally into these models), while solving the three-dimensional equations which include drifts, diffusion, convection, and energy change. The realization that particle drifts in the large-scale magnetic field play a dominant role in solar modulation has led to significant advances in understanding. Included in these has been a fundamental revision in our picture of the nature of modulation. The direction of the heliospheric magnetic field is now known to play a significant role; this realization led immediately to the discovery of a 22-year basic cycle.

As part of this new view, it is now apparent that the termination shock must also play an essential role in solar modulation. Diffusive shock acceleration of freshly-ionized interstellar atoms at this shock is now thought to give rise to the anomalous component of cosmic rays. Modeling this process has led to good agreement with the observed energy spectrum, composition, spatial gradients, and temporal variations of the anomalous component.

6.2.1.4 The Solar Wind as a Turbulent Magnetoplasma

Recent work has led to the resolution of the twenty-year-old debate about the question of whether the solar wind constitutes an actively evolving turbulent magnetofluid or reflects remnants of coronal processes. From simulations of MHD turbulence and studies of Helios and Voyager data, we have learned that dynamic processes, probably driven by stream shear, gradually destroy the Alfvénic signatures of coronal processes evident in data taken in the inner heliosphere.

6.2.1.5 Heat Conduction in the Solar Wind

Studying the origin of the electron heat flux in the solar wind helps us understand coronal processes better. Theoretical work in this area has demonstrated the importance of non-Maxwellian distributions in the evolution of the solar-wind plasma.

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6.2.1.6 Stream Interactions

Numerical models have been developed to study the role of stream interactions in the global evolution of the solar wind. High-resolution, two-dimensional studies have predicted the formation of merged interaction regions in the outer heliosphere; three-dimensional studies have confirmed the importance of north-south asymmetries in the interaction of high- and low-speed solar-wind streams.

6.2.1.7 The Interaction of the Solar Wind with Comets

The encounters with the comets Giacobini-Zinner and Halley provided a unique impetus for theoretical advances in our understanding of wave-particle instabilities. Because of the ionization of neutral water-group molecules, the initial conditions and boundary conditions of comet-plasma interactions are more easily modeled than is usually the case in the space physics environment. The interplay of analytic theory and numerical simulations in this area has led to a comprehensive understanding of the linear and nonlinear interactions involved. Although outstanding questions remain, the results from this work and from similar work motivated by the AMPTE releases have immediate application to similar physics involved in the ionization of interstellar neutrals in the heliosphere and pick-up ions in planetary magnetospheres.

In the field of cosmic and heliospheric physics, the source of coronal heating and the origin of high-speed streams and initial solar-wind acceleration are not yet understood. These significant phenomena could well be explained with the systematic application of theoretical tools.

6.2.2 Solar Physics

6.2.2.1 The Solar Interior

Global oscillations are now well understood, or at least sufficiently understood to be used to probe the physics of the interior. For example, the internal rotation rate has been approximated. This is providing new constraints for magnetic dynamo theory.

Progress has also been made in gaining an understanding of the generation and dissipation of these oscillations. The interaction of the oscillations with surface structures such as sunspots is currently an exciting area of research. It holds the promise of determining the subsurface structure of solar magnetic fields.

6.2.2.2 The Convection Region and Photosphere

Simulations have been made of solar convection. The simulations are now three-dimensional and fully compressible. The effects of radiation transfer and a passive magnetic field have been included in some simulations. Important results are that the simulations confirm the concentration of flux into granule boundaries and predict the existence of shocks in the lower chromosphere and of cold downdrafts in the deep convection region.

6.2.2.3 The Chromosphere

There has been pioneering work on the physics of thin flux tubes. We are nearing an understanding of the formation of photospheric fluxules. Studies of the generation and dissipation of MHD waves in flux tubes indicate they may be responsible for heating the lower chromosphere.

6.2.2.4 The Corona

Heating

In this region there have been new developments on two fronts: wave heating and DC current dissipation. The physics of resonance absorption in coronal loops is now understood, and detailed predictions of wave amplitude and spectra for comparison with future observations from OSL have been derived. With regard to DC heating, several models for current concentration have been developed and await testing by numerical simulation and observation.

Magnetic Structure

Small-scale. Major advances have been made on understanding the stressing of a coronal magnetic field by footpoint motions at the photosphere. Constraints on the structure and dynamics of the field have been derived. These results have implications for flares and CME's, *e.g.*, the "lack of equilibrium."

Large-scale. The observed evolution of the weak, large-scale field has been successfully modeled in terms of a model for supergranule diffusion and meridional flow. It is this field that provides the boundary condition for the interplanetary field.

6.2.2.5 Solar Activity

The response of coronal and chromospheric plasma to flare heating has been calculated. Simulations have provided detailed predictions of optical X-ray lines and profiles for comparison with SMM data.

The physics of electron beams in the corona has been greatly clarified. The observed hard X-ray emission has been explained by the beam models. The roles of reverse currents and collective effects in the propagation of the beams have been elucidated.

The field of gamma-ray spectroscopy has made great progress. Observed spectra by SMM have been used to derive fluxes, energies, and time scales for flare-accelerated particles. New diagnostic tools have been derived for interpreting gamma-ray lines and determining the physical parameters of the flare atmosphere. Interpretation of the SMM data has provided critical new constraints on the acceleration process.

There has been significant progress in understanding shock acceleration, in particular, on the gradient-drift process. Shocks appear to be a promising mechanism for explaining flare gamma-ray production.

6.2.3 Magnetospheric Physics

With the advent of the Solar-Terrestrial Theory Program, simulation techniques have become an integral part of magnetospheric research. These techniques have fallen into two general categories: numerical solutions of systems of equations (*e.g.*, the MHD equations) to investigate large-scale problems, and wave-particle studies using particle-in-cell (PIC) techniques to study smaller-scale phenomena. Modeling and independent analytic efforts that do not make use of intensive numerical techniques have also led to significant advances. The theory of planetary magnetospheres has progressed from the conceptual stage to the stage of well-defined models and, in several cases, to the stage of quantitative predictions.

6.2.3.1 Boundary Layers

The shapes and positions of bow shocks and magnetopauses can now be predicted with reasonable accuracy from ideal MHD models. The structures of these boundaries, however, are not yet well understood, although numerical simulations have significantly helped in gaining an understanding of collisionless shocks, rotational discontinuities, and the nonlinear development of shear-flow instabilities such as the Kelvin-Helmholtz instability. Numerical work has disclosed that, contrary to prior expectations, intermediate shocks can be stable. The acceleration of particles in planetary shocks can now be modeled, and predictions have begun to match observations.

6.2.3.2 Reconnection

Concepts such as steady reconnection, time-dependent reconnection, patchy reconnection, and impulsive injection have progressed to the model stage, and in some instances detailed agreement has been reached between theoretical predictions and observations of flow patterns near the subsolar magnetopause. Two- and three-dimensional numerical models of flux transfer events (FTE's) can reproduce their characteristic features, but the conditions that determine the occurrence of FTE's are not known.

6.2.3.3 Mass and Energy Transport

The transport of mass inside magnetospheres involves convection and diffusion. Convection is driven by both the solar wind and planetary rotation. Quantitative models of convection in the

Earth's magnetosphere and well-defined models of the rotation-dominated convection in the magnetospheres of Jupiter and Saturn have been developed. We can now predict with reasonable accuracy the evolution of the plasmapause during magnetic storms. The coupling of magnetospheric convection to the ionosphere involves field-aligned currents and parallel potential drops. Our understanding of the relation between these is not complete, although models based on single-particle motion in the converging magnetic field have been successful in explaining the large-scale inverted V precipitation structures in the auroral region. The diffusive transport of energetic particles in the inner magnetospheres and radiation belts can be modeled, but the magnitudes of the diffusion coefficients have not been calculated from first principles because the underlying physics is not yet clear. Loss of energetic particles occurs by charge exchange and pitch-angle scattering. Quantitative models have been constructed and yield good agreement with observations.

The theory of transport and energization of plasmas in the magnetotail of the Earth has evolved from the conceptual level to the modeling stage. Three-dimensional models of the tail have been constructed, and the role of reconnection as a driver of substorms has been elucidated. But neither the resolution of the numerical models nor that of observations is yet sufficient to allow for a quantitative comparison, and the importance of reconnection in the near-Earth plasma sheet is not yet established. On the other hand, the existence of a neutral line in the distant tail anticipated by the Dungey concept of the magnetosphere has been verified. The theoretically predicted ejection of plasmoids has also been observed.

6.2.3.4 Auroral Physics

Significant advances have been made in the theory of auroral-particle acceleration. The concept of parallel electric fields has been quantified by analytical theory and numerical simulations. We have begun to understand the physics of weak and strong double layers although their relative importance for auroral particle acceleration is not yet clear. The heating of ions and the generation of ion conics by wave-particle interactions have been simulated, and quantitative predictions are now possible.

6.2.3.5 Radio Emissions

All planetary magnetospheres are emitters of radio waves in several frequency bands. The concept of the relativistic electron maser instability has been quantified by analytical and numerical work. There is still a gap in our understanding because the observed gradients in the distribution functions of auroral electrons are not always large enough to account quantitatively for the amplification rates needed to produce the observed radio wave power. The high-frequency synchrotron radiation from Jupiter has been modeled accurately and quantitatively. Based on these calculations a remarkably accurate model of the Jovian magnetic field has been constructed prior to the ***in-situ*** probing by Pioneer 10.

6.2.3.6 Ion Pickup

The physics of ion pickup and its role in the formation of the induced magnetospheres of the unmagnetized planets and comets has also evolved from the conceptual level to analytic and numerical modeling.

6.2.3.7 Plasma Interactions with Planetary Moons and Rings

The interaction of moons with the corotating plasmas in the magnetospheres of the outer planets in terms of Alfvén waves had been theoretically anticipated and has now been verified by observations. The interaction of magnetospheric plasma with dust in the rings of the outer planets has been delineated on the conceptual level and is beginning to be studied quantitatively.

6.2.4 Ionospheric, Thermospheric, and Mesospheric Physics

Comprehensive theoretical models have been developed describing the large-scale, three-dimensional structure and dynamics of the thermosphere and the E- and F-region ionosphere, driven by solar EUV radiation and magnetospheric electric fields and precipitating particles. These models are comparable in their complexity and in their ability to simulate climatology to general circulation models of the troposphere. They have been used to study the response of the thermosphere to solar-activity forcing by electric-field, photon, and charged-particle flux inputs. Theoretical models of the thermosphere are now sufficiently comprehensive to constitute an essential tool in the detailed analysis and interpretation of the large observational data bases acquired by orbiting satellites.

Models of the polar wind have been developed to study the ionosphere's contribution of heavy ions to magnetospheric plasma, and models of global magnetospheric convection have been extended to study electrical coupling between high- and low-latitude ionospheres. Local and nonlocal plasma instability theories have been developed to explain equatorial and latitude phenomena.

In the past decade, considerable effort has been devoted to the theoretical study of the forcing vertical propagation and nonlinear saturation of internal gravity waves. Associated with wave saturation is the convergence of wave momentum fluxes, which has a profound influence on the momentum budget of the mesosphere and lower thermosphere. In addition, dissipation of wave energy and eddy heat-flux stresses can potentially affect the thermal structure of this region of the atmosphere.

6.2.4.1 Photochemistry and Energetics

In an effort to understand ionospheric and photoelectron transport, the efficiency for the energy deposition by EUV radiation was evaluated. Measured photoelectron spectra were reproduced, and important ionospheric reaction rates, which are difficult to measure in laboratory experiments, were determined. In these and other studies the importance of metastable ion chemistry was established for Earth and Venus.

6.2.4.2 Models of Thermosphere Dynamics

Time-dependent, three-dimensional models of the thermosphere have been developed, and have accounted for the heat input due to solar radiation and energy as well as momentum coupling from the magnetosphere. These models describe the wind field and the changes in temperature and composition, and thereby account for large-scale phenomena and propagating waves. During magnetically disturbed conditions, large wind velocities (on the order of 1 km/s) are induced by high-latitude plasma convection. The associated energy input from Joule heating is then of comparable importance to that from EUV radiation. It has been demonstrated that transport of minor atmospheric constituents significantly affects the energetics and dynamics of the thermosphere. Presently, it is believed that these models are as good as the input parameters (sources and boundary conditions) which characterize the coupling from the magnetosphere and lower atmosphere.

6.2.4.3 Models of the F-region

Numerical models have been developed to describe the temporal and spatial variations in the F-region ionospheric plasma for both molecular and atomic species. Solar radiation and precipitating electrons are considered as sources of ionization and energy. Electric fields and thermospheric winds are responsible for plasma transport and associated energization processes. These models describe the ionospheric large-scale dynamics and the chemical properties which are controlled essentially by magnetospheric processes at high latitudes, radiatively driven winds at middle latitudes, and dynamo processes at low latitudes. Traveling ionospheric disturbances were shown to be manifestations of gravity waves generated by Joule heating and electric-field driven momentum coupling in the auroral regions.

6.2.4.4 Polar Wind

A number of kinetic and semi-kinetic models have been developed to describe the polar wind under steady-state conditions. Recently, a hydrodynamic polar wind model has been coupled to a three-dimensional F-region model which is driven by magnetospheric processes.

6.2.4.5 Coupled Models of the Ionosphere and Thermosphere

Recently, global scale three-dimensional models have been developed to describe in self-consistent form the interactions between the thermosphere and F-region ionosphere, including the dynamo interaction.

6.2.4.6 Atmospheric Dynamo

Models have been developed to describe the dynamo electric fields generated in the E- and F-regions which are associated with solar and lunar tides. They can describe a major component of the quiet-time ionospheric electric field and currents observed at middle to low latitudes. A model has also been developed to describe the atmospheric dynamo induced by magnetospheric processes.

6.2.4.7 Magnetosphere-Ionosphere Coupling

Models have been developed which describe the solar wind's interaction with the magnetosphere coupled in self-consistent form to the ionosphere. An attempt has been made to describe the effect of the ionosphere on the magnetospheric convection electric field and the penetration of this field into the middle- and low-latitude ionosphere.

6.2.4.8 Coupling between Upper and Lower Atmosphere

Models have been developed describing the generation of tides in the lower atmosphere and their propagation into the mesosphere and thermosphere.

6.2.4.9 Plasma Structure, Dynamics, and Energization

Several linear and nonlinear theoretical models have been developed to explain the generation and evolution of small- and large-scale plasma irregularities in the high-latitude ionosphere which are driven by drift velocities parallel and perpendicular to the magnetic field. Numerical models have been developed to describe the transport of large-scale density enhancements, patches, and blobs.

6.2.4.10 Mesoscale Magnetosphere-Ionosphere Coupling

Numerical models of mesoscale magnetosphere-ionosphere coupling have been developed to explain the generation and evolution of ionospheric structures.

6.2.4.11 Anomalous Energization and Transport Processes

Theoretical models have been developed to explain anomalous thermal conductivities and energization processes in the F-region, and anomalous electron collision frequencies and electron heating in the auroral E-region.

6.2.4.12 Low-Latitude Instabilities

Linear and nonlinear theories for plasma instabilities have been developed to explain the observed irregularities in the equatorial electrojet. Nonlocal theories have been developed to explain the generation and evolution of equatorial F-region irregularities (spread F).

6.3 Key Problem Areas to be Addressed in the Coming Decade

The central task for theory in the next decade will be to reach a first-principles understanding of the physical processes governing the solar-terrestrial environment. The combination of new theoretical tools in nonlinear dynamics and in computing technology, and the vastly enhanced diagnostic capabilities provided by new experimental initiatives, place us in a position to make major advances in theory in a number of specific problem areas. Theory is at the threshold of an exciting new frontier, and this coming decade will involve its exploration.

6.3.1 The Nature of Flows and Turbulence

Perhaps the most dramatic advances to which nonlinear dynamics and numerical simulations will lead are in the areas of flow dynamics, and fluid and plasma turbulence. At the most fundamental level we have an extremely poor understanding of the nature of compressible convection, the interaction of radiation with fluids, relativistic flows, nonlinear wave-mean flow interactions, the onset of turbulence, and the nature of fully-developed turbulence in nonmagnetized and magnetized fluids and plasmas. A quarter century after the initial work on the solar wind, we still do not understand the processes which lead to solar-wind acceleration and heating, and our understanding of anomalous transport in turbulent fluids and plasmas remains primitive. All of these problems lie at the heart of the physics governing the solar-terrestrial environment. In addition to new theoretical tools, new diagnostics will also make a major impact in this problem area. For example, helioseismology will allow us to observe compressible convection, and *in-situ* measurements on missions such as Cluster and the Solar Wind Turbulence Explorer will directly constrain models of interplanetary MHD turbulence.

6.3.2 Acceleration and Transport of Particles

A remarkably obdurate problem in the space sciences has been establishing the origins of accelerated particles and describing their transport within the heliosphere. A large number of possible acceleration processes have been explored to date. These processes range from Fermi acceleration and relativistic and non-relativistic shocks to $E_{||}$, current sheet acceleration, and stochastic acceleration. A definitive understanding of their specific roles in specific locales within the heliosphere (and the interstellar medium), however, still eludes us. In many cases, we are still unsure about the very nature of the source of accelerated particles. For example, the paradigm of the heliospheric terminal shock as the ultimate source of the anomalous cosmic ray component remains to be directly verified. In other cases, we have essentially no consensus on the nature of the dominant acceleration process, as for example in solar flares and in the magnetotails of planets; and as a consequence, observations are still needed in many (but not all) areas of space physics to help establish a “cartoon” description, or interpretive framework, for the theory of particle acceleration and transport. This area of space physics theory thus still requires exploratory observations, in addition to more refined diagnostics.

6.3.3 The Coupling of Micro- and Macro-physics

The technological limits of theory often force a trade-off between the level of detail of a model and its scope. Some classic examples of this trade-off include the computation of local transport coefficients (such as those of heat and momentum) and their use in the fluid equations, and the detailed treatment of magnetic field reconnection, nonlinear wave saturation, critical-level interaction and models of flux transfer. Let us consider the problem of local transport properties in more detail. Local transport of heat, momentum, and mass are essential ingredients of any description of the solar-terrestrial environment. What makes this environment such a challenge to theory is the dramatic variation, or dynamic range, of basic physical attributes (such as particle density, temperature, and magnetic-field strength) and hence of plasma parameters (such as mean free paths, gyroradii, and characteristic collision and gyrofrequencies) encountered in the system as a whole. As a consequence of these variations, the description of local transport involves the transition from a purely local to an entirely nonlocal behavior, a transition which is very poorly understood. In addition, the role of plasma and fluid turbulence in modifying a purely kinetic particle-collision description remains uncertain. In these areas, the role of numerical simulations will become increasingly dominant.

