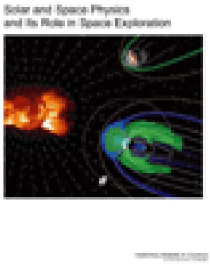

Solar and Space Physics and Its Role in Space Exploration

Committee on Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative, National Research Council

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Solar and Space Physics and Its Role in Space Exploration

Committee on the Assessment of the Role of Solar and Space Physics
in NASA's Space Exploration Initiative

Space Studies Board

Division on Engineering and Physical Sciences

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Cover: The heliospheric system—the Sun, the solar wind and space environment of Earth (lower right), the Moon (bottom), and Mars (upper right). This sketch is not to scale; for example, in reality the Sun is 100 Earth-diameters across and the Sun-Earth distance is 108 solar-diameters; Mars is half the size of Earth and 1.5 times farther from the Sun.

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Foreword

As this report is being issued the space science program of NASA is in transition. There is now a new agency goal to use humans and robots in synergy to explore the Moon, Mars, and beyond. This new priority for NASA presents both exciting possibilities and serious challenges to the space science program.

The transition in space science also places a task on the Space Studies Board. We have issued a series of decadal strategies for the various science disciplines of NASA that lay out priorities for science and recommended missions for the ensuing decade. Each of these studies, however, was completed before the announcement of NASA's new exploration vision, *The Vision for Space Exploration* (February 2004). There is value, then, in asking whether the priorities should in any way be changed to realize new opportunities or to offer additional support for the exploration goals. We should be cautious about altering decadal strategies, since their power stems from the fact that they are a well-honed and carefully reasoned consensus of the broad scientific community. Nonetheless, it is legitimate to ask whether the circumstances under which they were developed and the impact they are having have changed.

This report reviews the decadal strategy for solar and space physics, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, and evaluates it in the context of the exploration initiative. The most fundamental conclusion is that the basic priorities of the decadal strategy are still valid for the simple reason that the fundamental principles used in constructing the strategy were the need for a balanced program of basic and applied research that endeavors to recognize the solar-planetary environment for the complex system that it is. We do not know enough today to perform the predictive task required of us by the exploration initiative, and only by pursuing fundamental knowledge and employing a system-level approach can we hope to succeed.

The magnitude of the task before us—predicting the space environment through which we will fly—should not be underestimated. The report points out that within the expected budget envelope for this discipline it will not be possible to execute all of the missions judged to be essential to develop this predictive capability in a reasonable time frame. Missions such as Solar Probe, intended to explore the inner solar corona, which is the source of our space environment, or Sentinels, which are intended to study the coupling of the corona to the broader space environment, will be difficult to execute in a manner that supports the exploration initiative, within a program that considers all of the scientific issues this discipline must address. The report notes that other missions, which *are* expected to occur over the next decade, will still risk losing some of their power if they cannot be conducted simultaneously so as to achieve important scientific synergies. These issues deserve careful attention as NASA develops its plans for exploration.

Lennard A. Fisk, *Chair*
Space Studies Board

Preface

In 2003, the National Research Council (NRC) published the first decadal strategy for solar and space physics: *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics.*[1] That report included a recommended suite of NASA missions that were ordered by priority, presented in an appropriate sequence, and selected to fit within the expected resource profile for the next decade. In early 2004, NASA adopted major new goals for human and robotic exploration of the solar system, exploration that will depend, in part, on developing the capability to predict the space environment experienced by exploring spacecraft. The purpose of this report is to consider solar and space physics priorities in light of the exploration vision (see Appendix A for the statement of task).

NASA's solar and space physics program is conducted by the Sun-Earth Connection (SEC) Division of the Office of Space Science.[2] At the time of the decadal survey, the SEC program included one ongoing mission line called the Solar Terrestrial Probes (STP) and a longstanding series of smaller Explorer missions, plus a new series of missions that were planned to create a second mission line called the Living With a Star (LWS) program (for specific mission descriptions see Appendix B). Following introduction of the agency's new space exploration goals in early 2004, NASA planned to move forward with the LWS initiative, which focuses on aspects of space weather. However, elements of the STP and Explorer programs were subject to deferral in view of their being assigned a lower priority in the context of preparations for human missions to the Moon and Mars. The emphasis in the LWS program on applied science was seen as necessary to supply information on the environment for space travel between Earth and the Moon and Mars and on how that environment is controlled by solar activity. The STP and Explorer missions address basic scientific questions that were not viewed by NASA as being as immediately relevant to human exploration. Nevertheless, NASA has recognized that a strong basic research program is essential to the existence and growth of any applied science.

The NRC established the Committee on the Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative to provide advice on how and where the basic research aspects of the SEC program are needed to ensure that the applications requirements of the NASA exploration program are solidly grounded. In brief, the committee was asked to do the following:

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[1] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.

[2] Subsequent to the completion of the committee's report NASA implemented a reorganization that placed the Sun-Earth Connection program in a new headquarters program office—the Science Mission Directorate.

1. Analyze the missions and programs that were recommended in the NRC's first decadal strategy for solar and space physics (*The Sun to the Earth—and Beyond*) and assess their relevance to the space exploration initiative and
2. Recommend the most effective strategy for accomplishing the recommendations of the decadal strategy within realistic resource projections and time scales.

In June 2004 the President's Commission on the Implementation of United States Space Exploration Policy issued its report, *A Journey to Inspire, Innovate, and Discover*,[3] in which the commission described a broad role for science in the context of exploration (see Appendix C for a notional agenda for science research). The report treated science as being both an intrinsic element of exploration and an enabling element, and the committee responsible for this current study also shared that view. Consequently, the committee chose to interpret its charge in the broadest sense and to examine both the fundamental roles of solar and space physics as aspects of scientific exploration and the roles of the research in support of enabling future exploration of the solar system.

The committee included some members of the SSB Committee on Solar and Space Physics and several additional members of the SEC community, including experts who participated in the NRC decadal survey (committee member and staff biographies are presented in Appendix D). The ad hoc committee met in June 2004 at Woods Hole, Massachusetts; the committee also had extensive discussions via e-mail and teleconference.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

John T. Gosling, Los Alamos National Laboratory,
Michael Hesse, NASA Goddard Space Flight Center,
Margaret G. Kivelson, University of California, Los Angeles,
Robert P. Lin, University of California, Berkeley,
Glenn M. Mason, University of Maryland,
Jan Sojka, Utah State University,
Robert J. Strangeway, University of California, Los Angeles, and
Ellen Gould Zweibel, University of Wisconsin.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by John W. Leibacher, National Solar Observatory. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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[3] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy*, ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

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APPENDIXES

Executive Summary

In 2003, the National Research Council published the first decadal survey for Solar and Space Physics, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (referred to here as the decadal survey report).[1] The survey report recommended a research program for NASA and the National Science Foundation (NSF) that would also address the operational needs of NOAA and DOD. The report included a recommended suite of NASA missions, which were ordered by priority, presented in an appropriate sequence, and selected to fit within the expected resource profile for the next decade. In early 2004, NASA adopted major new goals for human and robotic exploration of the solar system,[2] exploration that will depend, in part, on an ability to predict the space environment experienced by robotic and piloted exploring spacecraft. The purpose of this report is to consider solar and space physics priorities in light of the space exploration vision.

In June 2004 the President's Commission on Implementation of United States Space Exploration Policy (also known as the Aldridge Commission) issued a report in which it described a broad role for science in the context of space exploration.[3] The report treated science as being both an intrinsic element of exploration and an enabling element:

> Finding 7 – The Commission finds implementing the space exploration vision will be enabled by scientific knowledge, and will enable compelling scientific opportunities to study Earth and its environs, the solar system, other planetary systems and the universe.

The commission also presented a notional science research agenda that comprises the three broad themes of origins, evolution, and fate (see Appendix C). Research in solar and space physics appears centrally under the topic "temporal variations in solar output—monitoring and interpretation of space weather as relevant to consequence and predictability" as an element of the fate theme, and it contributes in key ways to many aspects of several components of the origins and evolution themes. In light of the commission's findings, the Committee on the Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative chose to interpret its charge in the broadest sense and to examine

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[1] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.

[2] National Aeronautics and Space Administration, *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., February 2004.

[3] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy*, ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

the fundamental role of solar and space physics research both in scientific exploration and in support of enabling future exploration of the solar system.

From a purely scientific perspective, it is notable that the solar system, and stellar systems in general, are rich in the dynamical behaviors of plasma, gas, and dust that are organized and affected by magnetic fields. These dynamical processes are ubiquitous in highly evolved stellar systems, such as our own, and they play important roles in their formation and evolution. Magnetic fields produced in rotating solid and gaseous planets in combination with ultraviolet and x-ray photons from the planetary system's central stars create plasma environments called asterospheres, or in the Sun's case, the heliosphere. In its present manifestation, the heliosphere is a fascinating corner of the universe, challenging our best scientific efforts to understand its diverse workings. Consequently this "local cosmos" is a laboratory for investigating the complex dynamics of active plasmas and fields that occur throughout the universe, from the smallest ionospheric scales to galactic scales.[4] Close inspection and direct samplings within the heliosphere are essential parts of the investigations that cannot be carried out by a priori theoretical efforts alone.

Finding 1. The field of solar and space physics is a vibrant area of scientific research. Solar and space physics research has broad importance to solar system exploration, astrophysics, and fundamental plasma physics and comprises key components of the Aldridge Commission's main research themes of origins, evolution, and fate.

Interplanetary space is far from empty—a dynamic solar wind flows from the Sun through the solar system, forming the heliosphere, a region that encompasses all the solar system and extends more than three times the average distance to Pluto. Gusts of energetic particles race through this wind, arising from acceleration processes at the Sun, in interplanetary space, in planetary magnetospheres, and outside our solar system (galactic cosmic rays). It is these fast particles that pose a threat to exploring astronauts. The magnetic fields of planets provide some protection from these cosmic rays, but the protection is limited and variable, and outside the planetary magnetospheres there is no protection at all. Thus, all objects in space—spacecraft, instrumentation, and humans—are exposed to potentially hazardous penetrating radiation, both photons (e.g., x-rays) and particles (e.g., protons and electrons). Just as changing atmospheric conditions on Earth lead to weather that affects human activities on the ground, the changing conditions in the solar atmosphere lead to variations in the space environment—space weather—that affect activities in space.

The successful exploration of the solar system on the scale and scope envisioned in the new exploration vision will require a prediction capability sufficient to activate mitigation procedures during hazardous radiation events. The development of such a capability will require understanding of the global system of the Sun, interplanetary medium, and the planets. This is best achieved by a mixed program of applied space weather science and basic research. A balanced, integrated approach with a robust infrastructure that includes flight mission data analysis and research, supporting ground and suborbital research, and advanced technology development must be maintained. *The strategy outlined in the solar and space physics decadal survey report was designed to accomplish these goals; the committee believes that NASA should retain a commitment to the achievement of the goals of the decadal survey.* Indeed curtailing program elements that address the scientific building blocks of space weather research jeopardizes the goal of space weather prediction. However, in light of likely constraints on resources in future years, the committee offers findings and recommendations that address a realistic revision of mission timelines that will still permit a viable program.

Space weather conditions throughout the heliosphere are controlled primarily by the Sun and by the solar wind and its interaction with the magnetic fields and/or ionospheres of the planets. While simple statistical statements (analogous to "March tends to be colder than June") can be made as a result of empirical, short-term studies, accurate predictions (analogous to "a cold front will bring wind and rain late tomorrow afternoon") will require longer-term studies of the underlying processes as well as of how the whole heliospheric system responds. Both basic science and applied studies are necessary components of a viable program that facilitates space weather predictions.

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[4] See National Research Council, *Plasma Physics of the Local Cosmos*, The National Academies Press, Washington, D.C., 2004.

Finding 2. Accurate, effective predictions of space weather throughout the solar system demand an understanding of the underlying physical processes that control the system. To enable exploration by robots and humans, we need to understand this global system through a balanced program of applied and basic science.

NASA's Sun-Earth Connection program depends on a balanced portfolio of spaceflight missions and of supporting programs and infrastructure, which is very much like the proverbial three-legged stool. There are two strategic mission lines—Living With a Star (LWS) and Solar Terrestrial Probes (STP)—and a coordinated set of supporting programs. LWS missions focus on observing the solar activity, from short-term dynamics to long-term evolution, that can affect Earth, as well as astronauts working and living in the near-Earth space environment. Solar Terrestrial Probes are focused on exploring the fundamental physical processes of plasma interactions in the solar system. A key assumption in the design of the LWS program was that the STP program would be in place to provide the basic research foundation from which the LWS program could draw to meet its more operationally oriented objectives. Neither set of missions alone can properly support the objectives of the exploration vision. Furthermore, neither set of spaceflight missions can succeed without the third leg of the stool. That leg provides the means to (1) conduct regular small Explorer missions that can react quickly to new scientific issues, foster innovation, and accept higher technical risk; (2) operate active spacecraft and analyze the LWS and STP mission data; and (3) conduct ground-based and suborbital research and technology development in direct support of ongoing and future spaceflight missions.[5]

Finding 3. To achieve the necessary global understanding, NASA needs a complement of missions in both the Living With a Star and the Solar Terrestrial Probes programs supported by robust programs for mission operations and data analysis, Explorers, suborbital flights, and supporting research and technology.

The decadal survey report from the Solar and Space Physics Survey Committee recommended a carefully reasoned and prioritized program for addressing high-priority science issues within the constraints of what was understood to be an attainable timeline and budget plan (see Figure 3.1 (a) in Chapter 3 below).

The integrated research strategy presented in the decadal survey for the period 2003 to 2013 is based on several key principles. First, addressing the scientific challenges that were identified in the survey report requires an integrated set of ground- and space-based experimental programs along with complementary theory and modeling initiatives. Second, because of the complexity of the overall solar-heliospheric system, the greatest gains will be achieved by a coordinated approach that addresses the various components of the system, where possible, in combination. Third, a mix of basic, targeted basic,[6] and applied research is important so that the advances in knowledge and the application of that knowledge to societal problems can progress together. Finally, containing cost is an important consideration because the recommended program must be affordable within the anticipated budgets of the various federal agencies.

Finding 4. The committee concurs with the principles that were employed for setting priorities in the decadal survey report and believes that those principles remain appropriate and relevant today.

With those principles in mind, the decadal survey report recommended a specific sequence of high-priority programs as a strategy for solar and space physics in the next decade. To accomplish this task, the survey report presented an assessment of candidate projects in terms of their potential scientific impact (both in their own subdisciplines and for the field as a whole) and potential societal benefit (i.e.,

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[5] For a full discussion of the roles and relationships of spaceflight missions to supporting research and technology programs, see National Research Council, *Supporting Research and Data Analysis in NASA's Science Programs*, National Academy Press, Washington, D.C., 1998.

[6] By "targeted basic" research the committee means research that is conducted at a relatively fundamental level but that is intended to provide the scientific basis for specific future applications. The term "strategic research" has sometimes been used synonymously.

with respect to space weather). The survey report also took into consideration the optimum affordable sequence of programs, what programs would benefit from being operational simultaneously, the technical maturity of missions in a planning phase, and what programs should have the highest priority in the event of budgetary limitations or other unforeseen circumstances that might limit the scope of the overall effort. The recommended sequence of missions was supported by a strong base of Explorer missions, mission operations and data analysis (MO&DA), suborbital activities, and supporting research and technology (SR&T) programs, which together provide the core strength of the Sun-Earth Connection (SEC) program research base.

Finding 5. The committee concludes that, for an SEC program that properly fulfills its dual role of scientific exploration and of enabling future exploration of the solar system, the prioritized sequence recommended in the decadal survey report remains important, timely, and appropriate.

Although the recommendations and schedule presented in the decadal survey report were formulated in 2002—before the adoption by NASA of the new exploration vision—the essential reasoning behind the conclusions of the survey report remains valid: to explore and characterize the solar system and to understand and predict the solar-planetary environment within which future exploration missions will take place requires a scientific approach that treats the environment as a complex, coupled system. The extension of exploration beyond the environment close to Earth will require accurate prediction of conditions that will be encountered. Without programs such as the STP mission line, which study the physical basis of space weather, the development of accurate predictive tools would be placed at serious risk.

Recommendation 1. To achieve the goals of the exploration vision there must be a robust SEC program, including both the LWS and the STP mission lines, that studies the heliospheric system as a whole and that incorporates a balance of applied and basic science.

A robust program of SEC research depends on four foundation programs—Explorers, MO&DA, the Suborbital program of flights, and SR&T—for basic research and for development of technologies and theoretical models. The vitality of the Explorer mission line depends on the orderly selection of a complement of Small Explorer (SMEX) and Medium-Class Explorer (MIDEX) missions.

Recommendation 2. The programs that underpin the LWS and STP mission lines—MO&DA, Explorers, the Suborbital program, and SR&T—should continue at a pace and a level that will ensure that they can fill their vital roles in SEC research.

In the event of a more constrained funding climate, the timing of near-term missions may have to be stretched out. The committee recognizes that there may be a need to re-evaluate the order and timing of far-term missions in light of the way the exploration initiative evolves while keeping in mind the full scientific context of the issues being addressed.

Recommendation 3. The near-term priority and sequence of solar, heliospheric, and geospace missions should be maintained as recommended in the decadal survey report both for scientific reasons and for the purposes of the exploration vision.

Even with an SEC program that preserves the priorities and sequence of recommended missions, there will be important consequences from delaying the pace at which missions are executed as a means of dealing with resource constraints. First, there will be losses of scientific synergy due to the fact that opportunities for simultaneous operation of complementary missions will be more difficult to achieve. Furthermore, a number of missions that were recommended in the decadal survey report will be deferred beyond the 10-year planning horizon. This could be the case for the Jupiter Polar Mission, Stereo Magnetospheric Imager, Magnetospheric Constellation, Solar Wind Sentinels, and Mars Aeronomy Probe. These issues will demand careful attention as NASA develops its overall plan for science in the exploration vision.

1

Introduction

> The Sun is the source of energy for life on Earth and is the strongest modulator of the human physical environment. In fact, the Sun's influence extends throughout the solar system, both through photons, which provide heat, light, and ionization, and through the continuous outflow of a magnetized, supersonic ionized gas known as the solar wind. The realm of the solar wind, which includes the entire solar system, is called the heliosphere. In the broadest sense, the heliosphere is a vast interconnected system of fast-moving structures, streams, and shock waves that encounter a great variety of planetary and small-body surfaces, atmospheres, and magnetic fields. Somewhere far beyond the orbit of Pluto, the solar wind is finally stopped by its interaction with the interstellar medium . . . . (From *The Sun to the Earth—and Beyond,* p.1[1])

Space is far from empty—an often gusty solar wind flows from the Sun through interplanetary space, forming the heliosphere (see Figure 1.1 and Box 1.1). Bursts of energetic particles (also known as cosmic rays) arise from acceleration processes at or near the Sun and race through this wind, traveling through interplanetary space, impacting planetary magnetospheres, and finally penetrating beyond our solar system. It is these fast particles that pose a threat to exploring astronauts. The magnetic fields of planets provide some protection from these cosmic rays, but the protection is limited and variable, and outside the planetary magnetospheres there is no protection at all. Thus, all objects in space—spacecraft, instrumentation, and humans—are exposed to potentially hazardous penetrating radiation, both photons (e.g., x-rays) and particles (e.g., protons and electrons). Just as changing atmospheric conditions on Earth lead to weather that affects human activities on the ground, the changing conditions in the solar atmosphere lead to variations in the space environment—space weather—that affect activities in space.

In 2003, the National Research Council published the first decadal survey for solar and space physics, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (referred to here as the decadal survey report). The survey report recommended a research program for NASA and the National Science Foundation (NSF) that would also address the operational needs of NOAA and DOD. The report included a recommended suite of NASA missions, which were ordered by priority, presented in an appropriate sequence, and selected to fit within an expected resource profile during the next decade. In early 2004, NASA adopted major new goals for human and robotic exploration of the solar system,[2] exploration that will depend, in part, on our ability to predict the space weather experienced by exploring spacecraft. The purpose of this report is to consider research priorities in the light of the space exploration vision.

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[1] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.

[2] National Aeronautics and Space Administration, *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