6.3.4 The Coupling of Local and Global Dynamics

A distinct counterpart to the problem of translating microscopic phenomena to macroscopic consequences (and vice versa) is the problem of coupling or integrating behavior that occurs in spatially well-defined locations (“local” dynamics) to the behavior of a large-scale system (“global” dynamics). Perhaps the most classic example of this interplay between global and local dynamics is the role of boundary layers in determining the behavior of flows well away from boundaries. We now recognize that transitional regions between physically distinct domains (such as the boundary between the interplanetary medium and a magnetosphere, or between the solar convection zone and the corona) play a central role in fixing mass, momentum, and energy-balance relations between these domains. The key problem in this area is to obtain more effective observations of boundary layers and the domains that they bound (the problem of building both effective microscopes and telescopes), and to use such observations more effectively as constraints on models. This is again an area in which many observations will be exploratory in nature, and hence provide the basis on which theory can build (and in many cases, simply initiate) the "cartoon" level of description.

6.3.5 Nonclassical Plasmas

In addition to the "classical" fully-ionized, high-temperature plasmas with which most laboratory and space plasma physics have been concerned, space plasma physics has had to deal with relatively far fewer explored types of plasmas; namely, partially-ionized, low-temperature gases, non-neutral plasmas, and dusty plasmas. In each of these cases, the level of theoretical development is much more primitive than that in the fully-ionized, high temperature case; yet anticipated missions in space physics will provide a flood of new data in these areas which will desperately need an interpretative framework.

6.4 Evolution of Space Plasma Theory

6.4.1 Maturation of Space Physics

It is the nature of observational/environmental sciences to progress from exploration to understanding to prediction, and from the dominantly experimental to heavily theoretical. On the plane of human activity, this progression goes from a driving intellectual interest to general benefits, including: (1) tested theories for increasing scientific expertise, (2) environment predictability to aid in decision-making in the Nation's space endeavors, and (3) increased understanding which serves to stimulate and enhance new endeavors. The borders between the phases are indistinct and the transitions between them resemble fits and starts more than clean jumps. Though no science has completely achieved the ultimate stage, the quest for understanding and predictability is inevitable and desirable.

Space physics is an observational/environmental science. In its evolution toward full quantitative predictive capability, it has in the main moved into the border zone between exploration and understanding. Theory now plays an indispensable role in space mission definition and data utilization. Missions are becoming problem-focused; that is, they are being designed to supply answers to key theoretical questions and to test an inchoate predictive capability. This is a major step on the path from pure exploration to understanding.

6.4.2 Theory-Data Closure

Past theoretical investigations have brought about a significant increase in our understanding of space physics. To anticipate the future requirements for advancing space physics theory, it is important to understand how theory is carried out. As in other branches of physics, every theory cycles one or more times through a loop with four specific stages: (1) observations, (2) concepts, (3) models, and (4) predictions. Each cycle leads to the progressive refinement of a theory and, ultimately, to its acceptance or rejection. It should be emphasized that observations strongly motivate theoretical investigations (the concept stage). By necessity, concepts involve a "cartoon" picture of physical reality. If an idea is found to have merit, a theorist will decide on an appropriate model (which is often constrained by the assumptions made due to limitations regarding solvability). Models can be analytical or numerical. Once a model has been tested using realistic input (gained from observations), it can be used to predict the behavior of the physical system it represents. The prediction stage not only involves comparing model output and observations, but includes the development of scaling laws.

The theoretical process described above only has merit when detailed comparisons of scientific models are made with appropriate observations.

This comparison involves a confrontation between model results and observations, which leads to the revision of models to enhance the agreement, or at least provide feedback, on the analysis methods used on the raw data. Such feedback ensures that the theoretical models are relevant. It is therefore imperative to describe what theory-data closure means to the Space Physics Division at NASA and how the Theory Panel expects it to be implemented.

As space physics becomes more global and quantitative in its research thrusts, the need to close the theory-data loop has become more critical. The greatly increased complexity of both experimental observations and theoretical simulations requires routine, in-depth comparison of theory and data. Only then will necessary tests of theory, simulations, and models be available. Such comparisons, in turn, will guide future observations.

Past theory-data comparisons have contributed significantly to our understanding of space physics processes. Our present goal is to provide similar comparisons on a routine basis and make these available on all scales, from the microcosmic to the global, in each domain of space physics. For the quantitative thrusts being pursued, it is no longer appropriate for experimental data to be available as voltage/current curves or counts per second, nor will it be useful for theory to publish predictions only as dimensionless variables and offer no specific predictions of what should be observed. Both the data and theoretical results must be presented in physical units and displayed in comparable formats. Data must fulfill the dual role of providing input values for the simulations and providing the yardstick against which simulation results can be compared. Moreover, to fulfill our future science goals, it is necessary that both data and simulation results be readily available and accessible. Plans are currently being implemented on various projects to assure easy and rapid access to data. Similar plans must be made and implemented to provide general access to simulation results and to a more community-wide use and operation of codes.

Finally, a necessary condition for the effective closure of the theory-data comparison issue is that theorists and experimenters work together from the inception to the conclusion of space physics programs. Scientific elucidation, project definition, mission operation, data presentation, simulation operation, problem analysis, and theory-data comparison must be conducted with contributions from both the experimental and theoretical communities.

6.5 Organization of Future Theory Efforts

Presently, there exist three avenues for theorists to participate in research sponsored by the Space Physics Division. These are: (1) the Research and Analysis Program (RAP), (2) the Space Physics Theory Program (SPTP) which is composed of large critical-mass, co-located groups concentrating on central problems, and (3) Mission Oriented Theory Programs (MOTP's) which include critical-mass teams in direct support of missions. In addition to these three extant programs, we perceive a need for a new fourth category of programs such as Theory Centers which would emphasize cross-disciplinary approaches to central problems in Space Physics and also aid in the effort to increase the number of permanent positions for theorists at universities, in private industry, and in government laboratories. We note that it may be possible to meet these needs by modifying the existing theory programs instead of creating a new independent program. We discuss below our recommendations for future characteristics of the organizational structure of the existing theory programs.

6.5.1 The Future Research and Analysis Program (RAP)

The principal emphasis here is on the expansion of opportunities for theorists applying to RAP for all Space Physics disciplines. Small theory teams supported under the RAP programs are a prime source of innovative ideas. Since this research is independent of missions, theorists can investigate new ideas unconstrained by mission programmatic considerations. Small theory efforts have been a source of new ideas which larger programs such as SPTP have investigated.

Presently there exists a large number of excellent but unfunded theory proposals which have the potential to make significant contributions to our understanding of the physics underlying the results of present and past space physics missions. There is also a need for the acquisition of suitable hardware such as workstations and microcomputers. Given the advisability of coordinating theoretical investigations across discipline boundaries, it would be very valuable to have a Visiting Senior Scientist to oversee RAP theory grants from the various disciplines.

6.5.2 The Future Space Physics Theory Program (SPTP)

Since the inception of the Solar-Terrestrial Theory Program (STTP), which was the predecessor of the SPTP, there has been an erosion of grant size per investigation in real dollars. Although this erosion has been stabilized since the Program was taken over by the Space Physics Program, there still exists a large deficiency in funding the present SPTP when compared to the grant sizes envisioned by the "Colgate Report" which formed the basis for the Program's justification. Although the STTP, and now the SPTP, has been successful in leveraging resources to meet critical-mass requirements, there is a need for a budget increase of about 100% to realize the long-term program objectives. With such an increase in funding, our current program objectives could be realized much more quickly and efficiently.

The Theory Panel also recommends having a practicing theorist in a key position in the SPTP. Since the goals of SPTP are long term and stability is desired, an organizational structure similar to that of flight projects would be appropriate: positions for a NASA HQ Program Scientist and a Project Scientist at the Goddard Space Flight Center should be established. The roles would be similar to those for the Space Physics Flight Missions. The appropriate Program Scientist would be above the Branch level. The SPTP should also have an MOWG (Management Operations Working Group) in recognition of its Branch-level status.

6.5.3 Mission-Oriented Theory Programs (MOTP)

The primary difference between SPTP and MOTP investigators is that, whereas SPTP addresses central problems in space physics that are of relevance to present and future space physics missions, MOTP's are concerned with specific missions in order to maximize the scientific return of such missions that can be obtained by a close working relationship between a critical-mass team of theorists and experimentalists. The existence of MOTP's confirms the maturing of the discipline as it leaves the exploratory phase and takes on more of the attributes of classical physics research. The role model for future MOTP's is the theory component of the International Solar-Terrestrial Physics Program (ISTP). A key element in the implementation of the MOTP in ISTP has been the existence of a Deputy Project Scientist. However, for future missions, additional theory input in the planning process must be sought. In the past, for all missions, there has been a Study Scientist. Again given the increasing maturity of space physics missions, a Deputy Study Scientist for theory is a necessity to assure that theory is well integrated into the mission at an appropriate level early in the mission's development. The Deputy Study Scientist for theory would also determine the need for a distinct Deputy Project Scientist for theory should the mission be selected. It is envisioned that all major and moderate missions will include a Deputy Project Scientist for theory. It is possible that most Explorers and even some Small Explorers will also have this invaluable theoretical input.

6.5.4 Interdisciplinary Research Efforts

It has become increasingly clear that many of the key scientific problems (such as those described in section 6.3) are common to all four branches of space physics. Unfortunately researchers in one branch are rarely aware of the progress made in the others, and often research in one area duplicates that in another. This is not necessarily wasteful, because the plasma parameters are often so different that the problems do require different approaches. Nevertheless a closer cooperation between theorists from different branches would very likely lead to a considerably more general and deeper understanding of fundamental processes. The Theory Panel has considered several models for encouraging (stimulating) interdisciplinary research. These include the creation of a center for space physics theory, recurrent focused workshops, or summer schools. We strongly recommend that NASA establish an interdisciplinary panel to study these possibilities. If a theory MOWG is established, this study could be performed.

6.6 Space Plasma Theory Tools

6.6.1 Numerical Tools

Because of a desire to enhance the theoretician's ability to compare theoretical results with observations, a variety of new and/or improved numerical codes need to be developed which should be useful for all disciplines represented by the Space Physics Division. One of the outstanding theoretical numerical issues involving all these disciplines is how properly to represent numerically multiscale phenomena, particularly boundary-layer phenomena. For example, how can one best incorporate anomalous transport processes occurring in boundary layers (such as shocks), which occur on both temporal and spatial scales that are microscopic, into meso- or macro-scale numerical codes?

A number of numerical approaches have been developed that attack these problems directly, including especially adaptive gridding techniques based both on finite-element and finite-difference techniques, as well as pseudo-spectral methods using Chebyshev polynomials. Further progress requires that these methods be further refined, since we now know that correct treatment of multiscale phenomena is key to proper modeling of solar, interplanetary, magnetospheric, and ionospheric processes. In addition, we have recently witnessed the proliferation of computers based on entirely new computer architectures, which are based on various ideas and methods to combine vectorization and parallelization of codes. However, these hardware achievements of industry have not at all been matched by the corresponding development of computational software which takes advantage of these hardware developments. Indeed, by developing new algorithmic tools that exploit parallelization, it can be reasonably argued that optimal use of the new computer hardware now available (ranging from multiprocessor Cray Y/MPs to massive parallel processors) can have as large, or even larger, effects as further refinement of existing vectorized codes designed for single-processor architectures. For this reason, such development efforts in the space physics community should also be strongly encouraged and supported.

A second numerical issue relevant to the kinetic treatment of space physics phenomena is the need for fast and efficient multidimensional kinetic codes which will permit the study of physical processes that are initiated on a microscopic scale and evolve through to mesoscales and, if possible, macroscopic scales. This will in general require further advances in implicit particle pushing techniques, such as moment-implicit and direct-implicit PIC techniques.

Finally it is recommended that a NASA center establish and maintain a library of documented codes that the general space physics community can access and use. A similar library has been maintained by the MFECC for the fusion program and has been highly successful.

6.6.2 Technology

6.6.2.1 Supercomputers

Computing needs for support of large-scale space simulations have grown more rapidly than have our computer hardware systems. As a result, present-day computer systems are inadequate to handle the problems of 1990, much less those of the 21st century. Today it is not uncommon for codes to require 100 to 1000 hours on a Cray Y/MP per run. These resources are not generally available and severely limit our ability to improve the simulations by increasing resolution or adding new physics.

It is very difficult to obtain enough time on a supercomputer to run our codes today, and those of the 21st century could take 10,000 hours or more. One way in which supercomputer manufacturers have tried to increase the throughput of the computers is by increasing the number of processors. However, supercomputing centers try to maximize their throughput by running the system as a series of monotasking machines. Thus it is very difficult to get a timely turnaround for a calculation. In addition, the computer allocation often exceeds the supply, and some space physics problems are not very well suited to the vector supercomputers currently available. Some space-simulation codes are difficult to vectorize and cannot take advantage of the high speed of these machines.

6.6.2.2 Analysis Software

A separate set of problems is concerned with the analysis of the results from computer simulations. Some of these codes generate large quantities of results. For example, in the global MHD code discussed above, the system generates 2×10^7 words of output per second, and the time scales for magnetospheric problems are in hours. Thus we also need to find new ways to analyze and display this computer-generated data. This set of problems is frequently referred to as problems in output visualization.

The ultimate test of any theory or simulation is to confront theoretical predictions with observational tests. In the 21st century, we will need to be able to compare terabyte data sets from both theoretical calculations and observations. This too will severely tax our resources.

6.6.2.3 Computer Workstations

On the other side of computing resources, theorists often encounter NASA programmatic restrictions on obtaining even the simplest tools for carrying out their analyses. These most frequently occur as budgetary restrictions on computer hardware. These difficulties also befall analytical theorists, experimentalists, and modelers, all of whom have an increasing need for ready access to minimal computing support in the form of personal workstations.

6.6.3 The Search for Solutions

The Space Physics Strategy-Implementation Study Theory Panel recommends that NASA remove the arbitrary restrictions on the procurement of workstations on theory grants. On the problem of supercomputer resources, the Theory Panel recognizes that there is a range of possible solutions to the problem of obtaining adequate computer resources. We recommend that the Space Physics Strategy Plan implementation teams undertake an evaluation of these solutions. The possible solutions include access to state-of-the-art vector supercomputers where appropriate (see below). However, we also must consider alternative solutions especially for the largest problems (see section 6.6.5 on the computer architecture initiative). Finally, NASA funding of tools to analyze and display computer-generated results would be highly beneficial.

6.6.4 Supercomputers in the 1990's

During the 1990's a new generation of supercomputers will become available. An example of such a computer is the Cray-3. This system is expected to solve the problems associated with limited memory by providing up to 2×10^9 words of high-speed memory. In addition the computer speed will increase by a factor of three to six from present machines. The new systems will have approximately 100 times the throughput of the Cray-1. Like the other vector supercomputers, they will be expensive and therefore have to be shared facilities. Although these systems will be important for some physical problems (*i.e.*, those requiring large memory), the problem of timely turnaround will likely remain.

We also may benefit by considering new ways to program these computers. These include nonuniform grids, adaptive schemes (where the computational grid is adjusted at run time), and parallel use of the supercomputer processors. However, the latter may require dedicated supercomputers.

6.6.5 The Computer Architecture Initiative

In the late 1980's, development of an entirely new type of high-speed computer began. These are not general-purpose computers like the vector supercomputers but are parallel systems tailored to specific classes of problems. These systems provide a great deal of computing capability but are very difficult to program and use. Because of these difficulties, a new approach to computing has been developed. This approach requires close cooperation between the computer manufacturer and the users. It requires the industry computer experts to understand the details of the physical problems to be analyzed with the use of computers, and the scientist to understand the computer architecture. In some cases this approach will require the design of custom processors as nodes of the parallel computer array, the design of custom compilers, and the writing of completely new simulation codes. Therefore we suggest that NASA consider managing the development of these systems much as they manage the development of instruments for spacecraft. As with instruments, the computers would be designed and built as a cooperative effort by NASA, researchers, and industry.

6.7 Summary of Recommendations

6.7.1 Funding

Since we are now well beyond the initial exploratory phase in space physics research, significant advances in the future will come only from the close interaction of experiment and detailed theoretical models. At present we believe there is a healthy balance between theory and experiment in NASA's Space Physics Division. We strongly recommend, therefore, an increase in the SPTP and RAP theory budgets that will keep pace with the increase in the funding recommended by the Panel as a whole for the experimental program. The increased SPTP and RAP budgets would be used for modifications of the existing theory programs to promote a healthy research and analysis program for the support of theoretical space plasma research, independent of missions and mission programs, and provide ongoing support for experimental efforts. The modifications would be as follows:

> Appoint a Visiting Senior Scientist for Research and Analysis, overseeing across all disciplines in Space Physics.
>
> Install a small Management Operations Working Group to oversee the entire theory program.
>
> Restructure SPTP management along the lines of Flight Projects with a NASA Headquarters Program Scientist and a Project Scientist.
>
> Include a Deputy Study Scientist for Theory on all future mission studies. Incorporate a Deputy Project Scientist for Theory on missions where appropriate.
>
> Increase basic theory research funding, as it is seen to be absolutely required for any significant advances to be made in the field.

6.7.2 Research Structure

The following recommendations are concerned with permanent infrastructure building and interdisciplinary research:

> Investigate means of increasing the number of tenured faculty in Theoretical Space Physics. Such an increase would require a long-term trend of increased agency funding.
>
> Investigate approaches to creating a framework within which cross-disciplinary research may be enhanced. One possible avenue would be to give funding priority to applications using multidiscipline approaches.

Both studies should be conducted with consideration of the extent to which these needs can be accommodated within the present framework of theory programs, or alternatively whether new institutional structures such as Centers for Space Theory or Interdisciplinary International Coordinated Workshops are required.