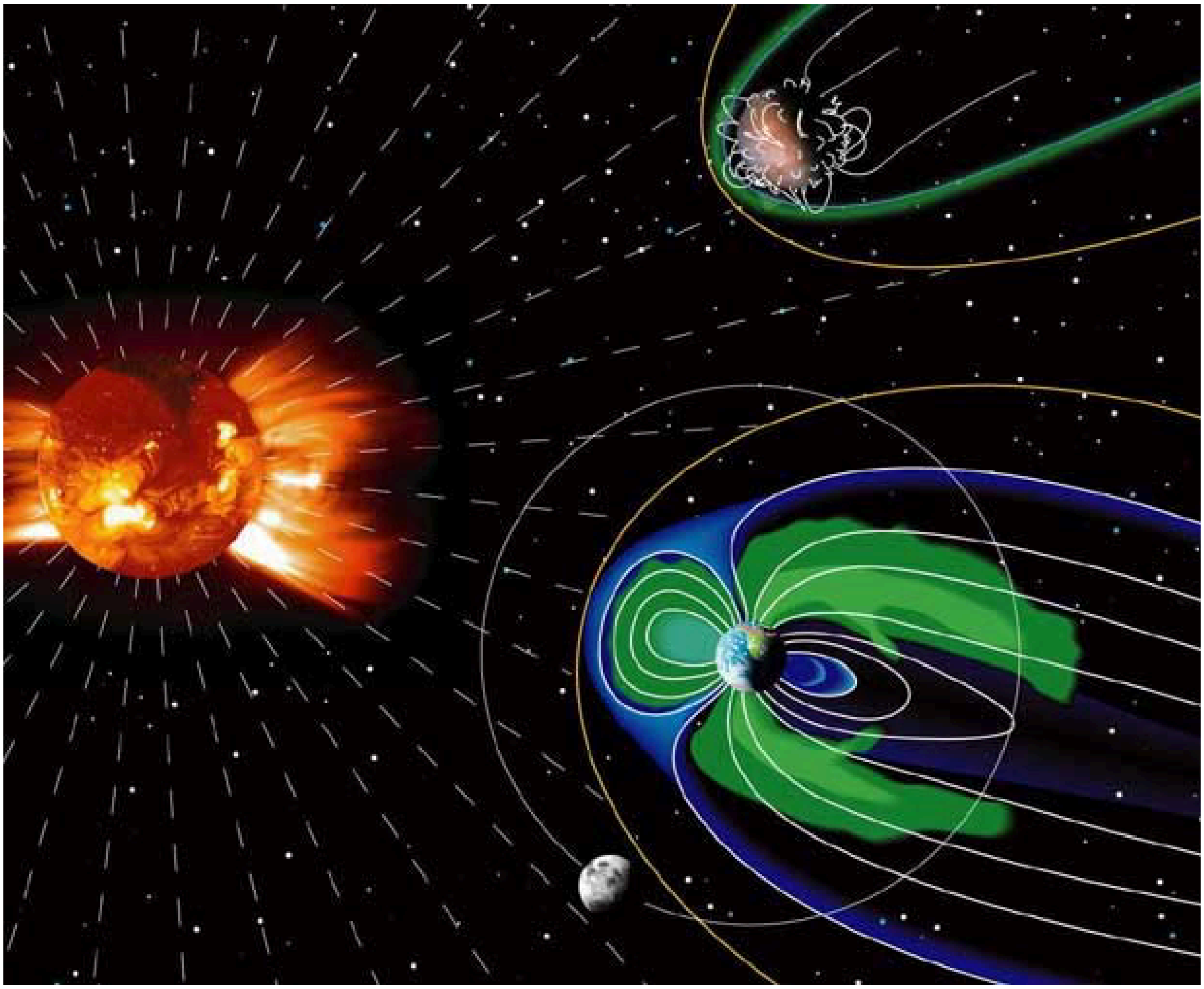

FIGURE 1.1 The heliospheric system—the Sun, the solar wind and space environment of Earth (lower right), the Moon (bottom), and Mars (upper right). This sketch is not to scale; for example, in reality the Sun is 100 Earth-diameters across and the Sun-Earth distance is 108 solar-diameters; Mars is half the size of Earth and 1.5 times farther from the Sun.

The report of the President's Commission on Implementation of United States Space Exploration Policy—*A Journey to Inspire, Innovate, and Discover* (the Aldridge Commission report)[3]—set forth 15 recommendations to address factors critical to achieving NASA's vision for space exploration. The commission report considered science in two contexts: *enabling science*, which is research that provides new knowledge or capability that facilitates exploration, and *enabled science*, which is research to create new knowledge by means of exploration.[4] The report also organized basic science around three themes—origins, evolution, and fate—that are defined broadly and that include exploration to understand the origin and evolution of the universe, the formation of planets and planetary systems, the origin and extent of life, and the environment and habitability of our own Earth (see Appendix C). That concept for a research agenda in the context of exploration explicitly includes (under "fate") studies of temporal

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[3] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy*, ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

[4] Finding 7 from the commission report (p. 36) states, "The Commission finds implementing the space exploration vision will be enabled by scientific knowledge, and will enable compelling scientific opportunities to study Earth and its environs, the solar system, other planetary systems, and the universe."

BOX 1.1
Energetic Particles in Space

The gas in space is a composite of several distinct classes of particles. In the interplanetary environment the dominant class is the solar wind (mostly ionized hydrogen, i.e., protons and electrons) that blows outward from the expanding corona of the Sun at supersonic velocities of 400 to 1000 km/s to fill the solar system with a hot, dilute plasma. This high-speed plasma not only fills interplanetary space but also controls the energy that drives aspects of space weather. These aspects include the very energetic and intense radiation belt particles that populate planetary environments, such as that of Earth and Jupiter, and the electrical currents and auroral particle acceleration that also characterize planetary environments.

A second important class comprises galactic cosmic rays, moving at close to the speed of light (c) and infiltrating in through the magnetic fields in the solar wind from the surrounding interstellar space. They are primarily protons plus a smaller number of heavier nuclei and a few electrons. Galactic cosmic rays are always present, although their intensity in the inner solar system is reduced somewhat as the solar wind drags the Sun's magnetic field out through interplanetary space. Outside the protecting magnetic field and atmosphere of Earth each square centimeter (about the area of a fingernail) is penetrated once or twice per second by a cosmic-ray proton. The lowest-energy cosmic rays (0.1 to 1.0 GeV, velocities of 0.4 to 0.9 c) are strongly suppressed during the years of maximum activity in the sunspot cycle. Above 1 GeV the number of cosmic-ray particles, and their reduction by the solar wind, decline rapidly with increasing energy. At 20 GeV (0.999 c) the reduction is at most only a few percent. The particles above 1 GeV pose a particularly difficult problem for human interplanetary travel, because their enormous energy makes them difficult to shield against. Upon collision with the nucleus of an atom, for example, in Earth's atmosphere or a spacecraft wall, a proton of 1 GeV or more produces many secondary fast particles (pions, gamma rays, electron-positron pairs, protons, and neutrons), which in turn create more fast particles as they collide with other nuclei. Therefore, the first 50 to 100 gm/cm^2 of shielding serves only to increase the number of fast particles. The higher the initial proton energy, the worse this becomes. Fortunately, the 1000 gm/cm^2 represented by the full terrestrial atmosphere is enough to stop most of the secondary particles, except for the neutron component and the muons. This provides adequate protection here at the surface of Earth. Out in space, however, devising a practical means for protecting astronauts remains a major technical challenge.

Finally, there are the energetic particles emitted by flares on the Sun, or accelerated in shock fronts near the Sun and in interplanetary space, that are typically referred to as solar energetic particles or solar cosmic rays. These particles (mostly protons, a few heavier nuclei, and some electrons) are usually at much lower energies (10 MeV to 10 GeV) than the galactic cosmic rays. However, their enormous numbers can do fatal damage to exposed electronics and astronauts. The problem is that these solar cosmic rays are highly variable and appear intermittently in unanticipated intense events—solar proton events (SPEs)—associated with individual flares and coronal mass ejections at the Sun. It is essential, therefore, to understand the physics of solar activity to know when such an event is likely to occur. Astronauts can then be warned not to stray far from shelter in case a potentially lethal burst occurs. Unfortunately, about once in 20 to 30 years there is an exceptional flare that produces a spectacular burst of particles with energies up to 20 GeV or more, supplying a potentially lethal dose of radiation that cannot be readily shielded against. The physics of these remarkable events (such events occurred in 1956, 1972, and 2003) has yet to be properly understood. Research to date indicates that the acceleration of solar energetic particles in SPEs is related primarily to fast coronal mass ejections (CMEs), possibly via the shock wave driven by them, at distances of ~2 to 40 solar radii (~0.01 to 0.2 AU) from the Sun (inner heliosphere), and to a lesser extent solar flares. However, some very fast CMEs are observed that do not appear to produce SPEs, and similarly fast shocks at 1 AU generally accelerate particles only up to MeV/nucleon energies, not the >10 to 100 MeV/nucleon energies of particles in SPEs. Thus, current understanding of the production of SPEs is very poor, although gaining the ability to recognize the magnetic configurations on the Sun that creates them would be an important next step.

BOX 1.2
Exploring the Universe Through Space Plasmas

"Our solar system, and stellar systems in general, are rich in the dynamical behaviors of plasma, gas, and dust organized and affected by magnetic fields. These dynamical processes are ubiquitous to highly evolved stellar systems, such as our own, but also play important roles in their formation and evolution. Stellar systems are born out of clumpy, rotating, primordial nebulas of gas and dust. Gravitational contraction, sometimes aided by shock waves (possibly from supernovas), passage through dense material, and other disruptions, forms condensation centers that eventually become stars, planets, and small bodies. Magnetic fields moderate early-phase contractions and may also play vital roles in generating jets and shedding angular momentum, allowing further contraction. The densest of the condensation centers become protostars surrounded by accretion disks. Dynamo action occurs within the protostars as the heat of contraction ionizes their outer gaseous layers, resulting in stellar winds. In similar fashion, rotating solid and gaseous planets form, and many of these also support dynamo action, producing magnetic fields. Ultraviolet and x-ray photons from the central stars partially ionize the upper atmospheres of the planets as well as any interstellar neutral atoms that traverse the systems. Viewed as a whole, the resulting plasma environments are called asterospheres, or in the Sun's case, the heliosphere. In its present manifestation, the heliosphere—the local cosmos—is a fascinating corner of the universe, challenging our best scientific efforts to understand its diverse machinations. It must be appreciated at the same time that our local cosmos is a laboratory for investigating the complex dynamics of active plasmas and fields that occur throughout the universe from the smallest ionospheric scales to galactic scales. Close inspection and direct samplings within the heliosphere are essential parts of the investigations that cannot be carried out by a priori theoretical efforts alone."

SOURCE: Reprinted from National Research Council, *Plasma Physics of the Local Cosmos*, p. 77, The National Academies Press, Washington, D.C., 2004.

variations in solar output so as to understand their consequences and to have a basis for making predictions.[5]

NASA's solar and space physics program is conducted by the Sun-Earth Connection (SEC) Division of the Office of Space Science.[6] NASA operates a range of SEC missions—from major multi-spacecraft programs to small, focused missions—with the goal of understanding the heliospheric system. The basic research thrust of SEC reflects the growing realization that the processes that control Earth's space environment are important throughout the universe,[7] and hence the SEC research constitutes an intrinsic form of exploration in its own right (see Box 1.2). Moreover, SEC exploration contributes to the broader goals of understanding the origin and evolution of planetary and astrophysical systems, as illustrated by the example of exploration of the heliosphere discussed in Box 1.3.

Some of the most exciting basic space research involves the underlying physical processes that are common to plasmas (i.e., the electrically ionized gases that permeate space). For example, the process of magnetic reconnection in a plasma (Box 1.4)—the dynamic change in the topology of a magnetic field—likely plays an important role in the ejection of energetic particle beams from the Sun as well as in triggering magnetic storms at Earth, and is likely to be a basic physical property of astrophysical plasmas ranging from stellar systems to supermassive black hole accretion disks. Similarly, the physical processes associated with particle acceleration, shocks, and turbulence occur in or near Earth's magnetosphere, and in all probability, around other planets and throughout the wider cosmos. These

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[5] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy*, p. 38, ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

[6] Subsequent to the completion of the committee's report NASA implemented a reorganization that placed the Sun-Earth Connection program in a new headquarters program office—the Science Mission Directorate.

[7] National Research Council, *Plasma Physics of the Local Cosmos*, The National Academies Press, Washington, D.C., 2004.

BOX 1.3
Heliosphere and the Local Interstellar Medium: Example of SEC Study of Origins and Evolution

The central contribution of the SEC program to scientific exploration is illustrated by the exploration of the heliosphere.[1] After the Voyager mission encounters with Jupiter, Saturn, Uranus, and Neptune over the period from 1979 to 1989, the two spacecraft continued their flights into the outer reaches of the solar system, where the science that they were accomplishing became as much the science of the interstellar medium as of the solar wind. Indeed, the interplanetary medium beyond about 10 AU is dominated, by mass, by neutral atoms of interstellar origin rather than by solar wind. Thus, exploration of the outer heliosphere offers the opportunity to learn about both the interplanetary and the interstellar medium, and the manner in which they interact.