In addition the following two programs should be initiated immediately to stimulate interdisciplinary research:

> **Frontiers of Space Physics Initiative**
>
> **Objective:** Directed, focused research on fundamental problems in space physics that are of direct relevance to present and future space physics missions such as the nature of turbu-

lence, the acceleration and transport of particles, the coupling of micro- and macrophysics, the coupling of local and global dynamics, and non classical plasmas. Would include both experimentalists and theorists as a next generation of CDAW-type studies.

Format: Series of iterated workshops. The start of each workshop could be staggered, for example, one per year. Each iterated workshop would concentrate on a single topic.

Duration: Three years per workshop with perhaps three meetings being held per workshop, meeting once per year.

Funding: Could range from a lower bound of meeting funding alone ($50K per workshop) to an upper bound wherein investigators would be funded ($1000K per workshop).

Topics: To be chosen by Theory Working Group in consultation with HQ branch MOWG's. At the higher funding level an NRA could be issued for competitive funding of up to 20 investigators (theorists and experimentalists) per workshop.

Fellowships

A young investigator fellowship program should be established, loosely patterned after the NAS–NRC fellowships, to provide a number of prestigious post-doctoral fellowships at the universities. The fellowships would be funded directly by NASA, at either the division or, if possible, OSSA level, using new funds. Applications would be made by a recent Ph. D. and an established researcher, with the award being made available in a time of several months.

The graduate student fellowship program should be augmented.

6.7.3 Computational Support

The following enhancements and studies for additional computational support for theory are recommended:

Workstation acquisition by researchers participating in theory programs where justified.

Increase availability of supercomputer support for researchers in theory programs where required.

Establish a study group to investigate new computer architectures which will be of use to theory researchers.

6.7.4 Theory-Data Closure

It is imperative that explicit measures be taken in the earliest stages of space physics missions to assure improved theory-data closure. This means that every mission announcement of opportunity (AO) should require that such closure be achieved within that mission. It is recommended that the quality, breadth, realism, and innovation of the theory-data closure elements of proposals (in response to mission AOs) be judged as a specific, high-priority part of the proposal evaluation process.

Finally, it is recommended for presently defined missions, in order to initiate activity in this area of critical need, that NASA consider the release of an AO specifically to solicit new, effective ideas of ways to achieve rapid, dramatic improvements in innovative theory-data interplay.

Appendix A: Mission Requirement Documents

A.1 Cosmic & Heliospheric Missions

A.1.1 Solar Probe

Target: Innermost heliosphere (inside 0.3 AU)

Theme: Includes both themes of the Cosmic and Heliospheric Program

Science Objectives:
Explore inner heliosphere (inside 0.3 AU) coronal structure; heating, solar wind acceleration; plasma turbulence within solar envelope acceleration; storage and transport of solar energetic particles; sources, sinks, and dynamics of interplanetary dust.

Mission Class: Major

Launch Vehicle Type: Titan-4/Centaur

Orbit(s) or Locations(s):

Interplanetary: Perihelion 4 solar radii, aphelion 5 AU

Duration: 4 years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Free flyer

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Particles and fields; See Solar Probe study (JPL D-6797)	135 kg total	103 W	0 kbps		

Mission Strategy:
Jupiter gravity assist (or alternative) to achieve near-Sun (4 solar radii) perihelion and 90° inclination. Primary mission phase—about 10 days inside orbit of Mercury Pole to pole about 14 hours.

Required Technology:
Low-sublimation heat shield
High bit-rate (KA Band) communications
Spacecraft power source (new RTG's)

A.1.2 Interstellar Probe

Target: The boundary of the heliosphere and the nearby interstellar medium

Theme: The next frontier: the global heliosphere and interstellar space

Science Objectives:
Explore the solar wind termination shock, the heliopause, and the nearby interstellar medium. Measure *in situ* acceleration of anomalous cosmic rays. Measure the composition of the nearby interstellar medium, and the properties of its plasma, particles, and fields. Measure the spectrum of low-energy cosmic rays outside the heliosphere.

Mission Class: Major

Launch Vehicle Type:

Orbit(s) or Locations(s):
Jupiter flyby, followed by a Solar flyby at ~4 R_s coupled with a rocket burn to achieve escape velocity

Duration: 20 years or more

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Spinner preferred, with spin axis towards Earth. No pointing requirements

Special Features (*i.e.,* despun platforms, booms, mag cleanliness, etc.):
Standard magnetometer and radio booms; need to measure 3-D plasma distributions

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Complement of particles and fields instruments incl. high-resolution spectrometers	~100 kg	~100 W	Several hundred bps	Store and dump	

Mission Strategy:
Achieve as high a terminal velocity as possible; pass through the termination shock and heliopause; and then penetrate as far as possible into the interstellar medium.

Required Technology:
Instruments are standard. Need to adapt Solar Probe technology to achieve required velocity, or use some other high-propulsion technology.

A.1.3 Polar Heliosphere Probe

Target: Distant Polar Heliosphere (to ≥20 AU)

Theme: The next frontier: the global heliosphere and interstellar space

Science Objectives:
To explore the distant polar heliosphere, in order to study new aspects of large-scale solar-wind structure and evolution, energetic particle acceleration and transport, solar wind interaction with the interstellar medium, and fundamental plasma processes.

Mission Class: Moderate

Launch Vehicle Type: Atlas Centaur

Orbit(s) or Location(s): Normal to ecliptic, over the Sun's pole to the outer heliosphere

Duration: 10–15 years

Spacecraft Requirements:
Spinner (Rate/Orientation) / Pointed(Accuracy):
Spinner, like Pioneer 10/11

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Standard magnetometer boom and radio antenna, etc., similar to Pioneer 10/11

Instrument Requirements:
Special Command, etc. Requirements:
none

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Magnetometer	75 kg total payload	75 W total	1 kbps total	Store and Dump	
Solar Wind Analyzer					
suprathermal ions/ electrons					
Cosmic Ray Analyzer					
Solar Particle Detector					
Radio/Plasma Waves					
UV Photometer					

Mission Strategy:
Use Jupiter gravity assist to go approximately normal to the ecliptic over the Sun's pole. This will be the first exploratory mission in the distant polar heliosphere.

Required Technology: No technology development necessary for propulsion, S/C or instruments

A.1.4 The Ultraheavy Element Spectrometer

Target: Composition of ultraheavy cosmic rays with $30 \leq Z \leq 100$

Theme: Particle acceleration and the evolution of matter

Science Objectives:
High-precision measurements of the elemental abundance of UH nuclei ($Z=30$ to 100).
Highest priority is to make definitive measurements of the actinide and trans-actinide abundances ($Z \geq 90$).
Measurements used to study questions of nucleosynthesis, galactic evolution, particle acceleration and transport.

Mission Class: Moderate

Launch Vehicle Type:

Orbit(s) or Locations(s): High-inclination Earth orbit or possibly lunar-based

Duration: 5 year +

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Orientation knowledge of about 1° required. Zenith pointing

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Electronic and passive detector options to be studied	Large but TBD				

Mission Strategy:
Achieve as large a collecting power as possible for cosmic rays with energies >300 MeV/nucleon.

Required Technology:
For the electronic detector option, in-orbit assembly may be required. The passive detector option would require instrument recovery for data analysis. A lunar-based detector is also under consideration.

A.1.5 Ultraheavy Solar/Galactic Isotope Explorer

Target: Measurements of ultraheavy cosmic rays outside the magnetosphere

Theme: Cosmic particle acceleration and the evolution of matter

Science Objectives:
High-resolution measurements of galactic and solar cosmic-ray isotopes in the trans-iron region of the charge spectrum (nuclear charge $Z \geq 30$). These will be used to study the origin and evolution of solar and galactic material, including processes of nucleosynthesis, particle acceleration and transport, and galactic evolution.

Mission Class: Explorer

Launch Vehicle Type: Probably Delta

Orbit(s) or Locations(s):
Outside the Earth's magnetosphere as much as possible; *e.g.*, an orbit about the sub-libration point or a circular orbit outside the magnetosphere. A polar orbit is also possible, but less desirable.

Duration: 4 years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Spinning, spin axis normal to ecliptic

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Will employ large area detectors (~0.1 to 1 m^2)

Instrument Requirements:
There are several possible detector approaches that may require long time-of-flight paths (>1 m) or large-area detectors (up to ~1 m^2).

Special Command, etc. Requirements:
none

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Solar Spectrometer	50 kg	50W	1 kb/s ave.	store and	Wide angle
Galactic Spectrom.	100 kg	50W	1 kbps	dump	Wide angle

Mission Strategy:
The requirement is to expose the detectors outside the magnetosphere with as high a duty cycle as possible. Depending on the detector technology employed, detector mass and size may limit the achievable orbits. The chosen detector technology may also preclude placing both instruments on a single spacecraft.

Required Technology:
Some detector development required to achieve high resolution for heavy isotopes.

A.1.6 Solar Wind Turbulence/Particle Acceleration & Transport Explorer

Target: Solar wind away from influence of Earth's magnetosphere

Theme: Particle acceleration

Science Objectives:
Measure statistical parameters of solar-wind turbulence (velocity, density, magnetic field) with simultaneous particle distribution function to understand turbulence, particle transport, and acceleration.

Mission Class: Explorer

Launch Vehicle Type: Delta

Orbit(s) or Locations(s): Outside magnetosphere, perhaps L_1 point

Duration: 5 years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Spinner

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Needs 2 or more small spacecraft with variable separations up to 0.1 AU

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Standard particles and fields	<50 kg	<50W average	several kbps	store and dump	

Mission Strategy:
Measure plasma and magnetic field correlation functions, together with energetic-particle distribution function from thermal energies to 10 MeV. Target shocks to study such acceleration.

Required Technology:
None

A.1.7 Matter/Antimatter Explorer (MAX)

Target: Abundance of cosmic ray antimatter

Theme: The evolution of matter

Science Objectives:
Search for antiprotons at energies below 1 GeV that would result from the annihilation of remnant supersymmetric dark matter particles in the Galactic halo. Search for antinuclei. Measure positron and electron spectra.

Mission Class: Explorer

Launch Vehicle Type: Delta II

Orbit(s) or Locations(s): Outside magnetosphere for extended periods

Duration: 3–5 years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Spinner

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Non-zero magnetic dipole moment will tend to align the spacecraft in any local magnetic fields.

Instrument Requirements:
Special Command, etc. Requirements:
None

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Magnetic Spectrometer	600–1000 kg	100–200W	10 kb/s avg.	Store and dump	Wide angle

Mission Strategy:
Place a high-resolution permanent magnetic spectrometer and time-of-flight telescope outside the Earth's magnetosphere to measure the mass and charge of light cosmic ray particles, identify antiprotons, and measure their energy spectra.

Required Technology:

A.1.8 Lunar Calorimeter

Target: Lunar-based measurements of high-energy cosmic rays

Theme:

Science Objectives:
Measurement of spectrum and elemental composition of protons through iron up past the "knee" in the cosmic ray spectrum, including cosmic rays with energies form ~10^{14} to 10^{17} eV.

Mission Class: Space Exploration Initiative

Launch Vehicle Type:

Orbit(s) or Locations(s): Lunar base

Duration: ≥3 years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	**Mass**	**Power**	**Data Rate**	**Data Storage**	**FOV**
Calorimeter lifted from the Earth	10–20 tons				wide angle

Mission Strategy:
Detector must be assembled on the Moon using lunar regolith for the bulk of the calorimeter material (>100 tons) together with active detector and structural elements brought from the Earth (10–20 tons).

Required Technology:
Lunar base
Detector assembly on the Moon

A.1.9 CRN on Mir Space Station

Target: Composition of high-energy cosmic rays

Theme: Particle acceleration and the origin of matter

Science Objectives:
Measurements of the individual elemental abundances of cosmic-ray nuclei for $4<Z<30$ for energies up to 10 TeV/nucleon

Mission Class:

Launch Vehicle Type: Proton rocket

Orbit(s) or Locations(s): Near-Earth equatorial orbit

Duration: ≥1 year

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Mir space-station attached payload

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
CRN	5,000 kg	300 W	10 kbit/sec		±30° zenith

Mission Strategy:
Launch existing instrument CRN on Proton rocket and attach to Mir Space Station.

Required Technology:
None, CRN instrument is flight proven on Space Shuttle.

A.1.10 HNC/Mir

Target: Composition of cosmic rays with $50 \leq Z \leq 100$

Theme: Evolution of matter

Science Objectives: Nucleosynthesis, cosmic-ray acceleration and transport, galactic evolution

Mission Class: Attached payload to Mir

Launch Vehicle Type: Proton rocket

Orbit(s) or Locations(s): Low-Earth orbit

Duration: 1–2 years

Spacecraft Requirements:

Spinner (Rate/Orientation)/Pointed (Accuracy): Must view zenith

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
~2 m^2 array of detectors

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Passive Glass Detectors	200 kg	none	Passive Detectors		~60°

Mission Strategy:
Attach ~2 m^2 array of passive glass detectors to Mir space station for 1–2 years. Return to Earth for etching and analysis.

Required Technology: None.

A.1.11 Solar Wind Sample Return

Target: Solar wind

Theme: Composition of matter

Science Objectives:
Determine the elemental and isotopic compositions of the solar wind, including rare species

Mission Class: Add-on to planetary sample return mission(s)

Launch Vehicle Type: As needed for planetary objectives

Orbit(s) or Locations(s): As needed for planetary objectives

Duration: At least 1 year in solar wind

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Small angle (less than 20°) to Sun

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):

Instrument Requirements:
Special Command, etc. Requirements:
Nearly passive instrument. Must be opened up and then closed/sealed before Earth return.

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Solar wind collector	<20 kg	~0	~0	~0	<30° to Sun

Mission Strategy:
Expose meter-sized solar-wind collectors during cruise phases of planetary sample return missions. Return to Earth for analysis.

Required Technology:
Ultra-high-purity collector materials

A.1.12 Instruments on Interplanetary Spacecraft

Target: Solar wind and heliospheric particles

Theme: Global heliospheric structure

Science Objectives:
Determine spatial and temporal variations of the solar wind and energetic particle populations.

Mission Class: As determined by planetary objectives

Launch Vehicle Type: As determined by planetary mission requirements

Orbit(s) or Locations(s): In solar wind. Determined by planetary objectives

Duration: As determined by the planetary mission design

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
As determined by planetary objectives

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Requires magnetic, electrostatic, and electromagnetic cleanliness.

Instrument Requirements:
Special Command, etc. Requirements:
Requires nearly continuous observations during cruise.

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Plasma spectrometer	TBD	TBD	TBD	TBD	Must view Sun
Magnetometer	≤30 kg				(but could spin)
Plasma wave detector	total				
Energetic particle detector					

Mission Strategy:
Include fields and particles instruments on planetary missions. Obtain nearly continuous data during mission cruise phase.

Required Technology: None

A.1.13 Mercury Orbiter (Collaboration on Magnetospheric Mission)

Target: Energetic particle and plasma measurements close to the Sun

Theme:
Exploration of the heliosphere, particle acceleration, evolution of matter, in addition to magnetospheric objectives

Science Objectives:
Close to Sun observations of solar wind and solar energetic particles. Acceleration of particles and solar wind, solar coronal composition

Mission Class: Moderate

Launch Vehicle Type: Titan IV/Centaur—single vehicle—2 spacecraft

Orbit(s) or Locations(s): Inner solar system to orbit around Mercury

Duration: >5 years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Spinner

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
See pre-Phase-A study

Instrument Requirements:
Special Command, etc. Requirements: See pre-Phase-A study

Instrument	Mass	Power	Data Rate	Data Storage	FOV
Super thermal particles	5 kg	5 W	0.5 kbps		15 *x* 45°
Solar wind analyzer	10 kg	10 W	1 kbps		5 *x* 180°
Energetic particles	10 kg	10 W	1 kbps		45° cones *x* 60° cone
X-ray detector	3 kg	1 W	0.3 kbps		
Magnetometer					
Neutral analyzer 15 kg	10 W	1 kbps			
Gamma-ray detector					

Mission Strategy: Orbit Mercury for close to Sun studies

Required Technology: None

Note: Mission objectives include magnetospheric and solar science in addition to this.

A.1.14 Coronal Imager Small Explorer

Target: Observations of the solar corona and solar wind acceleration region

Theme: Solar wind acceleration and coronal evolution

Science Objectives:
Mass, momentum, and energy transfer between corona (acceleration region of solar wind and source region of SEPs) and underlying transition region and chromosphere. Evolution of coronal structure (in solar wind and SEP source regions) over days to years.

Mission Class: Small Explorer

Launch Vehicle Type: Scout or larger

Orbit(s) or Locations(s): Low-Earth orbit, low inclination

Duration: 2 years minimum

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Spin about Earth-Sun line at 5 rpm

Special Features (*i.e.,* despun platforms, booms, mag cleanliness, etc.):

Instrument Requirements:
Special Command, etc. Requirements: None

Instrument	Mass	Power	Data Rate	Data Storage	FOV
EUV Spectrometer XUV Imager	TBD	TBD	TBD	TBD	TBD

Mission Strategy:
Global, synoptic (~1 per day) observations of solar disk and off limb with EUV spectrometer and XUV imager at low resolution (~10 arc seconds). Complementary to high-resolution observations from SOHO and OSL and to solar wind bulk and composition parameters from Wind and ACE.

Required Technology: None

A.1.15 Solar Flare Gamma-Ray/Neutron Small Explorer

Target: Sun

Theme: Particle acceleration and transport

Science Objectives:
Correlated observations of gamma-ray line and continuum emission for determining the abundances and properties of the particle beams and interaction regions in the Sun, and direct measurements of neutrons and energetic particles which escape from the Sun would provide unique information on particle acceleration, fractionation, escape and transport processes in the Sun and the interplanetary medium.

Mission Class: Small Explorer

Launch Vehicle Type: Scout

Orbit(s) or Locations(s): Circular, 600-km altitude equatorial orbit

Duration: 10 years (1997–2007)

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):

> 3-axis stabilized rim pointing with accuracy ~1°. 3-axis stabilized rim pointing with pointing accuracy ~1°

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Radiator cooler along the North-South direction

Instrument Requirements: Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
An array of 4 germanium detectors plus several pieces of BGO anticoincidence shield and a BGO calorimeter sensitive to high-energy gamma-rays and neutrons. An Oxford/BAC Stirling cycle cooler	80 kg	58 W	3 kbps normal up to 12 kbps after flare)	On-board processor 4 Mb RAM	

Mission Strategy:
The spacecraft should be placed in a circular, 600 km altitude equatorial orbit for optimizing the sensitivity and minimizing the radiation damage to the germanium detector due to trapped particles. It should be launched by a Scout Class Vehicle in the 1997–1998 time frame when ACE, OSL, and possibly Wind are operating.