The detailed interaction between the local interstellar medium (LISM; i.e., that region of space in the local galactic arm where the Sun is located) and the solar wind is not understood. This lack of understanding demonstrates the need for direct observations and for knowledge of the LISM's basic physical parameters. From physical reasoning, researchers know that boundary regions must separate the solar wind from the LISM. However, these regions are completely unexplored since they are so far out, well beyond the planets of our solar system. The boundary regions are likely separated by several enormous shocks. The innermost shock may be a site where cosmic rays are accelerated, thereby providing a link to supernova shocks thought to accelerate galactic cosmic rays. In the past year scientists working with data from Voyager-1 raised the exciting possibility that Voyager may be in the vicinity of the heliospheric boundary. There is indirect evidence for a "hydrogen wall" where the flow of neutral hydrogen from the LISM is slowed down, compressed, and heated before it penetrates the solar wind. Obtaining direct observations of the interstellar interaction remains a high priority for scientific discovery at the outer frontier of solar and space physics.

Sending future spacecraft to the boundaries of our heliosphere to begin the exploration of our galactic neighborhood will be one of the great scientific enterprises of the new century—one that will capture the imagination of people everywhere. Interstellar space is a largely unknown frontier that, along with the Sun as the source of the solar wind, determines the size, shape, and variability of the heliosphere, the first and outermost shield against the influence of high-energy cosmic rays. The interstellar medium is the cradle of the stars and planets, and its physical state and composition hold clues to understanding the evolution of matter in our galaxy and the universe. With plentiful bodies of all sizes and dust in the Edgewood-Kuiper Belt and in the Oort Cloud, the outer heliosphere is a repository of frozen and pristine material from the formation of the solar system. After the contents of our solar system, which is 4.5 billion years old, the LISM provides a second, more recent, sample of matter in our galaxy and in fact the only sample of the interstellar medium that can be studied close-up and in situ. Last but not least, the heliosphere is the only example of an asterosphere that is accessible to detailed study. These perspectives provide a natural bridge and synergism between in situ space physics, the astronomical search for the origins of life, and astrophysics.

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[1] For a more complete discussion of the exploration of the heliosphere see National Research Council, *Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report*, The National Academies Press, Washington, D.C., 2004.

fundamental processes play key roles in the origin and evolution of planetary and astrophysical systems and tie the results of SEC programs to the scientific goals of exploration.

By studying the physical processes that are the ultimate causes of space weather, we stand the best chance of making scientific breakthroughs of ultimately the highest practical importance to space weather prediction and addressing the goal (under "fate") of "temporal variations in solar

BOX 1.4
Reconnection

Explosive events in the Sun's corona, including solar flares and coronal mass ejections, and in planetary magnetospheres, including auroral and magnetic storms, are driven by the conversion of magnetic energy into high-speed plasma flows and high-energy particles. These explosions are the driver of space weather, and the penetrating radiation from these events poses significant hazards to unprotected spacecraft and their human and technological assets. One way for this energy to be released is for oppositely directed magnetic fields to annihilate in a process called magnetic reconnection, so named because magnetic fields must change their structure by "breaking" and "reconnecting" with their neighbors (see Figure 1.4.1). Significant progress in understanding how magnetic field lines "break" has been made though direct satellite measurements in Earth's magnetosphere and comparisons with theoretical predictions based on computer models. The mechanisms for particle energization and what determines the onset of the explosive energy release—critical for space weather forecasting—remain less fully understood. The broad importance of this topic is reflected in the high priority given in the decadal survey report[1] to the Magnetospheric Multiscale (MMS) mission, a four-satellite mission designed to explore the fundamentals of reconnection.

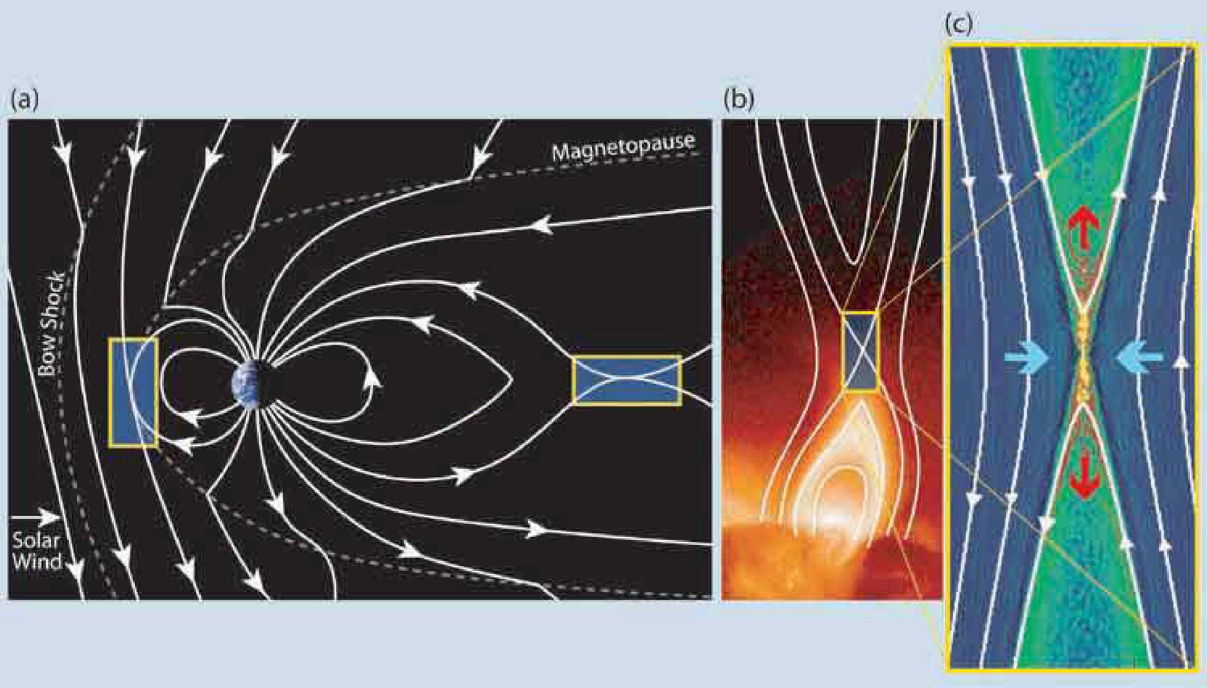

FIGURE 1.4.1 Regions of reconnection (boxed areas) occur in many locations in astrophysical systems, including (a) Earth's magnetosphere and (b) the solar corona. Panel (c) shows a computer simulation of reconnection showing magnetic field lines (white) and strong electrical currents. Oppositely directed magnetic field lines, together with the plasma, flow toward the center of the picture from the sides (light arrows). The field lines reconnect at the center and accelerate strongly outward (up and down) in a slingshot action. The resulting release of magnetic energy produces high-speed plasma flows (dark arrows) and large numbers of energetic particles. Electrons that are accelerated by electric fields to velocities close to the speed of light power the aurora and drive radio bursts from the Sun. SOURCES: (a) Committee on the Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative, (b) Yohkoh SXT science team, and (c) M. Shay, University of Maryland.

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[1] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.

output—monitoring and interpretation of space weather as relevant to consequence and predictability."[8] Continued aggressive pursuit of the basic research goals of SEC is crucial both to our eventual understanding of space plasma phenomena and to the effectiveness of the more applied work of the space weather and Living With a Star (LWS) programs.

Finding 1. The field of solar and space physics is a vibrant area of scientific research. Solar and space physics research has broad importance to solar system exploration, astrophysics, and fundamental plasma physics and comprises key components of the Aldridge Commission's main research themes of origins, evolution, and fate.

Research activities in space physics have provided critical information on space weather and on the conditions under which it can have disruptive and even hazardous effects on humans and their technological systems both in space and on Earth. The tremendous synergy among SEC space missions is enhanced by the theoretical and ground-based research programs of the NSF and by space-based measurements performed by NOAA and DOD spacecraft. The significant impact that space weather phenomena can have on technological systems on Earth and in Earth orbit has led to the establishment of the multi-agency National Space Weather Program. A significant space-based addition to this program is being developed by NASA through its LWS mission line (for specific mission descriptions see Appendix B). As NASA moves forward on its vision for space exploration the concept of space weather quite properly, and quite feasibly, will take on an expanded meaning in which the Sun's influence on the environment in interplanetary space and at other planets becomes as important as the need to understand effects in the terrestrial environment.

SEC science relates to the space exploration vision in two key ways. First, as noted above and in Boxes 1.2, 1.3, and 1.4, the scientific research in solar and space physics is a form of exploration that is closely aligned with those goals of exploration that focus not only on establishing presences in the solar system but also on understanding the histories and characteristics of various environments and their suitability for life, past and present. Second, from the perspective of providing science that enables exploration, new knowledge gained in understanding our Sun-Earth system will improve our knowledge of and our ability to explore new worlds safely. The new vision for space exploration for a long-term human and robotic program to explore the solar system and beyond will require that humans and our technology survive and operate successfully in a diversity of environments, including interplanetary space and planetary magnetospheres, ionospheres, and atmospheres. SEC missions will tackle the fundamental questions that must be answered to ensure the survival and performance of humans and robots. What is the long-term variability of the environments where our explorations will lead? How can we predict the occurrence of extreme hazardous conditions to safeguard our missions? How can we effectively combine our need to develop new technologies with our desire for scientific exploration and discovery? To address these questions we need to understand the workings of the pieces of the puzzle as well as how the pieces are interconnected into a whole system.

Finding 2. Accurate, effective predictions of space weather throughout the solar system demand an understanding of the underlying physical processes that control the system. To enable exploration by robots and humans, we need to understand this global system through a balanced program of applied and basic science.

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[8] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy*, ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

2

Enabling Exploration of the Sun-Heliosphere-Planetary System

NASA's Sun-Earth Connection (SEC) program is both an integral element of exploration of the solar system and beyond (discussed in Chapter 1 above) and an enabler of that exploration. The latter, more applied role is the topic of this chapter.

The objectives of NASA's vision for space exploration[1] include (among others):

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond;
- Extend a human presence across the solar system starting with the human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Conduct robotic exploration of Mars to prepare for future human exploration;
- Explore Jupiter's moons; and
- Understand the history of the solar system.

Among the key ways that science will be expected to enable exploration, the Aldridge Commission report cited "monitoring and interpretation of space weather as relevant to consequence and predictability."[2]

To implement a sustained human presence in space, either near Earth or elsewhere in the solar system, requires a comprehensive understanding of the heliospheric system and the effects of solar activity on the environment encountered by exploring humans. This chapter summarizes the approach to achieving this understanding by discussing (1) space weather hazards, (2) overarching themes in space physics that affect our ability to develop a predictive capability, and (3) the SEC's existing programs and how they would function together to support NASA's space exploration vision. Finally, Tables 2.1 and 2.2 presented toward the end of the chapter outline specific details of missions that are required to achieve success in support of the exploration vision, information that is augmented in Appendix B with one-page descriptions of the missions and their relevance to enabling exploration.