Required Technology: The Oxford/BAC Stirling cycle cooler needs to be tested.

A.2 Ionospheric/Mesospheric/Thermospheric Missions

A combination of ***in-situ*** and remote sensing missions, and strong suborbital and balloon programs will be required to provide the data bases necessary to resolve the open issues. Synoptic, long-term coverage will be essential to identify and quantify trends and processes. This section provides a short description of several ITMP mission concepts that have emerged out of preliminary discussions. They are listed in a priority order.

ITMP Mission Concepts:

A.2.1 Major Mission: The ITM Coupler

The Problem

The ITM is controlled from above by EUV/UV radiation from the Sun, energetic particles from the interplanetary medium and the magnetosphere, and the superimposed electric fields from solar wind-magnetosphere interactions. It responds dynamically with large variations in its charged and neutral particle density and energy distributions, its drifts, winds, and tides, and its polarization and dynamo electric fields. We do not know the global distributions of electric fields and thermospheric winds nor the specifications of EUV/UV radiation—the primary forces driving the system. Within this system we do not know the global distribution of intermediate plasma layers and their contributions to critically important dynamo fields, and specific controlling influences of the metallic, atomic, and molecular ion inventory. In the cause-effect chain we do not understand the interplay of wind-shear forces and electric fields in the formation of intermediate layers, their global distributions, and control of upper F-region dynamics by field-line coupling of electric fields. Neither do we understand the physics controlling the mesosphere/lower thermosphere interface, the upward and downward propagation of tides and waves and their ultimate coupling to the ionized constituents, and the cascade of energy between large-and small-scale structures.

Specific Mission Science Questions (unprioritized)

> What is the relative contribution to the energy budget of the system from the various energy sources (EUV, UV, cosmic rays, auroral and ring current particles, Joule heating, tides, and gravity waves)?
>
> What are the relative contributions to the energy budget of the various energy sinks (ionization, excitation, thermal conduction, radiative cooling, etc.)?
>
> What is the spectrum of dynamical motions in the mesosphere and lower thermosphere, and how are the various motions (gravity waves, tides, and impulsive perturbations) dissipated?
>
> What are the global distributions of electric fields and thermospheric winds under quiet and disturbed conditions?
>
> How is energy within the ITM system transferred and dissipated in transition between large- and small-scale phenomenologies?
>
> What is the effect of mesoscale structure on the mean circulation?
>
> What are the fundamental processes responsible for eddy diffusion, conduction, and viscosity; and

what are the consequences of these processes?

How do anomalous transport processes affect the flow of momentum and energy into and out from the ionosphere?

How does the dynamical behavior of the neutral atmosphere influence electrodynamic coupling?

How do the ionospheric plasma distributions and associated current systems respond to magnetic storms?

Where and how do the magnetospheric and atmospheric currents close in the ionosphere?

What is the role of the ionosphere in populating the magnetospheric plasma—what are the source regions and mechanisms for energetic ion outflow?

How important is the large-scale thermospheric circulation in changing the composition and energetics of the mesosphere?

What are the relative roles of winds, electric fields, and ion chemistry in plasma layer formations?

Measured Parameters

The following measured parameters are necessary to answer the above questions:

Neutral and ion mass composition
Neutral, ion, electron temperature, and number density
Ion drift velocity and neutral wind vectors
Electric and magnetic fields
Energetic particle environment
Trace constituent populations: (HO_x, NO_x, $O(^1D)$, $O(^1S)$,
    CO_2, O_3, H_2O, etc.)
Solar spectral irradiance (EUV/UV)
Global airglow emission rates

Coverage Required

The mission requires comprehensive coverage of the following:

Solar cycle
Season
Latitude
Local time
Universal time/longitude
Altitude:
    i) *In situ* down to ~120 km
    ii) Remote sensing down to stratopause

Orbital Considerations

The ITM Coupler Program will be composed of six spacecraft with common (but not necessarily identical) elements in various orbits. Three "constellations" have been discussed during the first workshop. Detailed tradeoff studies of scientific objectives/coverage/orbital geometries are required before any specific configurations can be recommended. Generic characteristics for spacecraft orbits include:

- A high-altitude, near-polar orbiter for monochromatic auroral and airglow imaging.
- Several low perigee (~120 km) elliptical orbiters at various inclinations (*e.g.*, true polar, Sun-synchronous, fast precessing, low inclination) for remote and *in-situ* sensing of the ITM system.
- Several F-region circular orbits (~450 km) for remote and *in-situ* sensing of the ITM system. All spacecraft will be 3-axis stabilized to allow for both *in-situ* and remote sensing. All spacecraft will be capable of orbital adjustment (~3–400 m sec^{-1} ΔV).

Suborbital and Complementary Programs

A significant suborbital component to this mission would be required to carry out detailed studies of electrodynamics (*e.g.*, contribution to the global circuit of lightning-induced electric field, etc.) and ionospheric structuring and to provide any necessary ground-truth or calibrations (*e.g.*, recalibration for solar EUV monitor). The ground-based component to this mission could evolve out of the present CEDAR activities.

Cost

This mission would be in the "major" new start category: ~$1B.

Additional Comments

A coordinated multi-spacecraft mission such as this would be feasible for a new start in the mid-1990's. Such a mission would be exciting, would contribute enormously to ITM and other disciplines, and is in accord with the recommendations of previous strategy documents. Technological challenges would be incorporated in instrumentation and spacecraft design, particularly in the area of imaging and of altitude profiling. This mission is the top priority for the ITM discipline and would also contribute greatly to magnetospheric and middle atmosphere physics.

A.2.2 Moderate Mission #1: Mesospheric Structure, Dynamics and Chemistry

The Problem

This mission would be designed to investigate the photochemistry, composition, dynamics, radiative heating, and cooling of the mesosphere in unprecedented detail using IR, UV, and visible remote sensing techniques. The mission would be designed for long duration in order to determine long-term trends in mesospheric chemistry. These trends are of great importance since it is expected that the mesosphere will be one of the first upper atmospheric regions to demonstrate unambiguously the effects of global change due to anthropogenic causes. The instrumentation will measure factors involved in ozone chemistry, various chemical families, noctilucent clouds, mesopause temperature structures, etc.

Specific Mission Science Questions

What long-term trends in mesospheric structures occur due to anthropogenically-induced chemical changes associated with increased CO_2 and methane levels?

What are the mesospheric consequences of relativistic electron precipitation and proton precipitation events?

What is the basic compositional, energetic, radiative, and dynamical structure of the mesosphere?

What dynamical and chemical controls are responsible for the summer mesopause anomaly?

What are the controlling interactions among the photochemistry, dynamics, and radiative transfer in the mesosphere?

What is the general circulation of the mesosphere?

What role do gravity waves play in mesospheric winds, temperatures, and composition?

Approach

The mission would comprise a single (or possibly pair or near-identical) spacecraft in a near-polar, Sun-synchronous orbit, over an 11-year period. Periodic rocket recalibration flights would be part of the mission concept. All instruments would be remote-sensing, limb-and-nadir scanning instruments.

Instrumentation/Measured Parameters

Instrumentation would include:

Microwave limb sounder: H_2O, CO, O_2, T, winds (Doppler shifts), O_3< HO_2, from 40–100 km with 3–6 km resolution for a 1 meter dish. Day and night UV spectrometer: NO_2, CO_2, T, Pressure, O_3, CH_4, H_2O, 3 km resolution near IR spectrometer O_2, Meinel OH bands, near IR O_2, infer H, 3 km resolution

UV imager for waves and imaging polar mesospheric clouds in daytime. Nadir IT imager for OH images at night for waves. Solar UV spectrometer: solar output from Lyman-alpha to 3100Å. Fabry-Perot interferometer/visible photometers: mesopause and lower thermosphere winds. ***In-situ*** plasma probes

Orbital Considerations

Sun-synchronous ~600 km circular orbit, 3-axis stabilized, with fine pointing

Suborbital and Complementary Programs

Correlative radar and rocket overflight programs

Cost

This mission would be in the "moderate" or "large Explorer" category: ~$200–400M.

Comments

This would be a primarily mesospheric mission, designed to complete and extend the work initiated by the SME spacecraft. Long-term trend measurement capability will provide important technology challenges and will lead to a much improved understanding of the perturbations caused by man in this system. The emphasis for this mission is quite different from that of the ITM Coupler mission described above, being primarily concerned with the detailed aeronomy of the mesosphere itself rather than the higher transition region.

A.2.3 Moderate Mission #2: Time-Dependent Global Electrodynamics

The Problem

Our present understanding of modeling capabilities within the thermosphere/ionosphere is limited by a lack of knowledge of the electrodynamic driving forces. Primary forcings on the high-latitude neutral atmosphere are due to the imposed electric field. Electric fields originating in the solar wind interaction with the magnetosphere project down along geomagnetic field lines into the ionosphere. The time constant for changes in this electric field from changes in the solar wind is of the order of ten minutes. All of our descriptions of these electric field patterns are based on long-term statistical studies and do not reflect actual patterns as changes evolve from variable solar wind parameters. We cannot derive a pattern based on physical principles. Electric fields channel and control energy deposition into the thermosphere from Joule heating and particle precipitation. These inputs constantly change with the time-dependent electric field structure. Yet we do not even agree on the pattern for IMF B_z north conditions. We also do not understand the coupling between the magnetospheric electric fields and the neutral-wind-dynamo electric fields generated from tidal winds and inertial neutral motions. Understanding and predicting the dynamic changes in the thermospheric composition, winds, and density, and its coupling to ion composition and density is critically dependent on real-time description of this driving force, the electric field, and the energy that it controls.

Specific Mission Science Questions

How do changes in the solar wind pressure and IMF drive a convection electric field?

How does a change in the electric field pattern on the dayside of the polar cap propagate to the nightside?

How much variability occurs from the mean electric field patterns?

How does the electric field pattern evolve with changing IMF conditions?

How does energy deposition vary in real time and what impact does that have on neutral density and composition?

What is the response of neutral winds to time-varying electric field patterns?

What are the mesoscale variations in the electrodynamics and how do they affect the global structure?

What controls the penetration of electric fields to middle and low latitudes?

What is the role of disturbance dynamo and fossil winds at middle, low, and equatorial latitudes?

What is the effect of the Appleton anomaly in shielding the equatorial ionosphere from high-latitude current and electric field perturbations?

What are the effects of the IMF on the low-latitude electric fields?

Measured Parameters

The following measured parameters are necessary to answer the above questions:

Class A: Vector electric fields
Vector perturbation magnetic fields
Suprathermal and auroral energy electrons
Class B: Vector electric fields
Vector perturbation magnetic fields
Suprathermal and auroral energy ions and electrons
In-situ and remote sensing of:
neutral density, temperature, and composition
neutral winds
ion density, temperature, and composition

Approach

An innovative approach is needed to provide global patterns with high temporal resolution (10 minutes). Mass production of satellites with a sounding rocket approach can provide multiple, low-cost measurements. Reproduction costs are estimated to be ~$2–3M per satellite. A dual approach is needed for this mission:

- Constellation of 36 "Micro-Sat" satellites to determine real time inputs (Class A measurement parameters)
- "EE-Class" satellite flown in tandem with two Micro-Sat satellites to determine thermospheric and ionospheric response to real-time inputs (Class B measurement parameters)

Orbital Considerations

Micro-Sat constellation:
  90° inclination; 4 orbit planes; 500 km circular
  9 satellites space out in each plane
Response Measurements:
  90 inclination; 550 km circular
  2 Micro-Sats in 90 inclination orbital planes, 3° either side

Suborbital and Complementary Programs

Complementary programs include: auroral imaging, radar measurements, magnetospheric generator source measurements.

Cost

This mission would be in the "moderate" category: ~$500M.

Additional Comments

This approach is an innovative new way of approaching the problem in which the catastrophic loss of any one Micro-Sat does not seriously impact the mission. Hence lower reliability criteria can be used to minimize costs and maximize return. We anticipate that a number of the Micro-Sats can be launched from the same vehicle (possibly Pegasus), thus minimizing launch costs.

The electric-field maps would allow for the investigation of thermosphere-ionosphere-magnetosphere coupling on a much more detailed level than will ever be possible using more conventional techniques (*e.g.*, DE, DMSP, etc.). The technological challenge is high and such a constellation system could be re-used with different instrumentation packages to study other parameters at the same level of detail. The focus and rationale for this mission concept is similar in nature to the earlier "multi-probe" concept for magnetospheric science. With simultaneous global auroral imaging, the subsequently inferred conductivities can be combined with the electric fields to produce a two-dimensional map or footprint of magnetospheric electrodynamics. Using techniques such as the Assimilative Mapping of Ionospheric Electrodynamics (AMIE), a technique to merge observations of electric fields and currents in order to generate a self-consistent global model, the much needed dynamic magnetospheric inputs to the thermosphere and ionosphere would be obtained.

A.2.4 Moderate Mission #3: Tether Mission to the Thermosphere and Ionosphere

Scientific Objectives

a) To study the vertical and horizontal profiles of thermospheric and ionospheric parameters to characterize small (~kms) and medium-scale (~100's km) variability in winds, composition, and temperatures
b) To measure vorticity and divergence in the atmosphere on a global scale
c) To map the dynamic structure of the lower E-region on a global scale with 5–10 km resolution
d) To investigate the Sq current system
e) To investigate 3-dimensional current systems in the ionosphere
f) To investigate the transition region between collisionless and collision-dominated regimes of gas kinetics
g) To determine the metallic ion inventory in the lower ionosphere and the interchange roles of winds and E-fields in the formation of intermediate layers

Mission Description

This mission concept would utilize a string of generalized detectors spaced by ~10 km along a non-conducting tether. It has become technologically feasible to deploy tethers up to 130 km in length. Thus altitudes as low as 140 km could be sampled. If cheap generalized detectors can be mounted in the "pearls-on-a-string" configuration, then very exciting measurements of vertical profiles, divergence, and vorticities become possible. A downward-directed tether deployed along field lines at high latitudes would be able to investigate upwelling ion streams, auroral electrodynamics, ion acceleration regions, neutral viscosity, and non-Maxwellian flows, etc. Detailed altitude profiles of minor constituents, state variables, and the vertical propagation of gravity waves and tides could also be studied. If the tether could be rotated in the horizontal plane along the orbital path of the mother vehicle, then horizontal gradients could be obtained. Such tether measurements would go a long way towards removing the problematical temporal/spatial ambiguity.

Instrumentation/Measured Parameters

The "pearls-on-a-string" configuration for a tether mission would involve ~10 duplicate simple instruments designed to measure the *in-situ* atmospheric parameters. Such parameters could include neutral wind, ion drift, neutral, ion and electron temperatures, particle flows, etc. The payload for such a mission would be technologically challenging, but enormously beneficial for the detailed study of ITM structures.

Orbit(s)

A downward or horizontally-rotating tether mission could be flown in association with the polar platform of the space station at relatively high inclinations. Low-inclination orbits would also be of great utility for equatorial ionospheric and thermospheric work.

Suborbital and Complementary Programs

Chemical release rocket experiments would allow for calibration and extension of tether measurements.

Relationship to Major Themes

A tether mission to the "ignorosphere" would be responsive to many of the themes discussed above. In particular, the exciting technological challenge and the unique and important nature of the scientific results would be very strong.

Cost

Few details on the costs for such tether missions are available, but a mission of the type sketched here would probably cost in the area of $200–300M.

Comments

The tether capability suggests extremely interesting mission concepts of all varieties. The provision of a set of measurements of almost any thermospheric and ionospheric parameter, separated by known distances would provide very valuable insights into the actual spatial gradients of these parameters. In addition, the use of a long downward non-conducting tether to investigate the lower thermosphere would provide very useful data on thermospheric viscosity, vertical profiles, and horizontal circulation, without the typical temporal/spatial ambiguities that bedevil conventional measurements.

A.2.5 Moderate Mission #4 Mars Aeronomy Observer

The Problem

The upper atmospheres and ionospheres of Earth and Mars are controlled by the same physical processes (*e.g.*, photoionization, dissociation, and excitation), but with quite different relative importances that are determined by variations with solar distance, atmospheric composition, planetary gravity, and magnetic properties of the planet. Existing theoretical models of our ITM system are believed to contain all of the relevant processes, but these models have been highly tuned to the conditions at Earth. Many parameters of the Earth ITM system are too poorly known, however, to avoid the need for *ad hoc* assumptions about the remaining free parameters in the theory, thus rendering more uncertain the identification of the relevant processes. The application of these Earth-driven models to the ITM system of Mars will provide a severe test of the models and consequent improvements in their ability to describe our own ITM system. This approach has been highly successful in comparative planetary studies involving the ITM system of Venus, and we can expect additional improvements in the models when Mars measurements are available.

Scientific Objectives:

a) To explore for the first time the ITM system of Mars and the effects of the interaction of the solar wind with these regions.

b) To investigate the photochemistry, heat budget, and dynamics of the Martian upper atmosphere in the context of our understanding of such processes from similar missions already conducted at Earth and Venus.

c) To examine the effects on the upper atmosphere of tropospherically generated atmospheric waves and dust storms.

d) To test current aeronomic theory against the reality of a different atmosphere which is subject to the same physical processes, but in different combinations, and with different results. (Comparative planetary study using our knowledge of the upper atmospheres of Earth, Venus, Mars, Titan, etc.)

Mission Description

The mission description has already been given in detail in the MAO Science Team Report (NASA/JPL Tech. Memo 89202). MAO comprises a dual phased mission in which a single spacecraft, initially in a highly eccentric orbit, employs aerobraking and onboard propulsion to attain and maintain circular orbits in the range of 200–300 km.

Instrumentation/Measured Parameters (Strawman defined in JPL Tech. Memo)

- Neutral ion composition
- Neutral ion and electron temperatures and densities
- Neutral and ion winds
- Magnetic and electric fields and plasma wave environment
- Solar wind and energetic particles
- UV, optical, and IR limb scanning and imaging
- Radio science (radio occultation)

Orbits

The eccentric phase employs a very low periapsis (110–150 km) to perform *in-situ* and remote measurements to the lowest possible altitudes as well as measurements of the solar wind and the energetic plasma environment within the magnetosphere and upper ionosphere. The circular phase of the mission will provide measurements of the global response of the upper atmosphere over extended periods to examine its local time, seasonal, and solar cycle behavior (detailed description given in MAO Science Team Report).