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[1] National Aeronautics and Space Administration, *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

[2] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy*, p. 38, ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

SPACE WEATHER HAZARDS

To achieve the space exploration vision objectives to “implement a human and robotic program to explore the solar system” and “extend human presence across the solar system,” we need the ability to make both short-term and long-term predictions of space weather across significant portions of the solar system. This is akin to knowing both the “travel” weather conditions and the average weather conditions at a destination. However, the stakes in space are much higher. Being unprepared for local weather conditions means getting wet or being too cold or too hot. In contrast, not having short- and long-term predictions of space weather adds to the challenge of protecting the health and perhaps even the lives of the human explorers.[3] Understanding the fundamental physics that allows short- and long-term predictions of space conditions is a primary goal of the SEC program.

Space radiation is among the top biological concerns for explorers beyond low Earth orbit (LEO), and it is also highly damaging to electronics, including critical spacecraft systems. Astronauts and their spacecraft will be exposed to penetrating particle radiation from three sources: terrestrial, solar, and galactic. The terrestrial source is Earth’s radiation belts (the Van Allen belts). Because they reach energies that penetrate matter to significant depths, ions in the inner belt and electrons in the outer belt pose the greatest hazards to astronauts and space hardware in the near-Earth phases of missions to the Moon or Mars. The risk of Earth’s radiation belts to astronauts depends strongly on the implementation scenarios developed for future missions and even more strongly on the nature of the missions that must be flown during the development of the systems that will eventually fly to the Moon and Mars. For example, Earth’s radiation belts do have substantial access to the relatively high inclination orbit occupied by the International Space Station. For the particular scenario of a near-equatorial launch with only minimal staging within low-inclination, low-altitude orbits, Earth’s radiation belts pose a relatively minor hazard because the astronauts spend very little time traversing them.

Radiation from the Sun is of much greater concern over both the short and the long term. Intense penetrating radiation from the Sun takes the form of solar particle events (SPEs), which typically last several days to a week. SPEs are composed mainly of protons generated by solar storms, so they share the statistical properties of these storms. They exhibit a quasi-11-year cycle loosely synchronized with the solar activity cycle as represented by sunspot numbers. The geomagnetic field shields low-latitude LEO satellites from SPEs. Shielding ceases, however, at high latitudes and/or at altitudes above about 4 Earth radii (1 Earth radius, or R_e, = 6,370 km) or less than one-tenth the distance to the Moon. Roughly, the dose accumulated by an astronaut in a spacesuit from one large SPE is equivalent to a dose accumulated over about 6 months by an astronaut inside the International Space Station.[4] During a solar cycle, there are approximately 20 such SPEs, mainly clustered around solar maximum. We do not know the underlying physics well enough to predict when these SPEs will occur, how intense they will be, or how they will couple to Earth’s radiation environment.

Galactic cosmic rays (GCRs) present a low-level, continuous source of highly penetrating radiation. They are partially shielded by the geomagnetic field so that on average a spacecraft in LEO receives about one third of the radiation dose of spacecraft in interplanetary space. In terms of total dose, the GCR component is roughly comparable to the SPE dose, and up to energies of a few GeV it is modulated by solar activity.

Space travel beyond LEO will require prediction and mitigation of all three major radiation sources (see Box 1.1 in Chapter 1). Prediction involves understanding how solar events form, evolve, and couple with a planet’s space environment. This prediction goes beyond estimates of total dose because the damage from radiation depends strongly on energy, which in turn depends strongly on how the radiation is produced. The fundamental physics of predicting solar events and their evolution and coupling with Earth and planetary environments is a prime focus of both the Solar Terrestrial Probes (STP) and Living With a Star (LWS) mission lines.

The state of space weather prediction today resembles the state of terrestrial weather prediction in the mid-20th century, because current space weather observations and modeling capabilities are quite limited. Coronographs on research satellites can warn of possible CMEs, but the arrival times and

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[3] See *Safe on Mars*, NRC, 2002; *Safe Passage: Astronaut Care for Exploration Missions,* Institute of Medicine, 2001; *The Human Exploration of Space*, NRC, 1997; *Radiation Hazards to Crews of Interplanetary Missions*, NRC, 1996 (The National Academies Press, Washington, D.C.).

[4] National Research Council, *Radiation and the International Space Station. Recommendations to Reduce Risk*, National Academy Press, Washington, D.C., 2000.

consequences of CMEs can only be estimated roughly. Similarly, while we can monitor the development of active regions on the Sun, we are unable to predict when an active region will erupt or if hazardous levels of solar energetic particles will be created. Significant advances in prediction abilities are needed before adequate safety can be assured on long-duration interplanetary travel and during long-term habitation on other solar system bodies. These advances will only occur, as with terrestrial weather prediction, through a long-term research effort involving coordinated observations and modeling.

There are numerous examples from the atmospheric sciences discipline of where research advances have led to improved operational capabilities.[5] For example, the use of balloon-borne experiments in the 1930s to better understand Rossby waves in the atmosphere led to an improved description of large-scale atmospheric flow and contributed importantly to the development of numerical weather prediction. Early numerical simulations of the three-dimensional structure of thunderstorms have let to an improved understanding of severe storm dynamics. And recent advances in data-assimilative modeling have increased the accuracy of our weather prediction. Capabilities in terrestrial weather prediction have evolved over the past century through steady advances in observational capabilities, in numerical modeling techniques, and in understanding of the underlying physical processes. A similar approach will need to be taken to advance capabilities in space weather prediction.

Space weather forecasters today rely on a variety of statistical relationships, some empirical and physics-based models, and qualitative assessments to predict important disturbances such as geomagnetic storms, radiation belt enhancements, and solar particle events. Although the availability of new data and scientific understanding have been improving forecast accuracy, the capabilities today do not yet provide the lead time or accuracy needed to ensure safe human travel through interplanetary space or habitation on unshielded planets and moons. For example, the extensive impact of the giant “Halloween Storm” of 2003 occurred with little warning. From solar and interplanetary observations forecasters knew that large solar storms would impact Earth, but they had only rough estimates of the timing and of the extent of the disruption of the terrestrial space environment that the Halloween events would cause. Through SEC missions such as SDO and STEREO, advances in helioseismology and in understanding the initiation and propagation of coronal mass ejections (CMEs) will give us greater capabilities to predict where active regions will develop, when they will erupt, and if they are likely to be major sources of energetic particles. Missions such as Magnetospheric Multiscale (MMS), Geospace Network, and Geospace Electrodynamic Connections (GEC) will improve our understanding of the resulting disturbances in planetary magnetospheres, ionospheres, and atmospheres. Data from these missions, coupled with data/results from the SR&T programs, will yield the quantitative, predictive models needed for space exploration. In the near term (1 to 5 years), the ever-improving models of the three-dimensional heliosphere and planetary environments should be used to model the transport of energetic particles throughout the solar system. This capability would allow us to assess the flux levels that would be experienced during a mission if a solar eruption occurred at any given location on the Sun. In the medium term (5 to 10 years), knowledge gained through techniques such as helioseismology, advanced imaging and image processing, and improved understanding of fundamental processes such as magnetic reconnection and shock acceleration will sharpen our ability to predict the location, evolution, and consequences of solar activity. In the long term, data-assimilative models that incorporate real-time data will be needed to obtain the most accurate predictions based on a given state of the space environment.

SOLAR SYSTEM SPACE PHYSICS

One of the major lessons from more than 40 years of solar and space physics research has been that making practical predictions of the space environment will require a broad, system-wide understanding of the fundamental physical processes in the Sun-heliosphere-planet system. Figures 2.1 through 2.3 illustrate the point that four key elements of that system—(1) the Sun as the driving energy source, (2) energy and mass transport interactions in the heliosphere, and (3, 4) the consequences at Earth and other planets—are all linked via a set of universal physical processes. Figure 2.1 also

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[5] See National Research Council, *The Atmospheric Sciences: Entering the Twenty-First Century*, Board on Atmospheric Sciences and Climate, National Academy Press, Washington, D.C., 1998.

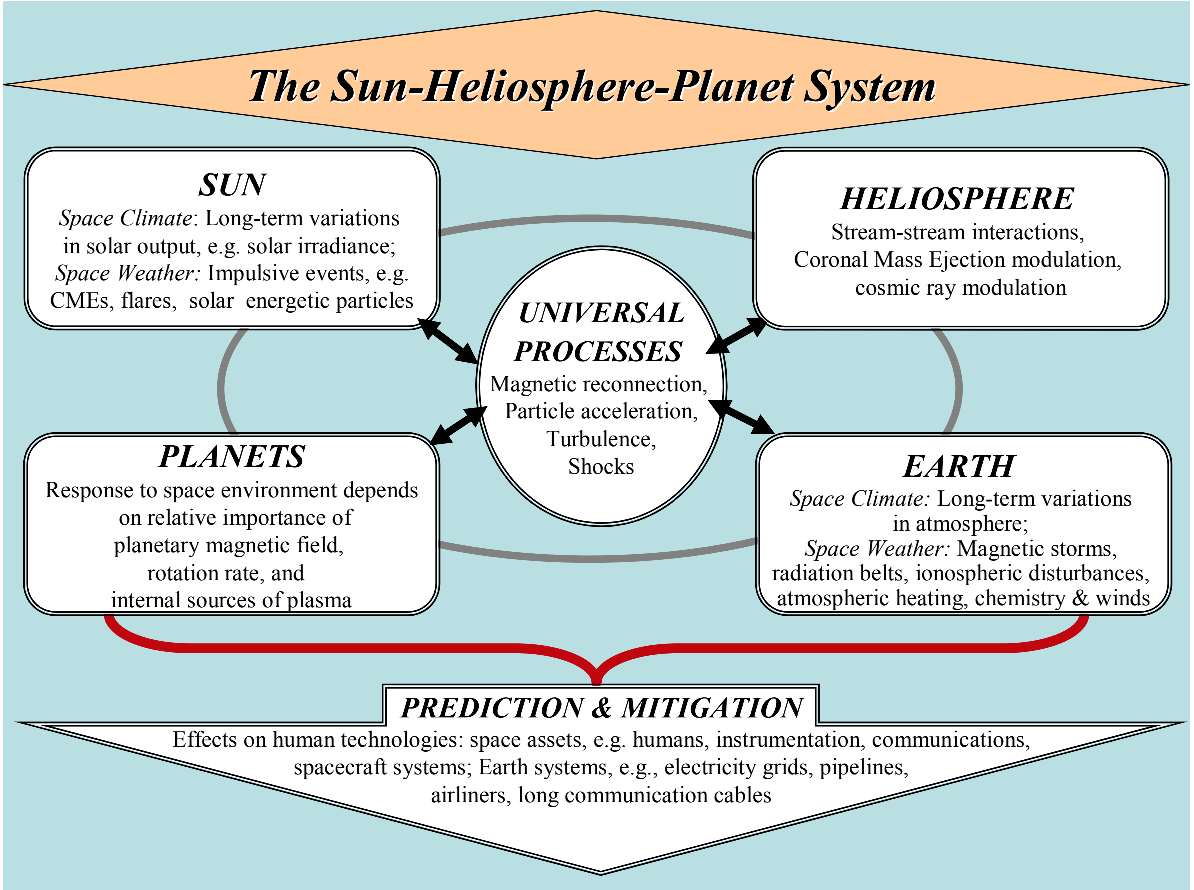

FIGURE 2.1 Understanding of the interconnected system of the heliospheric system allows prediction and mitigation of hazards in the space environment.

indicates that investigation of these processes and components leads naturally to enabling prediction and mitigation. Figures 2.2 and 2.3 give details of important cause-and-effect relationships and of the tools that should be developed in order to further increase our understanding of the four major components. The discussion below expands on these ideas.