Relationship to Major Themes

MAO relates to the comparative planetary atmospheres theme. It would allow us to view the upper atmospheres (Earth, Venus, and Mars) in the context of their common physical processes. Thus the theoretical models that have been developed to explain the observations at Earth can be tested against the reality of other planetary atmospheres. More specifically, the sometimes ***ad hoc*** assumptions used to tune the Earth models can be validated or refuted by application to Venus or Mars conditions. Examples from Venus are (1) the roles of metastable ions in the photochemistry of the ionosphere, (2) the rapid rotation of the Venus thermosphere has validated the superrotation theory of planetary atmospheres, (3) the ion and neutral gas escape processes at various planets, and their roles in the evolution of their atmosphere, and (4) the likelihood of the evolution of past or present life.

Cost

$250–400 M

Comments

MAO, proposed here as a key element of the ITMP plan, also has value as a robotic precursor to SEI. Knowledge of the upper atmosphere density and its variability is crucial to the use of aerocapture to achieve Mars orbit with the large payloads at low cost. MAO measurements will be particularly valuable in identifying Mars locations or conditions which lead to greatest risk for aerocapture.

A.2.6 Additional Mission Concepts and Infrastructural Issues

The above list of mission concepts is far from complete. Many additional ideas have surfaced during the pre-workshop discussions involving Explorer and Scout-class missions as well as balloon, rocket, and airplane-borne experiments. Moreover, certain individual component parts of the mission concepts discussed above could be re-packaged into other combinations of elements. Although there are obviously many approaches to planning for the ITMP report, certain fundamental requirements have become obvious and are discussed below.

SMEX and BEX Explorer-Class Missions

There is a strong continuing need for Explorer (BEX) and Scout-class (SMEX) missions within the ITM discipline. This is a community that has used Explorer-class missions to great effect in the past and one which has recently generated many novel and interesting mission ideas. The following is a partial list of some attractive SMEX and BEX mission candidates. Missions of this kind are considered to be of great importance to the continuing health of the discipline.

It would be very beneficial for the overall ITMP program to fly one or more explorer-class missions at the earliest possible date. This would allow for technology development of relevance to the ITMC mission and would prepare the community infrastructure for later efforts.

A.2.7 Space Exploration Initiative

The ITM discipline can make an important contribution to SEI. The practical benefits for aerobraking and STS re-entry have already been discussed, and these obviously relate directly to the manned space program. Monochromatic imaging of the ITM system could be accomplished from a permanently-manned Moon Base and would provide an extremely valuable continuous record of auroral and airglow distributions. In addition, meteor impact rates and distributions could be monitored. The MAO moderate mission could be supported most naturally within the context of the SEI program.

A.2.8 Suborbital, Ground-Based, and Laboratory Measurement Programs

It is clear that rockets and balloons continue to play a unique and important role in the study of the ITM system. This is particularly true for the mesosphere and lower thermosphere/ionosphere where coordinated rocket and balloon programs are an effective way to obtain regional data on electric fields and the corresponding electrodynamical processes induced by lightning discharges. It is also true for those active experiments which do not require the large orbital velocity for the required stimulated effects. These two areas, in particular, should be strengthened during the next decade. Several of the mission concepts discussed above would naturally require supporting rocket flights in order to perform re-calibrations or to establish ground truth.

The ground-based component for potential ITM missions is also crucial. Radars (both incoherent and coherent scatter types) and various optical instruments all have complementary roles to play. In this regard, the ground-based community of optical and radar specialists is well poised to assist in the development of the scientific and programmatic rationales because of the extensive level of coordination already present within the CEDAR program. It is anticipated that new ITM missions will have the strong involvement of ground-based experimentalists from the very beginning of the planning phases.

It is important also to maintain an active laboratory program that supports instrumentation development, simulations of space plasma processes, and studies of relevant collision and reaction cross-sections. Such efforts not only provide an important foundation for technology developments of future spaceborne diagnostic systems, but also allow detailed parameter studies (with re-validation and cross-correlation capabilities and unlimited spatial and temporal resolution) of mechanisms active in various components of the ITM system.

Another critical component of the infrastructural support necessary for the success of an ITM mission is the theoretical one. As mentioned above, sophisticated three-dimensional theoretical models exist for the ionosphere and thermosphere. Two-dimensional, zonally-averaged models exist for the mesosphere. These models are under continual development and will be used to refine the science objectives for the proposed ITMP missions and to ensure that the most appropriate parameters sets are chosen for the various measurement scenarios.

In summary, the essential infrastructure for optimization of ITM missions already exists and will be available during the next few years as some of the suggested missions come closer to realization.

Table A.2–1. Candidate Small Missions *(unprioritized and incomplete)*

Title	Objectives	Spacecraft Orbit Requirements
Ionospheric Irregularities	Source, evolution, and decay of irregularities Wave vector identification	250 *x* 1500 km 1–90° inclination 1–60° inclination
Active Experiments Satellite (chemical release)	Field-line tracking Field-aligned potentials and particle acceleration	Polar 2000–1000 km
WISP and Topside Sounder	Wave injection efficiency Wave-particle interactions	Polar TBD
Mesospheric Dynamics	Electrodynamics and chemistry of otherwise unreachable regions Role of aerosols in mesosphere	Sounding rockets and balloons
Tropospheric-ITM-Magnetosphere transients	Effects of lightning in ITM wave structure. Radiation belt loss to ionosphere Direct coupling of charge from lightning	Polar 2 S/C 200 *x* 3 Re
GITIM	Imaging of dynamics of ITM system	900 km, Sun synch
New Imaging Techniques for Electric Fields	Feasibility of radar imaging of mesoscale electric field patterns	Polar TBD
Gas Kinetics Explorer	Transition region between collisionless and collision-dominated regions	Inclination TBD; elliptical with low perigee
Sodium LIDAR from orbit	Mesospheric structure	STS system
MELTER	Mesosphere waves and chemistry	Phase A study (Delta launch)
Tidal Explorer	Lower thermospheric tides	SMEX mission
CHAMPION	Coupling of heliospheric, atmospheric, and magnetospheric processes in the ionosphere	SMEX mission

A.3 Magnetospheric Missions

A.3.1 Active Experiments

As space physics has progressed, its exploratory emphasis has evolved toward a more quantitative understanding of the systems and phenomena which have been discovered, leading in the direction of a predictive capability. During the course of this evolution, the increasing potential role of active experimentation in space has been widely recognized, but only partially realized in practice. In such experiments, by definition, the ambient or natural space environment is altered in a premeditated way, such as by the introduction of visible materials so as to reveal the motions of the medium or trace the path of magnetic field lines. Alternatively, processes are initiated which are analogous to natural processes, for example, beam-plasma or wave particle interactions driven by artificially generated beams of particles or waves or critical ionization velocity processes driven by high-velocity gas jets.

More recently, capabilities are in development which enable new experiments to be performed. The Space Transportation System orbiters have proved to emit large volumes of gases which lead to a comet-like interaction with the ionospheric flow past the orbiter, including the production of pickup ion populations which are much hotter than the ambient plasma and distributed as rings in velocity space. The development of a Tethered Satellite System will soon lead to the operation of an MHD dynamo powered by the motion of the long conducting tether through the conducting ionospheric plasma. Since the ionosphere itself will serve as an electrodynamic component of the resulting circuit, much stands to be learned about the way in which the ionosphere carries currents, and this new knowledge should carry over to our understanding of natural electrodynamic phenomena.

It has also been suggested that the orbital motion of a strong magnet in low-Earth orbit would lead to an interesting experiment which would support the general theme of comparative magnetospheres by adding a new member to the set of magnetospheres which are accessible to our study. Moreover, such an experimental magnetosphere would provide a reproducible capability to vary magnetospheric parameters, enhancing the opportunities for rapid interaction between space physics theory and observation. Now it appears that independent requirements will lead to the deployment of a strong magnet in low-Earth orbit in connection with the Astromag cosmic ray facility planned to fly on the U.S. Space Station. With suitable advance studies, and in conjunction with an appropriate plasma diagnostic probe, such a facility would synergistically serve the magnetospheric physics community as well as the cosmic ray community.

A.3.2 Supporting Services and Technical Requirements

Orbiting Magnet Assemblies. Both the cosmic ray and magnetospheric physics communities have developed needs for very strong magnets in low-Earth orbit. Astromag in particular has developed relatively complete technical requirements for a pair of superconducting ring magnets to be mounted in a "bucking" configuration so as to cancel dipole moments. Such a facility would serve both as a highly effective spectrometer for cosmic radiation and as a basis for an extremely interesting artificial magnetosphere for the simulation of certain well-known magnetospheric processes.

Deployable Plasma Diagnostic Probe. There is a continuing need for a deployable, maneuverable plasma diagnostic probe with capabilities similar to that of the PDP flown from the Spacelab 1 and 2 shuttle missions. Such a facility would serve well in the role of providing diagnostic measurements of the disturbed environment near the STS orbiter or the Space Station, particularly in conjunction with the comparative magnetospheric study opportunity presented by the presence of Astromag aboard the Space Station.

A.3.3 Active Experiment Accomplishments

Although active experimentation is a relatively recent development in space physics, it has already contributed in many ways to our understanding of natural phenomena. Chemical releases at low velocities have been used to create optically visible clouds which act as tracers of convective motions of magnetospheric plasmas. In some experiments, evidence supporting the concept of magnetic field-aligned electric fields has been obtained. A release in the solar wind has provided an artificial comet which provided insights into the interaction of real cometary gases with the solar wind. Energetic releases of gas have provided some confirmation of and insight into the critical velocity ionization effect of Alfvén. Accelerated beams of ions or electrons have provided insights into the energetics of wave instabilities in the auroral ionosphere, including the role of strong wave turbulence in impeding the flow of auroral field-aligned currents, and in heating the ambient plasma.

Among the most notable active experiments are the flights of the Space Transportation System orbiters themselves. They have proved to emit large volumes of gases which lead to a comet-like interaction with the ionospheric flow past the orbiter, including the production of pickup-ion populations which are much hotter than the ambient plasma and distributed as rings in velocity space. The development of a Tethered Satellite System will soon lead to the operation of an MHD dynamo powered by the motion of the long conducting tether through the conducting ionospheric plasma. Since the ionosphere itself will serve as an electrodynamic component of the resulting circuit, much stands to be learned about the way in which the ionosphere carries currents, and this new knowledge should carry over to our understanding of natural electrodynamic phenomena.

Despite this record of initial accomplishments and the demonstration of considerable promise, budgetary pressures and the Challenger disaster have in recent years led to the cancellation of the Spacelab mission known as Space Plasma Laboratory, which was to have been the centerpiece of the active experimentation effort. As NASA recovers from Challenger and prepares for the Space Station, it is time for a reassessment of active experimentation as a contributor to the goals of magnetospheric physics and space plasma physics. In particular, the flight of a strong magnet on the Space Station for the Astromag cosmic ray spectrometer facility will lead to an important experiment of opportunity for the refinement of space plasma theory in the area of comparative magnetospheres.

A.3.4 Imaging Super Cluster

Target:	Outer magnetosphere and deep tail
Spacecraft Type:	2 imaging platforms 1 cluster of 4 spinners
Class:	Major
Launch Vehicle:	3 separate launches 2 – Atlas II 1 – Titan III/TOS
Mission Duration:	≥2 years

Orbit: Polar, elliptical, 10–30 R_E apogee (imager)
Equatorial, elliptical, 10–30 R_E apogee (imager)
Double lunar swingby, tail tour, out to ~250 R_E (cluster)

Mass: Two @ ~1500 kg each
Four @ ~1000–1500 kg each

Primary Science Area/Measurement:
Global/macroscale imaging of magnetospheric charged particle populations with simultaneous measurement of geotail microstructure and dynamics. Science measurements on cluster of 4: B field to 10 kHz; E field to 1 MHz; ion composition (few eV–50 keV); 3-D electron (few eV–50 keV); energetic particles/electron to 1 MeV; ion composition to few MeV/nucleon; cold plasma density, temperature, and flow velocities.

Mission Strategy:
Stereoscopic imaging of the outer magnetosphere and tail to observe global morphology and dynamics while making *in-situ* observations of the physical processes within the tail.

Technology Development:
Interspacecraft accurate relative positions to 1% attitude to 0.01° for cluster; interspacecraft communication; imagers using O^+ resonantly scattered radiation; X-ray imager improvements; improved imaging of He^+ resonantly scattered radiation at 30.4 nm; continued development of ENA cameras.

Bit rates: for imagers; 50 kbs nominal, 1 mega bps burst
each cluster spacecraft; 10 kbs nominal, 1 mega bps burst
Attitude: determination to ≥0.01°
De-spun platform on imagers

A.3.5 Jupiter Polar Orbiter

Target: Jupiter's inner magnetosphere system

Spacecraft Type: New (modified observer class), spin-stabilized with de-spun platform; two spacecraft separated at Jupiter (single hybrid spacecraft alternative)

Class: Major

Launch Vehicle: Titan IV/Centaur

Mission Duration: 4 years in-transit; 2 years in-orbit (6 years total)

Orbit: High- and low-perijove polar elliptical

Mass: 4000–5000 kg (wet) injected into Jupiter trajectory

Primary Science Area/Measurement:
Jupiter science (aeronomy, atmosphere, *in-situ* auroral physics, gravity fields)
Satellite and rings (Io aeronomy, ring structure, and processes)

Plasma torus interactions, Io-torus coupling, high-energy particle processes, radio astronomy
Ion mass spectrometer, neutral mass spectrometer, electron temperature probe and spectrometer, plasma waves, magnetometer, IR mapping spectrometer, EUV/UV spectrometer, auroral imagers, CCD imager, gravity gradiometer, radio science.

Mission Strategy:
This mission utilizes the ΔVEGA trajectory technique to obtain sufficient mass from the Titan IV/Centaur launcher. Upon Jupiter approach, each spacecraft is separately targeted to polar elliptical orbit — one at very low perijove and the other at Io-distance perijove. Low-perijove orbiter optimizes Jupiter science while the high-perijove orbiter optimizes Io and torus science and provides high-altitude transpolar views of Jupiter's auroral regions. An alternate concept would be a single spacecraft with sufficient propulsive capability to change orbital regimes.

Technology Development:
Radiation-resistant sensor and electronic components; enhanced dust protection from Jupiter's rings

Ref: 1) JPO Workshop Report, UCLA, July 1985, George Siscoe (Chair)
2) "Jupiter Polar Orbiter Mission Concepts," AIAA Paper No. 86-2119 (CP), for NASA Headquarters (Code SL)

A.3.6 Mercury Orbiter (MeO)

Target:	Mercury magnetosphere
Spacecraft Type:	Spinning
Class:	Moderate
Launch Vehicle:	Titan IV (SRMV)/Centaur
Mission Duration:	6 years
Orbit:	200 km *x* 7 R_M
Mass:	800 kg *x* 2 spacecraft

Primary Science Area/Measurement:
Magnetospheric physics (substorm processes/particle acceleration)
Solar physics (flare processes: neutrons/gamma rays/energetic particles)
Heliospheric physics (solar wind source regions/transients)
Planetology (surface composition/crustal properties/magnetic field/gravity field)

Mission Strategy:

1) Cruise: Earth–Venus–Venus–Mercury–Mercury–Mercury–Mercury (cruise 4 years)

2) Orbit plan:

Phase I	S/C-1	Polar (200 km *x* 7 R_M)
	S/C-2	Deep Tail Survey (<90 R_M)
Phase II	S/C-1	Polar (200 km *x* 7 R_M)
	S/C-2	Near Tail Survey (<35 R_M)
Phase III	S/C-1	Polar (200 km *x* 7 R_M)
	S/C-2	Polar (200 km *x* 5 R_M)

Technology Development:
Mature; no new technology development required

Ref: Report of MeO Science Working Team (NASA TM scheduled for 5/90)

A.3.7 Magnetopause/Near-Plasma Sheet Equatorial Cluster

Target: Dayside equatorial magnetopause and tail from ~6–12 R_E

Spacecraft Type: Spinner—4 spacecraft

Class: Moderate

Launch Vehicle: Atlas II AS

Mission Duration: 2 years

Orbit: 0° inclination, ~2 *x* ~10–12 R_E

Mass: 100–150 kg payload/spacecraft

Primary Science Area/Measurement:
Intensive study of magnetopause structure and processes (FTE's, pressure pulses, surface waves, impulsive entry and steady-state merging, and exploration of near-Earth plasma sheet) requires simultaneous electric fields (DC–~1 MHz), Magnetic fields (DC–~10 kHz), and 3-D electron and ion distributions with composition (few eV to 30 keV) on all four S/C. Energetic particles and thermal plasma with composition on at least one spacecraft.

Mission Strategy:
Start mission on the day side and vary spacecraft spacing to cover range from ~100 km to a few R_E while precessing into the magnetotail region. High bit rates (up to MHz) required for short periods of time in the vicinity of the magnetopause. Could be accomplished with large onboard data storage with slower playback. Supporting measurements: continuous solar wind monitoring required; auroral and plasma imaging is desired from Inner Magnetosphere Imager.

Technology Development:
Inter-spacecraft relative position accurate to 1% and attitude to .01°; interspacecraft communication links

A.3.8 Inner Magnetosphere Imager

Target: Magnetospheric ring current/plasmasphere/auroral regions

Spacecraft Type: Spinner

Class: Explorer

Launch Vehicle: Delta

Mission Duration: >1 year

Orbit: High inclination (>65°), high eccentricity (apogee altitude 4–10 R_E)

Mass: S/C mass & instruments: 300 kg; launch vehicle capability determines S/C and instruments to be used

Primary Science Area/Measurement:
Global/macroscale observations magnetospheric characteristics and dynamics
Can observe substorm and magnetic storm effects
Can infer global magnetic and electric field configuration out to ~10–12 R_E
Pointing accuracy ~0.05°
10–100 kbps Data Rates

Mission Strategy:
Continuous observations of magnetosphere by imaging instruments from high-latitude, elliptical orbit

Technology Development:
Auroral UV—developed
Energetic Neutral Atom Camera—developed
Plasmasphere Imager (He^+, 30.4 nm)—to be developed

A.3.9 Auroral Cluster

Target: Auroral acceleration region 1000–12,000 km altitude

Spacecraft Type: Spinner—4 separate spacecraft

Class: Small

Launch Vehicle: Delta II (7920) or Atlas II AS

Mission Duration: 2 years

Orbit: Polar ~1000 *x* 12,000 km; variable separation between the S/C between 100 m to 100 km

Mass: 100–150 kg payload/spacecraft

Primary Science Area/Measurement:
Microphysical processes of auroral particle acceleration on scale sizes of a few meters to a few 100 km. Measurements: Electric field DC–5 MHz; Magnetic field DC–10 kHz; 3-D ion composition (up to 30 keV); 3-D electrons; imaging of loss cone; interferometric measurements; wave/particle correlator; thermal density fluctuations; thermal density and temperature. Wide band coverage in auroral regions. Faraday current probe.

Mission Strategy:
To separate temporal and spatial variations on various scale sizes of interest by utilizing different interspacecraft distances at different times in the mission. To obtain the required high data rate utilizing onboard mass storage and subsequent slower transmission. Supporting measurements: auroral imaging, solar wind monitor, ground-based images and radar. Inter-spacecraft relative position separation to 1% and 0.01% in attitude.

Technology Development:
Interspacecraft communication. Spacecraft requirements: electrostatic and electromagnetic cleanliness. Faraday current probe.

A.3.10 Magnetopause/Boundary Layer Explorer

Target: Magnetopause/boundary layer at all latitudes

Spacecraft Type: Spinner (1–2 S/C)

Class: Small

Launch Vehicle: Delta Class

Mission Duration: 2 years

Orbit: Polar 10 R_E circular (initial) to 10 *x* 30 R_E polar 35° apsides

Mass: up to 500 kg (direct); ~650 kg dual possibility (lunar swingby)

Primary Science Area/Measurement:
Measurements of magnetopause and boundary layer plasmas at all latitudes and all local times. Initial reconnaissance of high-latitude magnetopause tailward of the Earth. Investigation of generator region for magnetospheric driving currents. Measurement of magnetopause location and motion. Science measurements: electric field DC–5 MHz; B field DC–10 kHz; 3-D ion composition (few eV–30 keV); 3-D electrons (1 eV–30 keV); energetic particles.

Requirements on spacecraft: electrostatic & electromagnetic cleanliness; 30 kb/s

Mission Strategy:
Start with 10 R_E circular polar orbit. Increase apogee distance to stay at magnetopause as orbital local time changes through the first year, culminating in 10 x 30 R_E orbit with line of apsides inclined about 35° so that entire dayside magnetopause back to ~20 R_E downstream is skimmed when apogee is in magnetotail. Six months later, it becomes a near-Earth solar wind monitor for other missions. Best synergism with Magnetopause/Near-Plasma Sheet Equatorial Cluster if at same local apogee.

Technology Development: No new technology.

A.3.11 Active Field Line Tracing

Target:	Determine the magnetospheric magnetic configuration by tracing magnetic field lines
Spacecraft Type:	Scout
Class:	Small
Launch Vehicle:	Scout
Mission Duration:	2 months
Orbit:	Apogee 27,600 km, perigee 300 km, 30–35° inclination
Mass:	60 kg

Primary Science Area/Measurement:
1) Determine how the auroral field lines are connected to the ring-current region and the magnetotail plasma sheet;
2) Release barium gas with shaped charge at an altitude ~25,000 km and track the fluorescent barium streams with low-light-level imagers from ground.

Mission Strategy:
1) Launch the Scout vehicle from San Marco, or
2) The payload can be carried by Satellites from other missions.

Technology Development:
The technology has been tested in earlier barium shaped charge experiments.

Ref: Proposal to NASA by H.C. Stenback-Nielsen (University of Alaska): BARFLITE (Barium Field Line Tracing Experiment)

A.3.12 Analog Magnetospheric Plasma Laboratory (AMPL)

Target: Plasma interaction of Astromag with the ionosphere

Spacecraft Type: Deployable, maneuverable plasma diagnostic probe

Class: Small

Vehicle: STS/Space Station

Duration: Continuing

Orbit: Low latitude F region ionosphere

Mass: TBD, tens of kg

Primary Science:
Comparative magnetospheric physics, active experiment:

- Test space physics theory of fundamental processes under new conditions.
- Add new member to set of magnetospheres accessible to study.
- Provide reproducible experimental system which may be imaged and freely sampled, and altered or perturbed in a deliberate and controlled way.

Mission Strategy:
Use deployable maneuverable plasma diagnostic probe to study the interaction between Astromag and the ambient ionosphere. Various embellishments of the basic concept may be developed as experience is gained. This mission requires preliminary studies which should include the following:

1. Theoretical study sufficient to develop testable predictions concerning the Astromag system interaction.

2. Laboratory investigations of the concept of electromagnetic rotation drive for the spin-up of plasma in an orbiting magnet's field.

3. A "Scout class" precursor payload consisting of a simple permanent-magnet sphere (and perhaps another unmagnetized sphere of identical mass properties) should be launched into low-Earth orbit and tracked well enough to determine accurately the strength of its MHD drag and optical emission interaction with the ionosphere. This would rather quickly and efficiently determine the degree of activity which the electromagnetic interaction will generate, and the feasibility of future study of this type of artificial magnetospheric system.

Technology Development:
The greatest need for this mission, beyond the magnet system itself to be developed for Astromag, is for a freely maneuverable or manipulable plasma diagnostic probe with suitable instrumentation to characterize fully the essential characteristics of the interaction region.

Ref: Plasma Diagnostic Probe for SPACELAB 1 and 2, planned for Space Plasma Laboratory.

A.3.13 Solar Wind/IMF Input Monitor

Target:	Monitor of solar wind density and flow velocity and the interplanetary magnetic field (IMF)
Spacecraft Type:	Spinner
Class:	Small
Launch Vehicle:	Delta
Mission Duration:	>5 years
Orbit:	Double lunar swingby to maximize time in solar wind just upstream of the magnetosphere
Mass:	50 kg payload

Primary Science Area/Measurement:
Monitor solar wind and IMF in support of all magnetospheric missions.

Mission Strategy:
Time mission to replace the Wind spacecraft when necessary.

Technology Development:
None required.

A.3.14 Energetic Injection Plasma Laboratory

Target:	Interaction of energetic particle beams and waves with the ionosphere
Spacecraft Type:	Injector payload and deployable, maneuverable plasma diagnostic probe
Class:	Small
Vehicle:	Delta
Duration:	1 year
Orbit:	Elliptical polar, 200 km *x* 6000 km
Mass:	200–300 kg payload

Primary Science:
Plasma physics and remote sensing of ambient plasma structures

- Particle beam-plasma interactions, beam echoes from auroral potential structures
- Wave-particle interactions of emitted waves across VLF frequency spectrum
- Remote sensing of plasma structures by wave echoes

Mission Strategy:
Use deployable maneuverable plasma diagnostic probe to study the interaction between injectors and the ambient ionosphere. Various embellishments of the basic concept may be developed as experience is gained.

Technology Development:
Development of effective VLF transmitter antenna, having dimensions on the order of hundreds of meters from tip to tip. Considerable development work has been performed by the WISP team

Ref: 1) Plasma Diagnostic Probe for Spacelab 1 and 2, planned for Space Plasma Laboratory
2) WISP investigation plan for Space Plasma Laboratory
3) SEPAC on Spacelab 1 and 2

A.3.15 Lunar-Based Magnetopause Mapper

Target:	Earth's magnetosphere
Spacecraft Type:	Lunar base
Class:	SEI
Launch Vehicle:	SEI
Mission Duration:	3 years +
Orbit:	Lunar base
Mass:	

Primary Science Area/Measurement:
Radio transmitter swept in 2–60 kHz range to sound magnetopause and boundary layers from lunar base (distance, structure, and motion). If sensitivity allows, may even get echoes from plasmoids approaching and leaving the lunar distances.

Mission Strategy:
Use phased-array receiver (colinear dipoles) placed on lunar surface in support of radio telescope needs. Add transmitter wires (square ~30 km on a side) to allow directional beaming of output signal. 10 ms pulses allow 0.25 R_E spatial resolution. 1 W transmitted power yields return signal at least 25 db over continuum background for lunar dayside site, up to 99 dB signal to noise from lunar farside site.

Technology Developed:
Deployed wires on lunar surface. Computer modeling of wave transmission and reflection to determine required power and frequency ranges.

A.3.16 Lunar-Based Magnetospheric Imaging Observatory

TBD

A.4 Solar Missions

A.4.1 Science Accomplishments

A.4.1.1 Global Solar Mission—OSL

Target:	Solar atmosphere
Spacecraft Type:	Three-axis stabilized, pointed with fine guiding
Class:	Moderate
Launch Vehicle:	Delta II
Mission Duration:	3 years required, 10 years desired
Orbit:	Sun-synchronous
Mass:	3400 kg

Primary Science Goal:
Investigate:
- The interaction between convection and magnetic fields in the solar atmosphere.
- The generation, evolution, and destruction of magnetic flux.
- The mechanisms which convert magnetic energy into kinetic and thermal energy.
- How non-potential energy is stored in large-scale configurations and how this energy is released in flares and coronal mass ejections.

Measurement:
The OSL will have three primary data collection systems. These include:
- A visible-light telescope with an aperture of about 1 meter which is equipped with imaging and spectroscopic instruments for study of the solar photosphere and chromosphere.
- A UV telescope-spectrograph combination.
- A soft X-ray imaging experiment capable of visualizing the corona against the solar disk.
- The OSL meter-class telescope is intended to provide images with approximately 0.1 arc second resolution in the visible portion of the spectrum, which corresponds to a distance of approximately 100 km at the Sun's surface. With this resolution, it is anticipated that it will be possible to detect previously unresolved details of the solar atmosphere.

- The UV and X-ray instruments provide a vital augmentation of the observational material by extending the investigation to the upper levels of the chromosphere, transition zone, and lower corona.

Mission Strategy:
OSL will be launched into a Sun-synchronous orbit which will allow a unique opportunity for long periods of solar viewing. The observations will complement the SOHO, Solar-A, and the proposed NOAA X-ray imaging monitor in the objective of understanding details of the solar magnetic activity cycle.

OSL, with a unique spatial resolution and high spectral resolution over a rather broad range of wavelengths, is capable of contributing to the understanding of how magnetic energy is stored and catastrophically released in the flare process. If the OSL is launched at the beginning of the rise to maximum of the magnetic activity cycle in 1997, it will be possible to range the span of solar conditions from near minimum to maximum during the duration of the mission. The OSL is capable of making a vital contribution to the HESP mission.

Successful operation during this phase of the activity cycle will also permit insights gained to be used in the design and fabrication of a new generation used to support long-term manned presence on the Moon and the exploration of Mars.

Technology Development:
CCD detector camera systems with appropriate dimension, spectral sensitivity, and dynamic range characteristics to meet the mission performance objectives.

A.4.1.2 HESP

Target : The Sun

Theme: Solar high-energy astrophysics/flare physics

Science Objectives:
Identify the particle acceleration mechanisms at work during different phases of flares and coronal disturbances. Determine the contributions of high-energy particles to flare energetics, specifically by following the bremsstrahlung and nuclear line radiations spatially and temporally. Study particle transport (distribution functions, drifts, and scattering) during flares and coronal disturbances. Study abundances and abundance variations in the solar plasma as revealed by nuclear line intensities.

Class:	Intermediate to small moderate
Launch Vehicle:	Medium expendable launch vehicle (MELV)
Mission Duration:	3 years required, 10 years desired
Orbit:	Low inclination, 600 km; alternatively, a Sun-synchronous orbit offers significant advantages

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):

3-axis stabilized spacecraft stabilized for pointing at Sun. A spinner could be considered if significant cost savings are achieved with a spinning spacecraft.

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
The optical axis of the high energy instrument must be pointed to the Sun within 1 arc min. The stability of the pointing should be a few arc seconds (rms) or better over a minute.

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
High Energy Imaging Spectrometer	1550 kg	500 W	50 kbps	40MB	0.6°
EUV/XUV Spectrograph/Imager	60 kg	30 W	50 kbps	40MB	0.6°
White-Light Telescope (H_a, magnetograph)	30 kg	30 W	50 kbps	40MB	0.6°

Mission Strategy:
Preferred launch is in 1998 prior to rise of activity to maximum in cycle 23; could be launched two to three years later and still achieve significant science. Simultaneous operation with both SOHO and OSL is highly desired. If simultaneous operation with SOHO/OSL is possible, elimination of the EUV/XUV Spectrograph/Imager on HESP is a descope option.

Technology Development:
Trade-off studies of spacecraft/instrument capabilities versus cost in order to achieve goal of flying HESP as an intermediate mission. Active control of large structures (instrument structures of the order of 10 m length). Large format (2048^2) CCD's and data systems.

A.4.1.3 Global Solar Mission—Solar Polar Orbiter

Target : The Sun as viewed from high latitudes/1 AU particles & fields

Theme: Global view of solar magnetic activity and influence on the solar system—polar viewpoint

Science Objectives:
Observe global Sun; measure polar magnetic fields accurately; measure high-latitude differential rotation; investigate pole-equator temperature differences; observe coronal streamers, mass ejections from above; measure particles and fields in solar wind as function of latitude; measure helioseismology p-modes free of rotational splitting from the pole.

Mission Class: Major as part of GSM; moderate if fly-alone

Launch Vehicle Type: TBD

Orbit(s) or Location(s): Solar polar orbit (inclination ≥45°); spacecraft should be approximately 1 AU from Sun during polar passage

Duration:
3 years or more for operations in polar orbit, including the peak of Cycle 24 in 2011± 2

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
3-axis stabilized spacecraft or spin-stabilized with despun platform for solar instruments

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Pointing—coronagraphs pointed to Sun center within ±10 arc seconds; pointing stability about 1 arc second rms. Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained.

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
X-ray imager	30 kg	30 W	50 kbs	TBD	0.6°
WL/UV coronagraph	100 kg	50 W	50 kbs	TBD	1-20 $R_\odot$
Magnetograph/Doppler telescope	50 kg	60 W	50 kbs	TBD	0.6°
Solar irradiance	15 kg	20 W	1 kbs	TBD	full Sun
In situ fields/particles*	50 kg	50 W	5 kbs	TBD	TBD

* *e.g.*, payload for Polar Heliospheric Probe

Mission Strategy:
The polar orbiter (SPO) should be placed in an orbit (with a period of several years or less) which is approximately 1 AU from the Sun during polar passages. Planetary gravity assist(s) will be used to place the spacecraft into a high inclination orbit. The GSM in-ecliptic spacecraft should be launched sufficiently early that it (they) will be in full operation well before the first polar passage of SPO. *In-situ* fields and particles instruments operate through entire mission to explore the latitudinal structure of heliospheric fields and flows through the mission lifetime. The orbit of the polar orbiter allows long periods of time during which some solar structures may be observed constantly (so that observations of their evolution is not modulated by solar rotation). SPO, in combination with the GSM in-ecliptic spacecraft, provides stereoscopic and global solar observations. (If necessary, SPO could operate as a fly-alone mission, resulting in a loss of the latter science.)

Required Technology:
Trade-off studies between capabilities of the SPO spacecraft (size, mass, instrument accommodations, telemetry) and orbital parameters.

A.4.1.4 Global Solar Mission—Ecliptic Network

Target: The Sun; 1 AU particles and fields

Theme: Global view of solar magnetic activity and influence on the solar system; determination of the mechanisms and processes governing the magnetic activity cycle of the Sun

Science Objectives:
Study of the magnetic activity cycle and the evolution of the solar field at a variety of spatial and thermal regions. Study of the role of the Sun in shaping the structure and dynamics of the heliosphere

Mission Class: Major

Launch Vehicle Type: TBD

Orbit(s) or Location(s):
First spacecraft: located at L_1 or in LEO at 1 AU; second spacecraft: located in 1 AU solar orbit over the west limb. Additional spacecraft, if available, (*e.g.*, for SEI) to be located over the east limb and behind the Sun as viewed from Earth.

Duration:
Prefer launch after GSM polar orbiter so as to maximize probability that at least one in-ecliptic spacecraft is operational during polar passage of polar orbiter. If SEI support, launch prior to maximum of Cycle 23 (for relevant solar flare prediction research) with replacement spacecraft as needed to maintain continuous operation throughout SEI missions.

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):

> 3-axis stabilized spacecraft with coronagraphs pointed to Sun center within ±10 arc seconds; 0.3 arc second rms pointing stability for the Earth orbiter and about 1 arc second stability (rms) for the solar orbiting spacecraft

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained.

Instrument Requirements:
Earth Orbiting Spacecraft

Special Command, etc. Requirements:

> Prefer L_1 position so that science package may contain solar wind particles and fields instruments. For a lower cost mission, one can consider a low-Earth orbit with a height >600 km to insure long lifetime.

Instrument	Mass	Power	Data Rate	Data Storage	FOV
WL coronagraph	50 kg	50 W	50 kbs	TBD	1-30 $R_\odot$
X-ray imager	30 kg	30 W	50 kbs	TBD	0.6°
Vector magnetograph/Dopplergraph	50 kg	60 W	100 kbs	TBD	full Sun
UV coronagraph/disk telescope with spectrograph	175 kg	40 W	50 kbs	TBD	1-20 $R_\odot$
Solar irradiance	15 kg	20 W	1 kbs	0	full Sun
In situ fields/particles*	50 kg	50 W	5 kbs	0	TBD

* *e.g.*, payload for Polar Heliospheric Probe (assumes L_1 orbit)

In-ecliptic Solar Orbiting Spacecraft

Instrument	Mass	Power	Data Rate	Data Storage	FOV
X-ray imager	30 kg	30 W	50 kbs	TBD	0.6°
WL/UV coronagraph	100 kg	50 W	50 kbs	TBD	1-20 $R_\odot$
Magnetograph/Doppler telescope	50 kg	60 W	50 kbs	TBD	0.6°
Solar irradiance	15 kg	20 W	1 kbs	TBD	full Sun
In situ fields/particles*	50 kg	50 W	5 kbs	TBD	TBD

* *e.g.*, payload for Polar Heliospheric Probe

Mission Strategy:
Place L_1 (or Earth-orbiting) spacecraft in orbit first and then launch the west limb observatory. The L_1 position is preferable so that particles and fields instruments can be included in the payload. If possible (*e.g.*, for SEI), augment the 2 spacecraft with two duplicates of the west limb spacecraft, placing one over the east limb and one approximately at opposition to the Earth. Mission options (depending on cost, schedule, etc. considerations): (1) fly two in-ecliptic spacecraft plus SPO as a unified mission, (2) fly the L_1 in-ecliptic spacecraft plus SPO together, and (3) fly the two in-ecliptic spacecraft together.