Solar Drivers

The Sun drives the majority of dynamic interactions in the solar system. These arise both from its long-term variability on time scales of the solar cycle (11 years), and from short-term variability on time scales of minutes to days. Long-term variation in solar radiative output is a main source of "climate" in the target exploration environments. Short-term variability—or equivalently "weather"—includes impulsive events such as solar flares, coronal mass ejections, and acceleration of high-energy solar particles. Complete understanding of these critical sources of variability requires a balanced, long-term program that observes both solar evolution and dynamics, measures solar properties from the solar interior outward through the extended solar atmosphere, and develops validated models.

Heliospheric Interactions

The dynamic extension of the solar atmosphere is the solar wind, and its domain is the heliosphere, a region that encompasses all the solar system and extends more than three times the average distance to Pluto. Dynamic solar phenomena propagate outward through and are modulated by the ambient solar wind. For example, coronal mass ejections, high-speed solar wind streams, and

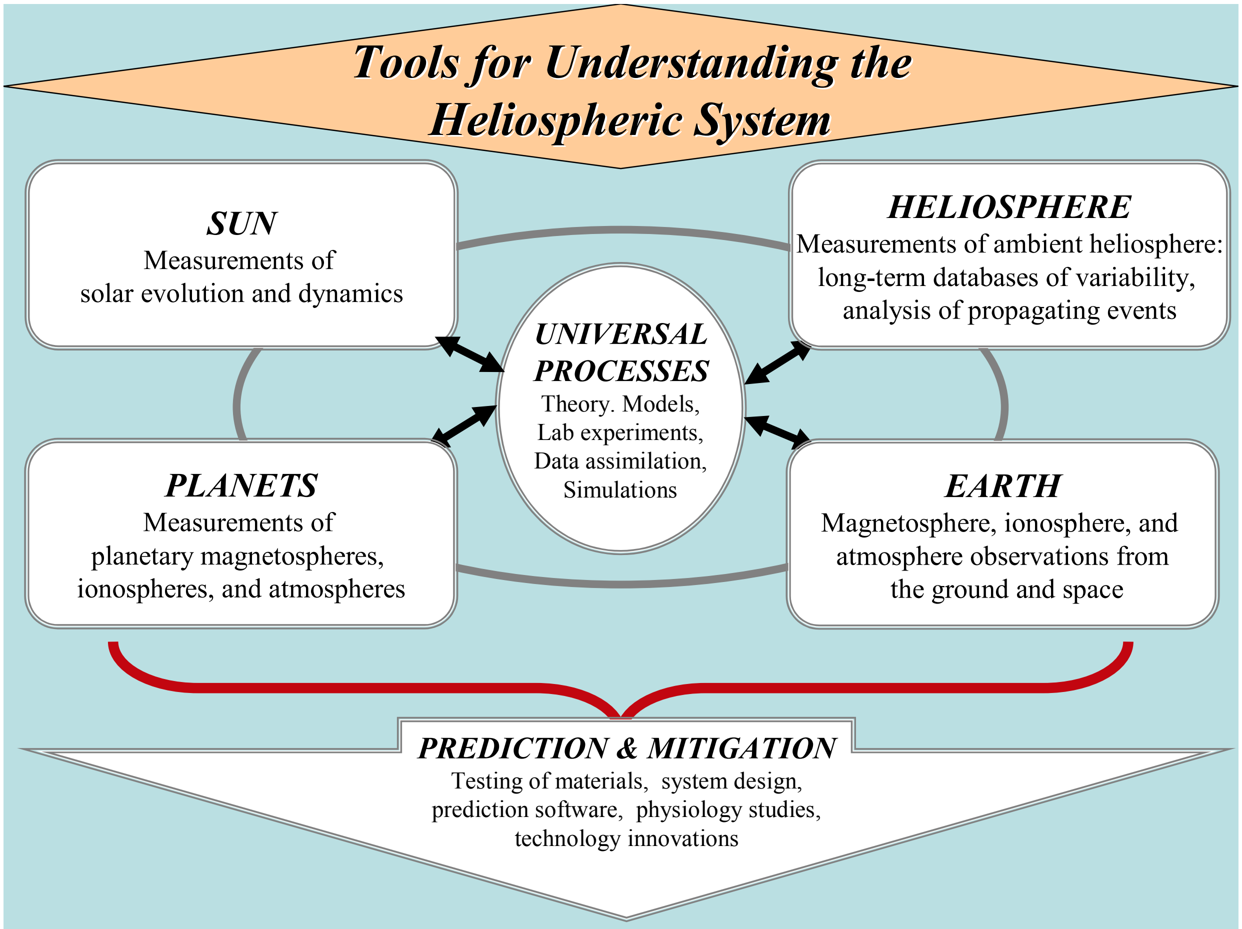

FIGURE 2.2 Tools necessary for understanding the heliospheric system and the impact of the environment on humans and technology in space.

energetic particles may evolve as they propagate through the interplanetary medium. Similarly, the propagation of galactic cosmic rays is affected by magnetic shielding produced by CMEs as they propagate through interplanetary space. Understanding these interactions requires understanding first the ambient background by drawing, in part, on long-term databases of solar and heliospheric variability, along with models. One can then combine this information with observations of the propagating disturbances to develop quantitative models of the evolution of dynamic structures through the heliosphere.

Earth Consequences

Dynamic structures in the heliosphere affect Earth in a variety of ways. Long-term solar variability causes changes in Earth's atmosphere and climate. Short-time-scale space weather can lead to magnetospheric storms, ionospheric disturbances, atmospheric heating, changes in atmospheric chemistry, and winds. To understand the full potential ramifications of these disturbances, observations (both from the ground and from space) and modeling are required of the magnetosphere, ionosphere, and atmosphere. Our own terrestrial magnetosphere-ionosphere system is a laboratory in which to investigate the basic phenomena that drive the environments of other solar system locations and to test our predictive capabilities.

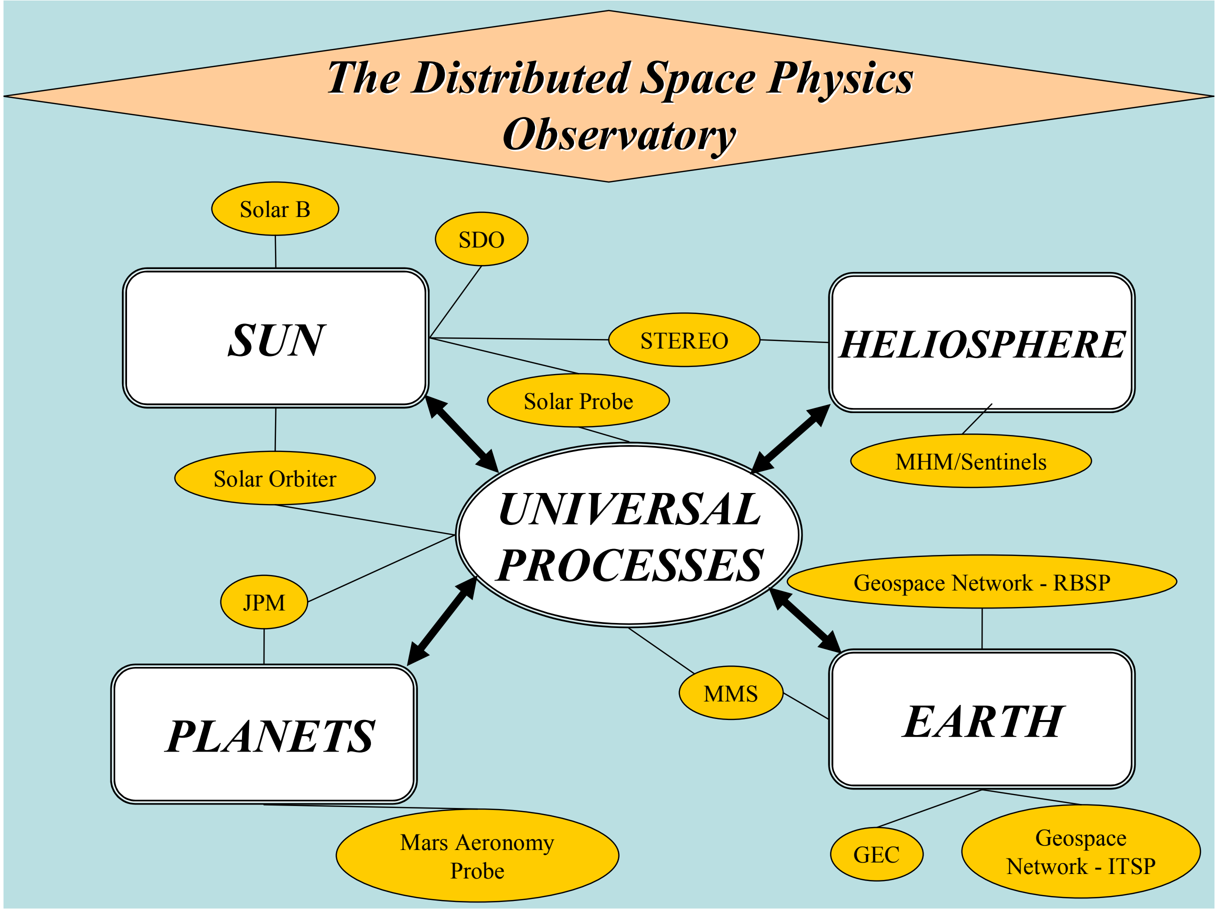

FIGURE 2.3 Missions throughout the solar system form a space physics observatory, with each mission addressing components of the heliospheric system.

Planetary Comparisons

The space environment of a planet is affected by several factors, including the relative importance of the planetary magnetic field, the planet's rotation rate, and any internal sources of plasma for the system. One learns the most by pushing a physical model of the environment to a "breaking point" and then discovering what changes in the assumptions of the underlying physics are needed to "fix" it to match observations. Thus, by comparing different planetary environments, one can test current understanding of universal processes under very different conditions. In the case of the rapidly rotating Jupiter, for example, comparisons of auroral processes with those at Earth test our theories of coupling between the solar wind, and the magnetosphere and ionosphere, of particle acceleration and the electrical currents that link the magnetosphere to the planet's rotation. In the case of Mars, it is important to determine the extent to which the solar wind and cosmic rays penetrate the martian atmosphere or are deflected by patches of strong crustal magnetization. Continuous, long-term investigation of the Sun-Earth system, together with observations of the magnetospheres, ionospheres, and atmospheres of other planets, will enable critical estimates to be made of the likely range in conditions that instrumentation and exploring astronauts will need to withstand.