Required Technology: Trade-off studies of science vs. cost of above mission options

A.4.1.5 Pinhole/Occulter Facility

Target: Sun

Spacecraft Type: Facility

Class: Medium

Launch Vehicle: Shuttle

Mission Duration:

Orbit: 600 km, 57° inclination

Mass: 4000 kg

Primary Science Area/Measurement:

Solar Physics:
Study the impulsive phase of flares, solar activity, the corona, and coronal transients/mass ejections. X-ray and gamma-ray astronomy: provide large area and high-angular imaging of a variety of galactic sources; map extended sources, resolve confused regions, provide spectroscopy at energies >10 keV of a variety of galactic sources.

Mission Strategy:
P/OF can be flown on the Space Station Freedom or as a free-flyer. An advanced P/OF could be operated from the lunar surface. If it is flown as a free-flyer, P/OF will be placed into a 300 km 57° inclination orbit by the STS shuttle vehicle. A mono-propellent hydrazine system will be used to spiral up to 600 km, its final destination. At the final orbit P/OF will be oriented toward the Sun, the solar array deployed, and the boom extended. After sufficient time for out gassing and system verification, science operations will commence. Communications will be via TDRSS data link to a P/OF control center where science observations and data disseminations could be coordinated.

A.4.1.6 Ultra High-Resolution Extreme Ultra-Violet Spectroheliograph (UHRXS)

Target: Sun

Spacecraft Type: Space Station attached payload

Class: Small instrument

Launch Vehicle: STS

Mission Duration: 1 year

Orbit: SSF

Mass: TBD

Primary Science Area/Measurements:

Mission Strategy:

Enabling Technology Development:
Normal incident mirror coatings
High precision pointer

A.4.1.7 Solar Probe (SP) Coronal Companion

Target: Solar corona

Theme: Physics of solar wind generation

Science Objectives:
Obtain observations of large-scale, time-varying, global coronal environment through which the SP flies. Obtain observations of lower atmospheric source of plasma and fields measured by SP, including transients (*e.g.*, CME's). Acquire complementary remote sensing data simultaneously with SP so that SP measurements can serve as "ground truth" for remote sensing techniques.

Mission Class: Low-end moderate

Launch Vehicle Type: Delta class

Orbit(s) or Location(s): Low-Earth orbit

Duration : At least 1 year

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
3-axis pointed, ~1 arc second pointing stability

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained. Occulter for coronagraphs may be on long boom.

Instrument Requirements:
Special Command, etc. Requirements:

Instrument	Mass	Power	Data Rate	Data Storage	FOV
WL coronagraph	20 kg	35 W	50 kbps	TBD	30 R_s
UV/EUV coronagraph	50 kg	40 W	50 kbps	TBD	20 R_s
Soft X-ray imager	3.0 kg	30 W	50 kpps	TBD	1.2 R_s

Mission Strategy:
If P/OF is available, it can serve as SP companion. If P/OF is not available, need Explorer or low end moderate mission launched when SP is ~1 AU from Sun on inbound leg to observe coronal origin of solar wind throughout time SP is within 1 AU of Sun. Solar Probe would also benefit from GSM observations.

Required Technology:
Existing technology for coronagraphs; soft X-ray imager would benefit from multilayer technology research (especially stability for long-term space environment).

A.4.1.8 Solar Variability Observatory

Target: Sun

Theme: Solar variability, solar terrestrial relations

Science Objectives:
Measure with high precision the solar luminosity and the solar spectral irradiance (15 nm<l<400 nm) over long periods (2 solar cycles and longer).

Mission Class: Explorer

Launch Vehicle Type: Delta II

Orbit(s) or Location(s): Equatorial

Duration: >22 years, requires exchange of spacecraft every 5 years for recalibration.

Spacecraft Requirements
Spinner (Rate/Orientation)/Pointed (Accuracy):
3-axis pointed, ~0.5 arc second stability

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained.

Mission Strategy:
Instruments may have a lifetime up to 5 years, new set of instruments needs to be orbited to overlap with old instruments.

Required Technology:
XUV photometer, X-ray photometer and imager need development. The others exist.

A.4.1.9 Solar Luminosity Explorer (SOLEX)

Target: Sun

Theme: Variability of solar luminosity on all time scales

Science Objectives:
This mission addresses the commitment of NASA to undertake the long-term measurement of the full disk solar irradiance with high precision. This includes the measurement of the "solar constant" and of the UV irradiance (X-rays to 400 nm). To enhance our understanding of solar variability, disk imaging at selected wavelengths will also be included.

Mission Class: SMEX

Launch Vehicle Type: Scout, Pegasus, or similar

Orbit(s) or Location(s): Typically Earth equatorial (>600 km)

Duration:
Commitment to have an SVO active at all times for a period of >22 years. This likely includes multiple spacecraft each with a lifetime of approximately five years.

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
The spacecraft can be of many designs,: spinner, three-axis stabilized, etc.

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.**):**
Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained.

Instrument Requirements:
Special Command, etc. Requirements: low power, data rate, and pointing requirements.

Mission Strategy:
The most important issue is the long-term commitment to assure that the solar irradiance is measured without interruption into the indefinite future.

Required Technology:
All of the proposed instruments exist and have been flown.

A.4.1.10 Solar EUV Explorer

Target: Sun

Theme: Dynamics, mass, and energy flow at coronal base

Science Objectives:
Study the mass and energy flow between the chromosphere and corona. Role of small-scale phenomena in the energetics of the corona. Utilize imaging, spectroscopic diagnostics of small-scale transient phenomena.

Mission Class: Small

Launch Vehicle Type: Delta

Orbit(s) or Location(s): Low-Earth orbit (>500 km)

Duration: Several years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed(Accuracy):
3-axis pointed, 0.5 arc second stability

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained.

Instrument Requirements:
Special Command, etc. Requirements: Δλl0.05Å, spatial resolution 1 arc second, EUV 300–1600Å

Mission Strategy:
Obtain measurements simultaneously over wide temperature range -K. Good time and spatial resolutions.

Required Technology:
Existing technology

A.4.1.11 Solar Composition Explorer

Target: Solar corona

Theme: Measure variations of coronal chemical composition, determine cause

Science Objectives:
Measure spatial and temporal variations in coronal chemical composition, obtain basic data for understanding these variations, first ion state problem detected from solar particle data.

Mission Class: Small

Launch Vehicle Type: Scout-class/Delta-class

Orbit(s) or Location(s): Low-Earth orbit (>500 km)

Duration: At least 1 year

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
3-axis pointed, 0.5 arc second pointing stability

Special Features (*i.e.*, despun platforms booms, mag cleanliness, etc.):
Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained.

Instrument Requirements:
Special Command, etc. Requirements:
Few arc second spatial resolution, Δλ0.1Å, 150–1600Å.

Mission Strategy:
Acquire EUV/XUV spectra in variety of solar features, phenomena (including flares) or determining spatial and temporal variations in coronal chemical composition.

Required Technology:
Multilayer mirrors and gratings for EUV/XUV could permit use of normal incidence technology. Alternate possibility is grazing incidence system (existing technology). Inflight calibration source (highly desirable) for EUV/XUV.

A.4.1.12 Solar Infrared Explorer (SIRE)

Target: Sun

Theme: Use infrared observations to explore Sun. Use variation of a height discriminator.

Science Objectives:
Determine temperature structure of solar atmosphere. Search IR spectrum for additional spectrum lies. Determine center-limb variation of IR emission lines, including hydrogen lines of all.

Mission Class: Explorer

Launch Vehicle Type: DELTA

Orbit(s) or Location(s): Equatorial—maybe Sun-synch if possible

Duration: 1 year

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Sun-pointed with offset

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Cryogenic for IR, but at moderate level (Sun is bright)

Instrument Requirements:
Special Command, etc. Requirements:
Ability to scan spectrum in IR. Fabry-Perot, with prefilters for various H lines (7–8, 8–9, etc.), thru spectrum. Wide-range FTS to supplement ATMOS measurements in S6 array for obs. t 1.6.

Mission Strategy:
At 1.6 microns, the point at which we see deepest into the Sun, some lines appear dark. In the 8–12 micron region, a height where the temperature was thought to be decreasing, dozens of emission lines of various elements are observed. Through the 30–100 micron region, a range of emission lines is observed, the hydrogen lines steadily growing in relative intensity as we go outwards. The actual brightness temperatures of the Sun in this range are probably unknown. The IR emission lines are expected to show a sizable center-to-limb variation. Because these lines are strongly limb-brightened, an imaging system is critical. Thus SI should include:

- An absolute radiometer which can measure the solar flux and intercalibrate it to other astronomical sources (such as the Moon) from 1 to 1000 microns.
- A cooled IR telescope which can measure the center-to-limb variation of the hydrogen and magnesium

lines through this region, and explore the region for additional lines. The telescope must be able to image other sources (Moon, Betelgeuse) for calibration.

- A high-resolution IR telescope for continuum observations at 1.6 microns.

Required Technology:

Advanced IR detectors. A ground-based program of the hardware developments to observe the 12 micron lines.

A.4.1.13 Coronal Imager

Target: Sun

Theme: Solar/heliospheric

Science Objectives:
This mission will make global and synoptic measurements of the velocity fields in the inner corona. These observations will be directly related to *in-situ* measurements of the solar wind (*e.g.*, ACE, Wind, etc.).

Mission Class: SMEX

Launch Vehicle Type: Scout, Pegasus, or similar

Orbit(s) or Location(s): Typical low-Earth orbit (<600 km)

Duration: Three to five years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
The spacecraft can be of various designs including a spinner or 3-axis stabilized.

Special Feature (*i.e.*, despun platforms, boom, mag cleanliness, etc.):
Spacecraft and instrument cleanliness (volatiles and particulate) must be maintained.

Instrument Requirements:

Special Command, etc. Requirements:
Low power, low data rate, and modest pointing requirements

Mission Strategy:
The single most important aspect of this mission is the global and synoptic attribute of the data set. It is only in this way that the solar measurements can be directly related to the solar wind observations.

Required Technology:
These are existing instruments flown numerous times on sounding rockets and selected for SPARTAN (205).

A.4.1.14 Lunar Solar Radio Observatory

Target: Coronal disturbances, dynamic phenomena

Theme:

Science Objectives:
Mapping of coronal, heliospheric dynamic phenomena, including Earth's magnetosphere, Jupiter, etc.

Mission Class: NA

Launch Vehicle Type: NA

Orbit(s) or Location(s): Moon-visible hemisphere

Duration: Several years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
NA

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
NA

Instrument Requirements:
Special Command, etc. Requirements:

Mission Strategy:
Deploy an array of simple radio antennae on the surface of the Moon, distributed over a large area, and housed at a central station (perhaps in lunar orbit). Low frequencies 10 kHz–10 MHz.

Required Technology:
Access to Moon

A.4.1.15 Mercury Orbiter

Target: Mercury magnetosphere

Theme: Magnetospheric physics

Science Objectives:
Magnetospheric physics: substorm processes, particle acceleration
Solar physics: flare processes—neutrons, gamma rays, energetic particles
Heliospheric physics: solar wind source regions, transients
Planetology: surface composition, crustal properties, magnetic field, gravity field

Mission Class: Moderate

Launch Vehicle Type: Titan IV (SMRU)/Centaur

Orbit(s) or Location(s): Mercury polar orbit, 200 km *x* 7 R_M

Mass: 2 spacecraft @ 800 kg each

Duration: 6 years

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
Spinners (2 spacecraft)

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
TBD

Instrument Requirements:
Special Command, etc. Requirements: TBD

Instrument	**Mass**	**Power**	**Data Rate**	**Data Storage**	**FOV**
DC Electric Field Analyzer	14.6 kg	6.0 W	TBD	TBD	TBD
Energetic Particle Detector	15.0 kg	15.0 W	TBD	TBD	TBD
Fast Electron Analyzer	4.0 kg	5.0 W	TBD	TBD	TBD
Fast Ion Analyzer	4.0 kg	5.0 W	TBD	TBD	TBD
Gamma Ray Spectrometer	17.0 kg	14.3 W	TBD	TBD	TBD
Ion Composition Plasma Analyzer	10.0 kg	12.0 W	TBD	TBD	TBD
Line Scan Imaging (& TEC)	5.1 kg	11.0 W	TBD	TBD	TBD
Magnetometer	5.3 kg	5.5 W	TBD	TBD	TBD
Optimized Solar Wind Analyzer	10.0 kg	10.0 W	TBD	TBD	TBD
Radio/Plasma Wave Analyzer	4.6 kg	6.5 W	TBD	TBD	TBD
Solar Neutron Analyzer	10.0 kg	10.0 W	TBD	TBD	TBD
Line Scan Imaging (WL, Ly a)	10.0 kg	12.0 W	1–10 kbps	TBD	TBD
Line Scan Imaging (XUV)	10.0 kg	12.0 W	1–10 kbps	TBD	TBD

Mission Strategy:
Cruise: Earth–Venus–Venus–Mercury–Mercury–Mercury–Mercury (cruise 4 years)

Orbit plan:

Phase I	S/C-1	Polar (200 km *x* 7 R_M)
	S/C-2	Deep tail survey (<90 R_M)
Phase II	S/C-1	Polar (200 km *x* 7 R_M)
	S/C-2	Near tail survey (<35 R_M)
Phase III	S/C-1	Polar (200 km *x* 7 R_M)
	S/C-2	Polar (200 km *x* 5 R_M)

Required Technology:
None

Note:
Two additional solar instruments are proposed, a white light/Lyman alpha line-scan imager and an XUV line-scan imager. The white light/Lyman alpha imager can use Mercury as an occulter for making "eclipse" observations of the outer corona. It should be possible to observe coronal structures such as streamers out to large distances from the Sun. Coronal observations from Mercury (in conjunction with coronagraphic observations from Earth or Earth orbit) also can provide stereoscopic information on coronal structures. For long-lived structures the Mercury observations alone can be used to acquire stereoscopic data, because of the relatively high angular rate at which Mercury orbits the Sun. Scans of the solar disk outside of eclipses will provide information on large-scale features from different perspectives (including the opposite side of the Sun as viewed from the Earth); scans made as the edge of Mercury covers the Sun can provide information on small-scale structures on the disk.

A.4.1.16 Solar Probe (SP) Coronal Companion

Target: Solar corona

Theme: Physics of solar wind generation

Science Objectives:
Obtain observations of large-scale, time-varying, global coronal environment through which the SP flies. Obtain observations of lower atmospheric source of plasma and fields measured by SP, including transients (*e.g.*, CME's). Acquire complementary remote sensing data simultaneously with SP so that SP measurements can serve as "ground truth" for remote sensing techniques.

Mission Class: Low-end moderate

Launch Vehicle Type: Delta class

Orbit(s) or Location(s): Low-Earth orbit

Duration: At least 1 year

Spacecraft Requirements:
Spinner (Rate/Orientation)/Pointed (Accuracy):
3-axis pointed, ~1 arc second pointing stability

Special Features (*i.e.*, despun platforms, booms, mag cleanliness, etc.):
Spacecraft and instrument cleanliness (volatiles and particulates) must be maintained. Occulter for coronagraphs may be on long boom.

Instrument Requirements:
Special Command, etc. Requirements: TBD

Instrument	Mass	Power	Data Rate	Data Storage	FOV
WL coronagraph	120 kg	35 W	50 kbps	TBD	1–30 $R_\odot$
UV/EUV coronagraph	150 kg	40 W	50 kbps	TBD	1–20 $R_\odot$
XUV/Soft X-ray imager	30 kg	30 W	50 kbps	TBD	1–1.2 $R_\odot$

Mission Strategy:
If POF is available, it can serve as SP companion. If POF is not available, need Explorer or low-end moderate mission launched when SP is ~1 AU from Sun on inbound leg to observe coronal origin of solar wind throughout time SP is within 1 AU of Sun. Solar Probe would also benefit from GSM observations.

Required Technology:
Existing technology for coronagraphs; soft X-ray imager would benefit from multilayer technology research (especially stability for long-term space environment.