Universal Processes

The disparate regimes discussed above (i.e., the Sun, interplanetary medium, Earth, and other planets) share in common the fact that they are the sites of a few universal physical processes.[6] For example, the ability of global-scale magnetic fields to reconnect, releasing large amounts of magnetic energy in the process, may be responsible for the acceleration of high-energy particles at the Sun, throughout the solar system, and in the distant universe. Solar flares and coronal mass ejections, as well as magnetospheric substorms, are believed to originate in such reconnection events. Similarly, signatures of shocks and turbulence have been observed at the Sun, upstream of planetary magnetospheres, and at the outer boundary of the heliosphere. Shocks are also an important source of energetic particles throughout the universe. An understanding of these fundamental processes is essential to progress in understanding the behavior of the space environment. Theoretical models, computational simulations, laboratory experiments, and (whenever possible) direct observations are necessary tools in developing this understanding.

Prediction and Mitigation

As we embark on the exploration of new worlds, decisions will have to be made on issues such as the entry of orbiting (human and robotic) space vehicles into ionospheres and atmospheres, communication within and through planetary ionospheres, and survivability in the radiation environments of interplanetary space and within planetary magnetospheres. By combining observations from the various solar system regimes with physical analyses of the universal processes that unite them, steps may be taken to mitigate the effects of space climate and weather on humans, instrumentation, and communications and spacecraft systems. To that end, input from space physics observations and analysis will help in modeling and developing predictive capabilities for the extreme disturbances that occur, quantifying the long-term variability, and understanding the effects on humans and spacecraft systems. This information can then be incorporated in prediction software development, system design, materials testing, technology innovations, and physiology studies.

UNDERSTANDING THE INTEGRATED HELIOSPHERIC SYSTEM

Figure 2.3 illustrates some of the main connections between NASA missions and the four major components of the Sun-heliosphere-planet system. This coherent set of interrelated missions may be considered collectively as a “Great Observatory” for the field of solar and space physics. Missions exploring Earth’s space environment provide an up-close laboratory in which to observe solar system plasmas, providing insights and understanding that can be applied to more-distant areas of the heliosphere.

Solar system plasmas are complex systems. Their complexity arises from nonlinear coupling, both within a single system, such as the solar drivers in Figure 2.1, and between two or more systems such as the solar drivers and heliospheric interactions. These plasma systems interact across a multiplicity of spatial and temporal scales. The physical processes by which they interact determine the evolution of the systems through the creation of both large- and small-scale structures. Examples of such cross-scale coupling are magnetic reconnection and plasma turbulence, which involve the nonlinear interaction of large-scale, relatively slow behavior and small-scale, very rapid processes. Finally, distinct regions are coupled across relatively thin boundaries in a highly nonlinear, dynamic fashion. Processes at the outer boundaries of planetary magnetospheres, where the solar wind and the planets’ magnetic fields interact, are examples of this coupling.[7]

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[6] See National Research Council, *Plasma Physics of the Local Cosmos*, The National Academies Press, Washington, D.C., 2004.

[7] For a more detailed discussion, see National Research Council, *Plasma Physics of the Local Cosmos*, National Academies Press, Washington, D.C., 2004.

The study of the coupled system as defined in the decadal survey report[8] and as depicted in Figure 2.1 requires the overlap of specific missions in key regions. For example, the study of solar drivers requires coordination with measurements of effects in Earth's magnetosphere such as radiation belt creation and modification. Similarly, observations of the high-altitude radiation belts in equatorial regions and of consequences at lower ionospheric altitudes needs mission overlap. Other studies do not require overlap, but do require synergy among missions. For example, the results from the study of the fundamental process of reconnection by MMS will provide important comparison with reconnection processes on the Sun observed by SDO.

Two missions can be singled out for their particular importance to both planetary science and space physics. These two planetary missions, Mars Aeronomy Probe (MAP) and Jupiter Polar Mission (JPM), are in the Solar System Exploration roadmap[9] but are mentioned here because they offer significant advances in space physics through comparison of planetary environments.

The goal of exploration of Mars elevates the significance of the MAP mission. From a purely scientific perspective, a mission of this type was cited in *New Frontiers in the Solar System: An Integrated Exploration Strategy*, the NRC's recent decadal survey for solar system exploration,[10] as a priority for Mars flight missions. Furthermore, the entry, descent, and landing requirements for complex payloads to Mars are sensitive to the density of the martian upper atmosphere, which in turn varies according to inputs from both the Sun and the lower atmosphere. A comprehensive understanding of the behavior of the martian upper atmosphere will therefore be required for extensive robotic and human exploration of Mars. Moreover, the interaction of the solar wind with Mars's crustal magnetic field and upper atmosphere results in substantial atmospheric escape and hence may have played a critical role in Mars's climate evolution and, hence, habitability.

The objective to explore Jupiter's moons and understand the history of the solar system[11] makes JPM particularly important. A Jupiter Polar Mission also addresses goals (in the Aldridge Commission report under the "origins" and "evolution" themes[12]) of understanding the interior structure and composition of this archetypical giant planet; plus, JPM provides estimates of the angular momentum loss (thought to be an important process in the evolution of stars and giant planets) through the planet's coupling to the magnetosphere. From a space physics perspective, Jupiter is an excellent test bed of fundamental magnetospheric processes (plasma transport, auroral emissions, particle acceleration, wave generation, and so on) under conditions very different from those experienced at Earth. Furthermore, Jupiter's moons are major sources of magnetospheric plasma and are electrodynamically coupled to the planet, triggering radio emissions and auroras in Jupiter's polar regions.

THE NASA SUN-EARTH CONNECTION PROGRAM

As is the case with all of NASA's science programs, the SEC program depends critically on having a properly balanced portfolio of spaceflight missions, which are developed and phased strategically to address the objectives of the program, and of supporting programs and infrastructure, which provide the resources and capability to capitalize on the results from spaceflight missions, translate their results into scientific progress, and lay the scientific and technological foundation for the next steps in the program. For the SEC program, this portfolio is very much like the proverbial three-legged stool. There are two strategic mission lines—Living With a Star (LWS) and Solar Terrestrial Probes (STP)—and a coordinated set of supporting programs. LWS missions focus on observing the solar activity, from short-term dynamics to long-term evolution, that can affect Earth, as well as astronauts working and living in the near-Earth space environment. Solar Terrestrial Probes are focused on exploring the fundamental

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[8] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.

[9] National Aeronautics and Space Administration, *Roadmap for Solar System Exploration*, NASA, Washington, D.C., 2002.

[10] National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.

[11] NASA, *The Vision for Space Exploration*, NP-2004-01-334-HQ, National Aeronautics and Space Administration, Washington, D.C., 2004.

[12] *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy*, ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

physical processes of plasma interactions in the solar system. A key assumption according to which the LWS program was designed was that the STP program would be in place to provide the basic research foundation from which the LWS program could draw to meet its more operationally oriented objectives. LWS relies heavily on other programs to either provide data such as that obtained with solar wind monitors and ground observatories, or use the data services as established by other programs, specifically the services that have been developed through NASA's mission operations and data analysis (MO&DA) efforts. Furthermore, neither the STP nor LWS set of spaceflight missions can succeed without the third leg of the stool. That leg provides the means to (1) conduct regular small Explorer missions that can react quickly to new scientific issues, foster innovation, and accept higher technical risk; (2) operate active spacecraft and analyze the LWS and STP mission data; and (3) conduct ground-based and suborbital research and technology development in direct support of ongoing and future spaceflight missions.[13]

The SEC program plays a key national role by providing NASA's contribution to the National Space Weather Program (NSWP). The NSWP is an interagency effort that also involves NSF and the Departments of Commerce, Defense, Energy, and Transportation and that is intended to provide timely, accurate, and reliable space environment observations, specifications, and forecasts to serve a variety of commercial and government activities. NASA and NSF, in particular, provide the research upon which new or improved capabilities depend, and DOD and NOAA have key responsibilities for translating that research into operational systems for modeling and predictions of space weather. Current SEC missions such as the Advanced Composition Explorer and SOHO are providing key data sets that are being used by NOAA and DOD forecasters. The LWS program, including both its spaceflight measurement missions and its theory, modeling, and data analysis components, is particularly important for meeting the future needs of DOD and NOAA.

The Explorer Program

The Explorer program contributes vital elements that are not covered by the mainline STP and LWS missions. Explorers fill critical science gaps in areas that are not addressed by strategic missions, they support the rapid implementation of attacks on very focused topics, and they provide for innovation and the use of new approaches that are difficult to incorporate into the long planning cycles needed to get a mission into the strategic mission queues. The Explorer program can also provide opportunities to respond rapidly to specific needs of human exploration. The Explorers also provide a particularly substantial means to engage and train science and engineering students in the full life cycle of space research projects. Consequently, a robust SEC science program requires a robust Explorer program.

Because the full benefits of the SEC program accrue when the heliospheric system is understood as a unified system, it is vital to have a mechanism for filling critical gaps that are left open by the strategic STP and LWS missions. For example, the multi-spacecraft International Solar-Terrestrial Program (ISTP) in the 1990s identified a major uncertainty in understanding geomagnetic storms in the nightside of Earth's magnetosphere: whether magnetic reconnection is a cause of dynamic behavior of the middle magnetosphere or is a consequence of such dynamics. The Explorer program will allow the THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission to answer this one outstanding critical question. THEMIS also will complement the larger MMS mission by providing data on fundamental processes in space plasma physics at longer time and spatial scales than MMS will be able to sample.

Mission Operations and Data Analysis

No mission can achieve its research objectives until it is launched, delivered to its operating orbit or mission location, operated to collect the necessary scientific data, and the data delivered for processing and scientific analysis. Hence, the MO&DA phase constitutes the final critical step for a mission. All missions are transferred from a development phase to an MO&DA phase after

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[13] For a full discussion of the roles and relationships of spaceflight missions to supporting research and technology programs, see National Research Council, *Supporting Research and Data Analysis in NASA's Science Programs*, National Academy Press, Washington, D.C., 1998.

commissioning (typically a few months or less after launch). The duration of the MO&DA phase varies. There may be an interplanetary cruise phase, or the mission may immediately enter a prime mission lasting one to several years. A mission extension may last many more years, often at a cost that is a small fraction of the initial mission development cost. Prime mission funding is provided under the mission budget, while extended mission funding is competed through periodic review of all ongoing missions.

The objectives of mission operations and data analysis are to support:

- All postlaunch mission operations,
- Prime mission data analysis,
- Verification and validation of flight data sets,
- Data archiving, and
- Participation by a more significant number of researchers.

MO&DA is the lifeblood of a mission because it constitutes the phase of the mission at which the investments in hardware development and launch are translated into scientific results. Optimum science return from missions often comes from extending the most productive science missions beyond their prime mission lifetimes.[14] Missions are extended to create synergy with other missions or overlap with new missions. The senior review process[15] is one mechanism for determining the value of extending an individual mission. The science during an extended mission is typically cutting-edge and new, providing measurements and synergy that would cost considerably more to produce in new mission concepts.

For example, the extension of the Wind mission provided measurements of solar wind variability, while the Polar mission, which was launched later, measured the response of the magnetosphere to solar wind perturbations. Extension of the Voyager missions provided measurements of the outer heliosphere, including the exciting possibility of signatures of the heliospheric boundary.

Part of the overall MO&DA budget often goes to a Guest Investigator program, which has the benefit of bringing a larger number of researchers to bear on the scientific utilization of ongoing SEC missions for a very small incremental cost. A Guest Investigator program provides the opportunity for both young and established scientists to participate in exciting, new science from ongoing missions. Fresh insight into the science is provided through the Guest Investigator program, enhancing the overall science return.