Appendix B: Agenda

SPACE PHYSICS STRATEGY-IMPLEMENTATION STUDY
FUTURE MISSIONS WORKSHOP #1

Omni Inner Harbor Hotel
Baltimore, Maryland
21-26 January 1990

AGENDA

Sunday, 21 January 1990

Pre-Workshop Planning

1300–1500 hours	Organizational Session FOX presiding

Review of Workshop Agenda
Discussion of Panel & Workshop Charges
Consideration of Late Issues
Clarification of Panel Interactions
Outline of Workshop Report

WORKSHOP COMMITTEE:

KENNEL & KRIMIGIS (Mission Integration & Divisional Science)
ASHOUR-ABDALLA & ROSNER (Theory)
MEWALDT & MASON (Cosmic & Heliospheric Physics)
SZUSZCZEWICZ & KILLEEN (Ionospheric Physics)
BURCH & POTEMRA (Magnetospheric Physics)
WITHBROE & FISHER (Solar Physics)

1500–TBD hours	Panel Caucuses (as needed)
Results of Organizational Session Business of Panels	All Panel Chairs, Co-Chairs, and Members

1700–1900 hours	Registration

Appendix B: Agenda

Monday, 22 January 1990

Plenary Session #1

0800–0900 hours	Registration
0900–1200 hours	Background SISCOE presiding
Workshop #1 Plans	FOX
NASA & OSSA Plans	SHAWHAN
Space Exploration Initiative	BOHLIN
International Collaborative Programs	ACUÑA
1300–1700 hours	Panel "White" Papers FOX presiding
Mission Integration & Divisional Science	KENNEL & KRIMIGIS
Theory	ASHOUR-ABDALLA
Cosmic Ray/Heliospheric Physics	MEWALDT
Solar Physics	WITHBROE
Magnetospheric Physics	BURCH
Ionospheric/Mesospheric/Thermospheric Physics	SZUSZCZEWICZ
1900–2100 hours	Technology Assessment COOPER presiding
TBD	GSFC
Implementation of Future Programs	ROBERTS
Mission Opportunities— Trajectories & Performance Requirements	FRIEDLANDER
TBD	JPL

Tuesday, 23 January 1990

Panel Session #1

0900–1200 hours	Panel "Green" Papers
Ionospheric/Mesospheric/Thermospheric Physics	KILLEEN
Magnetospheric Physics	POTEMRA
Solar Physics	FISHER
Cosmic Ray/Heliospheric Physics	MASON

1300–1700 hours	Panel Caucuses
Themes & Thrusts Enhancement of Research Bases Small Missions Utilization of Space Station Freedom Space Exploration Initiative	All Panel Chairs, Co-Chairs, and Members

1900–2100 hours	Technology Assessment TBD presiding
TBD	JPL
Mission Costing	STANCATI
TBD	GSFC
TBD	JPL

Wednesday, 24 January 1990

Mid-Workshop Planning

0800–1200 hours

Integrational Session
KENNEL presiding

Results of Panel Caucuses
Prospects for Panel Interactions
Themes & Directions
Status of Workshop Report

Workshop Committee and
MIDS Panel Members

Plenary Session #2

1300–1700 hours

Progress
FOX presiding

Summaries of Panel Caucuses
Focus on Responses & Suggestions
Themes, Thrusts & Directions

Thursday, 25 January 1990

Panel Session #2

Measurements & Missions with Options

0800–1200 hours Panel Caucuses

1300–1700 hours Panel Caucuses

All Panel Chairs, Co-Chairs, and Members

Friday, 26 January 1990

Plenary Session #3

0800–1200 hours	Recommendations SISCOE presiding
Outcomes & Priorities of Panels Progress on Workshop Report	

Post-Workshop Planning

1300–1700 hours	Future Directions SHAWHAN presiding
Thrusts from Workshop #1—Conclusions & Priorities Studies of Technologies for Missions—Assessments Agenda for Workshop #2—Issues	Workshop Committee and MIDS Panel Members and Tech Assessors

Appendix C: Bibliography

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2. National Research Council. 1988. *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015—Solar and Space Physics.* Washington: NRC.
3. National Aeronautics and Space Administration. 1988. *Solar-Terrestrial Sciences: Report from the Science Strategy Workshop.* Washington: NASA.
4. National Aeronautics and Space Administration. 1986. *The Crisis in Space and Earth Science: A Time for a New Commitment.* Washington: NASA.
5. National Research Council. 1985. *An Implementation Plan for Priorities in Solar-System Space Physics.* Washington: NRC.
6. National Research Council. 1984. *A Strategy for the Explorer Program for Solar and Space Physics.* Washington: NRC.

Appendix D: Attendees at Workshop #1

Mario H. Acuna	NASA/Goddard Space Flight Center
Lee Ann Adams	Science Applications International Corporation
Spiro Antiochos	Naval Research Laboratory
John L. Anderson	NASA/Headquarters
Roger L. Arnoldy	University of New Hampshire
Maha Ashour-Abdalla	University of California
Aaron Barnes	NASA/Ames Research Center
Daniel N. Baker	NASA/Goddard Space Flight Center
W. Robert Binns	Washington University
J. David Bohlin	NASA/Headquarters
Larry H. Brace	NASA/Goddard Space Flight Center
Guenter E. Brueckner	Naval Research Laboratory
M. Kristine Butera	Science Applications International Corporation
James L. Burch	Southwest Research Institute
David Burks	Science Applications International Corporation
Leonard F. Burlaga	NASA/Goddard Space Flight Center
Cynthia A. Cattell	University of California
Davis P. Cauffman	Lockheed Research Laboratories
C. Richard Chappell	NASA/Marshall Space Flight Center
Andrew F. Cheng	APL/Johns Hopkins University
Michael L. Cherry	Louisiana State University
Andrew B. Christensen	The Aerospace Corporation
David H. Collins	Jet Propulsion Laboratory
Nathaniel Cohen	Science Applications International Corporation
Robert A. Cooper	Science Applications International Corporation
Steven Curtis	NASA/Goddard Space Flight Center
Thomas M. Donahue	University of Michigan
David Dunham	Computer Sciences Corporation
Paul Dusenbery	National Science Foundation
Jan Emming	Ball Aerospace
Robert W. Farquhar	NASA/Goddard Space Flight Center
Harvey Feingold	Science Applications International Corporation
Bela Fejer	Utah State University
Richard R. Fisher	NCAR/High Altitude Observatory
Kenneth Fox	Science Applications International Corporation
Louis A. Frank	University of Iowa
Alan L. Friedlander	Science Applications International Corporation
Harold Geller	Science Applications International Corporation
Francis P. Glosser	Science Applications International Corporation
Christoph K. Goertz	University of Iowa
Richard A. Goldberg	NASA/Goddard Space Flight Center
Melvyn L. Goldstein	NASA/Goddard Space Flight Center
Velma L. Gordon	Science Applications International Corporation
James L. Green	NASA/Goddard Space Flight Center
Akira Hasegawa	AT&T Bell Laboratories
Roderick A. Heelis	University of Texas
Ernest Hildner	NOAA/Space Environmental Laboratory
J. Todd Hoeksema	Stanford University

Robert A. Hoffman	NASA/Goddard Space Flight Center
Thomas E. Holzer	NCAR/High Altitude Observatory
Hugh Hudson	University of California
Theresa Jefferson	Science Applications International Corporation
J.R. Jokipii	University of Arizona
W. Vernon Jones	NASA/Headquarters
Charles F. Kennel	University of California
Michael J. Keskinen	Naval Research Laboratory
Tim L. Killeen	University of Michigan
Margaret G. Kivelson	University of California
S.M. Krimigis	APL/Johns Hopkins University
William S. Kurth	University of Iowa
Heather A. Lancaster	Science Applications International Corporation
Lou-Chang Lee	University of Alaska
James C. Ling	NASA/Headquarters
Robert M. MacQueen	NCAR/High Altitude Observatory
Elizabeth V. Manning	Science Applications International Corporation
Glenn M. Mason	University of Maryland
Geoffrey Maugham	Science Applications International Corporation
Nelson C. Maynard	Air Force Geophysics Laboratory
Hans G. Mayr	NASA/Goddard Space Flight Center
C.I. Meng	APL/Johns Hopkins University
Richard A. Mewaldt	California Institute of Technology
Peter Meyer	University of Chicago
Ronald L. Moore	NASA/Marshall Space Flight Center
Thomas E. Moore	NASA/Marshall Space Flight Center
Marcia Neugebauer	Jet Propulsion Laboratory
John C. Niehoff	Science Applications International Corporation
Jonathan F. Ormes	NASA/Goddard Space Flight Center
Dennis S. Peacock	National Science Foundation
Thomas A. Potemra	APL/Johns Hopkins University
Richard R. Radick	Geophysics Laboratory
Arthur Reetz	Science Applications International Corporation
Patricia H. Reiff	Rice University
William T. Roberts	NASA/Marshall Space Flight Center
Raymond G. Roble	NCAR/High Altitude Observatory
Robert Rosner	University of Chicago
Gary Rottman	University of Colorado
Thomas E. Ryan	NASA/Goddard Space Flight Center
Rita C. Sagalyn	Air Force Geophysics Laboratory
Robert W. Schunk	Utah State University
Philip Scherrer	Stanford University
Anita Seckinger	Science Applications International Corporation
Rikhi R. Sharma	Science Applications International Corporation
Stanley D. Shawhan	NASA/Headquarters
Edward G. Shelley	Lockheed Research Laboratories
George L. Siscoe	Massachusetts Institute of Technology
James A. Slavin	NASA/Goddard Space Flight Center

Appendix D: Attendees at Workshop #1

Edward J. Smith	Jet Propulsion Laboratory
Daniel Spicer	NASA/Goddard Space Flight Center
Michael L. Stancati	Science Applications International Corporation
Darrell F. Strobel	Johns Hopkins University
Simon Swordy	University of Chicago
Edward P. Szuszczewicz	Science Applications International Corporation
Theodore Tarbell	Lockheed Research Laboratories
Gregory Tarle	University of Michigan
Raymond J. Walker	University of California
Donald J. Williams	APL/Johns Hopkins University
George L. Withbroe	Smithsonian Astrophysical Observatory
Harold Zirin	California Institute of Technology
Ronald D. Zwickl	NOAA/Space Environmental Laboratory

Appendix E: Panels for Workshop #1

Cosmic & Heliospheric Physics Panel

Richard A. Mewaldt (chair)	California Institute of Technology
Glenn M. Mason (co-chair)	University of Maryland
Aaron Barnes	NASA/Ames Research Center
W. Robert Binns	Washington University
Leonard F. Burlaga	NASA/Goddard Space Flight Center
Michael L. Cherry	Lousiana State University
Thomas E. Holzer	NCAR/High Altitude Observatory
J. R. Jokipii	University of Arizona
Vernon Jones	NASA/Headquarters
James C. Ling	NASA/Headquarters
Marcia Neugebauer	Jet Propulsion Laboratory
Simon Swordy	University of Chicago
Gregory Tarle	University of Michigan

Ionospheric-Thermospheric-Mesospheric Physics Panel

Edward P. Szuszczewicz (chair)	Science Applications International Corporation
Tim L. Killeen (co-chair)	University of Michigan
Roger L. Arnoldy	University of New Hampshire
Larry H. Brace	NASA/Goddard Space Flight Center
Andrew B. Christensen	The Aerospace Corporation
B. Fejer	Utah State University
Roderick A. Heelis	University of Texas
Michael J. Keskinen	Naval Research Laboratory
Nelson C. Maynard	Air Force Geophysics Laboratory
Hans G. Mayr	NASA/Goddard Space Flight Center
C.-I. Meng	APL/Johns Hopkins University
Raymond G. Roble	NCAR/High Altitude Observatory
Robert W. Schunk	Utah State University

Magnetospheric Physics Panel

James L. Burch (chair)	Southwest Research Institute
Thomas A. Potemra (co-chair)	APL/Johns Hopkins University

Maha Ashour-Abdalla	University of California
Daniel N. Baker	NASA/Goddard Space Flight Center
Cynthia A. Cattell	University of California
Andrew F. Chang	APL/Johns Hopkins University
Louis A. Frank	University of Iowa
Christoph K. Goertz	University of Iowa
Margaret G. Kivelson	University of California
Lou-Chuang Lee	University of Alaska
Patricia H. Reiff	Rice University
Edward G. Shelley	Lockheed Research Laboratories
James A. Slavin	NASA/Goddard Space Flight Center

Mission Integration and Divisional Science Panel

Charles F. Kennel (chair)	University of California
S. M. Krimigis (co-chair)	APL/Johns Hopkins University
C. Richard Chappell	NASA/Marshall Space Flight Center
Thomas M. Donahue	University of Michigan
Robert W. Farquhar	NASA/Goddard Space Flight Center
James L. Green	NASA/Goddard Space Flight Center
Akira Hasegawa	AT&T Bell Laboratories
William S. Kurth	University of Iowa
Robert MacQueen	NCAR/High Altitude Observatory
Jonathan F. Ormes	NASA/Goddard Space Flight Center
Robert Rosner	University of Chicago
Edward J. Smith	Jet Propulsion Laboratory
Darrell F. Strobel	Johns Hopkins University

Solar Physics Panel

George L. Withbroe (chair)	Smithsonian Astrophysical Observatory
Richard R. Fisher (co-chair)	NCAR/High Altitude Observatory
Spiro Antiochos	Naval Research Laboratory
Guenter Brueckner	Naval Research Laboratory
J. Todd Hoeksema	Stanford University
Hugh Hudson	University of California
Ronald Moore	NASA/Marshall Space Flight Center
Richard R. Radick	Sacramento Peak Observatory
Gary Rottman	University of Colorado
Philip Scherrer	Stanford University

Daniel Spicer	NASA/Goddard Space Flight Center
Theodore Tarbell	Lockheed Research Laboratories
Harold Zirin	Big Bear Solar Observatory

Theory Panel

Maha-Ashour Abdalla (chair)	University of California
Robert Rosner (co-chair)	University of Chicago

Spiro Antiochos	Naval Research Laboratory
Steven Curtis	NASA/Goddard Space Flight Center
B. Fejer	Utah State University
Christoph K. Goertz	University of Iowa
Melvyn L. Goldstein	NASA/Goddard Space Flight Center
Thomas E. Holzer	NCAR/High Altitude Observatory
J. R. Jokipii	University of Arizona
Lou-Chuang Lee	University of Alaska
Hans G. Mayr	NASA/Goddard Space Flight Center
George L. Siscoe	Massachusetts Institute of Technology
Daniel Spicer	NASA/Goddard Space Flight Center
Darrell F. Strobel	Johns Hopkins University
Raymond Walker	University of California

Appendix F: Acronyms, Abbreviations, and Project Names

ACE	Advanced Composition Explorer
AE	Atmosphere Explorer
AIAA	American Institute of Aeronautics and Astronautics
AMIE	Assimilative Mapping of Ionospheric Electrodynamics
AMPL	Analog Magnetospheric Plasma Laboratory
AO	Announcement of Opportunity
APL	Applied Physics Laboratory
Astromag	Superconducting Magnetic Spectrometer Facility on Space Station
ATD	Advanced Technology Development
AU	Astronomical Unit
BARFLITE	Barium Field Line Tracing Experiment
BEX	Big Explorer
CAT	Computerized Axial Tomography
CCD	Charge Coupled Device
CDAW	Coordinated Data Analysis Workshop
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CHAMPION	Coupling of Heliospheric, Atmospheric, and, Magnetospheric Processes in the Ionosphere
Cluster	Element of ISTP: Multiple Spacecrafts
CME	Coronal Mass Ejection
COHO	Coordinated Heliospheric Observation Program
CRAF/Cassini	Comet Rendezvous Asteroid Flyby/Cassini
CRN	Cosmic Ray Nuclei
CRRES	Combined Release and Radiation Effects Satellite
CSSP	Committee on Solar and Space Physics
DC	Direct current
DE	Dynamics Explorer
DMSP	Defense Meteorological Satellite Program
DSN	Deep Space Network
DVEGA	Delta Velocity Earth Gravity Assist
EIPL	Energetic Injection Plasma Laboratory
ENA	Energetic Neutral Atoms
ESA	European Space Agency
EUV	Extreme Ultraviolet Explorer
FAST	Fast Auroral Snapshot Explorer
FPEG/VCAP	Fast Pulse Electron Gun/Vehicle Charging and Potential Experiment
FTE	Flux Transfer Event
Galileo	Jupiter Orbiter and Probe Spacecraft
GAS	Getaway Special
GCR	Galactic Cosmic Rays
Geotail	Element of ISTP; Geomagnetic Tail Exploration Satellite
GGS	Global Geospace Science

Giacobini-Zinner	Comet
GITIM	Global Imaging of Thermosphere, Ionosphere, and Mesosphere
GRS	Gamma Ray Spectrometer
GSI	Accelerator Facility in Darmstadt
Halley	Comet
Helios	Mission to Study Basic Solar Processes
HERON	Human Exploration Radiation Orbiting Network
HESP	High Energy Solar Physics
HNC	Heavy Nucleus Collector
ICE	International Cometary Explorer
IMF	Interplanetary Magnetic Field
IMI	Inner Magnetosphere Imager
IMP	Interplanetary Monitoring Platform
IR	Infrared
ISC	Imaging Super Cluster
ISTP	International Solar-Terrestrial Physics
ITM	Ionospheric, Thermospheric, and Mesospheric
ITMC	ITM Coupler
ITMP	ITM Panel
JPL	Jet Propulsion Laboratory
JPO	Jupiter Polar Orbiter
LIDAR	Light Detection and Ranging
LISA	Large Isotope Spectrometer for Astromag
LSEP	Large Solar Energetic Particle
MAO	Mars Aeronomy Observer
MAX	Matter/Antimatter Explorer
MELTER	Mesosphere and Lower Thermosphere Explorer
MeO	Mercury Orbiter
MHD	Magnetohydrodynamic
Mir	USSR Space Station
MIDS	Mission Integration and Divisional Science
MLT	Mesosphere/Lower Thermosphere
MNPSEC	Magnetosphere/Near-Plasma Sheet Equatorial Cluster
MO&DA	Mission Operations and Data Analysis
MOTP	Mission-Oriented Theory Program
MOWG	Management Operations Working Group
MPEX	Magnetopause/Boundary Layer Explorer
MRI	Magnetic Resonance Imaging
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NRC	National Research Council
OSL	Orbiting Solar Laboratory
OSSA	Office of Space Science and Applications
PIC	Particle-In-Cell
Pioneer	Solar System Exploration Spacecraft

POEMS	Positron Electron Magnet Spectrometer
Polar	Element of ISTP; Polar Orbiting Satellite
R&A	Research and Analysis
RAP	Research and Analysis Program
Rosetta	ESA Comet Nucleus Sample Return Mission
SAMPEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SCIN/MAGIC	Spectra, Composition, and Interaction of Nuclei/Magnet Interaction Chamber
SEI	Space Exploration Initiative
SEP	Solar Energetic Particle
SEPAC	Spare Experiments with Particle Accelerators
SIS	Strategy-Implementation Study
SME	Solar Mesosphere Explorer
SMEX	Small Explorer
SMM	Solar Maximum Mission
SOCCER	Planetary Sample Return Mission
SOHO	Element of ISTP: Solar and Heliospheric Observatory
Solar-A	Japanese Solar Research Satellite
STTP	Solar-Terrestrial Theory Program
SPACELAB	A General Purpose Orbiting Laboratory for Manual and Automated Activities in Near-Earth Orbit
SPD	Space Physics Division
SPIDDP	Space Physics Instrument Definition and Development Program
SPTP	Space Physics Theory Program
SSAAC	Space Science and Applications Advisory Committee
STS	Space Transportation System
SVE	Solar Variability Explorer
SWT	Science Working Team
S/C	Spacecraft
Tether	Mission to Earth's Thermosphere and Ionosphere
TM	Telemetry
TSS	Tethered Satellite System
UV	Ultraviolet
Viking	Swedish Auroral Region Exploration Satellite
VLF	Very Low Frequency
Voyager	Solar System Exploration Spacecraft
Wind	Element of ISTP: Interplanetary Physics Laboratory
WISP	Waves in Space Plasmas
Wizard	Experiment on Astromag for Measurement of Cosmic Rays
XUV	X-ray Ultraviolet