Suborbital Program

Suborbital sounding rocket flights and high-altitude scientific balloons can provide a wide range of basic science that is important to meeting SEC program objectives. For example, sounding rocket missions targeted at understanding specific solar phenomena and of the response of the upper atmosphere and ionosphere to those phenomena have potentially strong relevance. Missions in this category include high-time- and high-spatial-resolution imaging of the solar chromosphere, studies of ionospheric neutral winds and vortex structures, and measurements of noctilucent clouds that represent a near-Earth icy, dusty plasma. This science is cutting-edge, providing some of the highest-resolution measurements ever made and, in many cases, providing measurements that have never been made before.

The Suborbital program serves several important roles, including:

- Conducting important scientific measurements in support of orbital spaceflight missions,
- Providing a mechanism to develop and test new techniques and new spaceflight instruments, and
- Training future scientists and engineers in effective space experimentation.

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[14] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, pp. 150-151, The National Academies Press, Washington, D.C., 2003.

[15] For a fuller discussion of the senior review process, see National Research Council, *Assessment of the Usefulness and Availability of Data from NASA's Earth and Space Science Missions*, The National Academies Press, Washington, D.C., 2002.

Development of new scientific techniques, scientific instrumentation, and spacecraft technology is a key component of the Suborbital program. Many of the instruments flying today on satellites were first developed on sounding rockets or balloons. For example, instruments on the SOHO and TRACE solar satellites were enabled by technology and experimental techniques developed in the Suborbital program. The low cost of sounding rocket access to space fosters innovation: instruments and technologies warrant further development before moving to satellite programs. Development of new instruments using the Suborbital program provides a cost-effective way of achieving high technical readiness levels with actual spaceflight heritage.

The fact that any long-term commitment to space exploration will place a concomitant demand on the availability of a highly trained technical work force makes the training role of the Suborbital program especially important.[16] For example, a 3-year sounding rocket mission at a university provides an excellent research opportunity for a student to carry a project through all of its stages—from conception to hardware design to flight to data analysis and, finally, to the publication of the results. This "hands on" approach provides the student with invaluable experience in understanding the spaceflight mission as a whole. Indeed, over 350 Ph.D.s have been awarded as part of NASA's sounding rocket program.[17] A significant fraction of these scientists have gone on to successfully define, propose, and manage bigger missions such as Explorer and even strategic missions.

Supporting Research and Technology Programs

Supporting research and technology (SR&T) programs are crucial for understanding basic physical processes that occur throughout the Sun-heliosphere-planet system, and for providing valuable support to exploration missions.[18]

The objectives of Supporting Research and Technology programs include:

- Synthesis and understanding of data gathered with spacecraft,
- Development of new instruments,
- Development of theoretical models and simulations, and
- Training of students at both graduate and undergraduate levels.

SR&T programs support a wide range of research activities, including basic theory, numerical simulation and modeling, scientific analysis of spacecraft data, development of new instrument concepts and techniques, and laboratory measurements of relevant atomic and plasma parameters, all either as individual projects or, in the case of the SEC Theory program, via "critical mass" groups. These programs also are especially valuable for training students, at both the undergraduate and the graduate level, who will support and advance the NASA space exploration initiative.

Theory and modeling, combined with data analysis, are vital for relating observations to basic physics.[19] Numerical modeling can also be a valuable tool for mission planning. Insights obtained from theory and modeling studies provide a conceptual framework for organizing and understanding measurements and observations, particularly when measurements are sparse and when spatial-temporal ambiguities exist. For example, theories on radiation belt formation and dynamics of the plasmasphere during magnetic storms formed the essence of mission objectives for the IMAGE (Imager for

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[16] See National Research Council, *The Sun to the Earth—and Beyond: Panel Reports*, Chapter 5, The National Academies Press, Washington, D.C., 2003.

[17] For a list of Ph.D. degrees awarded to students who worked on sounding rocket research projects, see http://rscience.gsfc.nasa.gov/education.html.

[18] For a full discussion of the roles of supporting research and technology programs, see National Research Council, *Supporting Research and Data Analysis in NASA's Science Programs*, National Academy Press, Washington, D.C., 1998.

[19] For example, see National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, p. 64, and *The Sun to the Earth—and Beyond: Panel Reports*, Chapter 4, The National Academies Press, Washington, D.C., 2003.

Magnetopause-to-Aurora for Global Exploration) mission, which subsequently confirmed, and in some cases led to modification of, theories. Theory and modeling will be especially important in the context of the space exploration initiative as exploration missions become more complex and the need for quantitative predictions becomes greater.

Finding 3. To achieve the necessary global understanding, NASA needs a complement of missions in both the Living With a Star and the Solar Terrestrial Probes programs supported by robust programs for mission operations and data analysis, Explorers, suborbital flights, and supporting research and technology.

Relevance of Specific SEC Missions to NASA's Space Exploration Initiative

Tables 2.1 and 2.2 present the science highlights of specific SEC missions and their relevance to the objectives of NASA's space exploration initiative listed at the beginning of this chapter. Table 2.1 shows the exploration program benefits derived from these objectives and activities, the SEC contributions to exploration program success, and the SEC missions identified in the decadal survey report that are required to achieve these successes. Table 2.2 includes more detail on each mission. It identifies each mission that is listed in the right-hand column of Table 2.1, indicates the mission's objectives, and outlines its relevance to the space exploration initiative. Finally, one-page descriptions of the missions and their relevance to the exploration initiative are included in Appendix B.

TABLE 2.1 Contributions of Planned Solar and Space Physics Missions to Exploration

Exploration Program Benefit	SEC Contribution to Program Success	SEC Missions Required
Limit astronaut exposure to radiation	Predictive models of CME formation and release, CME propagation, solar flare onset, radiation belt dynamics	STEREO, SDO, MMS, RBSP, Solar Probe, Solar-B, MHM/Sentinels
Avoid spacecraft hardware radiation damage/disruption	Predictive models of SEP fluxes, radiation belt fluxes	STEREO, SDO, Solar Orbiter, RBSP, MMS, MHM/Sentinels
Maintain continuous, robust communication systems	Predictive models of ionospheric dynamics, total electron content, solar flare x-rays	GEC, ITSP, MAP, SDO
Understand aerobraking and orbital stability at Earth, Mars, and beyond	Predictive models of thermospheric structure and dynamics at Earth and Mars	SDO, ITSP, MAP, GEC
Understand past and future solar wind–planet and planetary–moon interactions	Predictive models of Mars's thermosphere/ ionosphere/exosphere structure, magnetosphere–moon interactions, loss of Jupiter's angular momentum via coupling to the magnetosphere	MAP, JPM

TABLE 2.2 Objectives and Relevance of Planned Solar and Space Physics Missions

Mission	Objective	Relevance to Exploration
Solar-B	Understand the creation and annihilation of solar magnetic fields; understand the generation of energetic photons (EUV, x-ray); understand modulation of solar luminosity.	By defining a quantitative relationship between the release of magnetic energy and the magnitude of the resulting flares, Solar-B will improve greatly our ability to forecast major eruptions that affect space weather.
Solar-Terrestrial Relations Observatory (STEREO)	Understand the fundamental origin, nature, and interplanetary propagation of coronal mass ejections (CMEs).	Needed to understand and ultimately predict the arrival of CMEs, which are a primary cause of a range of hazardous space weather effects that impact all the planets.
Solar Dynamics Observatory (SDO)	Develop better understanding of the Sun's influence on the planets by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously.	Needed to understand solar conditions that lead to flares and CMEs and the strong effects that these energetic phenomena produce throughout interplanetary space and the planetary environments.
Magnetospheric Multiscale (MMS)	Understand reconnection and the associated acceleration of energetic particles.	Needed to provide the scientific foundation for the eventual development of a predictive capability for solar and planetary magnetic disturbances (flares, CMEs, auroral and magnetic storms).
Geospace Network	Understand the formation of radiation belts and the global solar-induced variability of the upper atmosphere and ionosphere.	Understanding the formation and dynamics of radiation belts is crucial for the mitigation of hazards to astronauts and spacecraft systems. Understanding of the ionosphere/thermosphere system will lead to better application of aero-braking and communication systems to Mars missions.
Geospace Electrodynamic Connections (GEC)	Understand the electrodynamic processes in Earth's lower ionosphere and its response to solar and magnetospheric inputs.	Understanding of Earth's ionosphere will include physical processes that are common to other planetary ionospheres, specifically to Mars.
Solar Probe	Understand how the solar wind is heated and accelerated.	Understanding the source of the heliosphere is necessary for ultimate understanding of solar activity and how hazardous particles travel through the heliosphere.
Multisatellite Heliosphere Mission (MHM/Sentinels)	Determine how the global character of the inner heliosphere changes with time and how propagating solar disturbances (CMEs, shocks, co-rotating interaction regions) propagate and evolve.	Needed for a better understanding of the role of interplanetary disturbances in modifying the radiation environment that poses dangers to the goals of NASA's space exploration initiative.
Solar Orbiter	Identify the links between activity on the Sun's surface and the resulting evolution of the corona and inner heliosphere.	By combining high-resolution images of the sources of solar activity with in situ observations of the resulting inner heliospheric processes, Solar Orbiter will help characterize and ultimately predict the occurrence and effects of solar energetic particles and CMEs.
Mars Aeronomy Probe (MAP)	Understand how the upper atmosphere and ionosphere of Mars are affected by solar variability and energy inputs.	Knowledge gained from MAP will provide important planetary comparison of atmospheric response to solar variability and will be crucial for the conduct of aero-capture and aero-braking maneuvers for Mars-bound spacecraft.
Jupiter Polar Mission (JPM)	Understand magnetospheric processes in the context of a rapidly rotating gaseous planet with embedded plasma sources.	Provide a critical test of current understanding of fundamental auroral processes. Understanding of the space environment of Jupiter and its moons will be crucial for future exploration of this system.

3

Implementation Strategy and Recommendations

The decadal survey report[1] recommended a carefully reasoned program for addressing high-priority science issues within the constraints of what was understood to be an attainable timeline and budget plan (Figure 3.1 (a)). Priority missions in both the STP and LWS lines were included, balancing underlying basic science with space weather applications to serve national needs. With respect to space weather, the decadal survey report focused on research support for the National Oceanic and Atmospheric Administration and the Department of Defense, and this committee believes that providing such research support remains an important role for NASA that is highly complementary to the NASA exploration vision. The recommended sequence of missions was supported by a strong base of Explorer missions, MO&DA, suborbital activities, and SR&T, which provide the core strength of the SEC research base.

The integrated research strategy presented in the decadal survey for the period 2003 to 2013 is based on several key principles. First, addressing the scientific challenges that were identified in the survey report requires an integrated set of ground- and space-based experimental programs along with complementary theory and modeling initiatives. Second, because of the complexity of the overall solar-heliospheric system, the greatest gains will be achieved by a coordinated approach that addresses the various components of the system, where possible, in combination. Third, a mix of basic, targeted basic,[2] and applied research is important so that the advances in knowledge and the application of that knowledge to societal problems can progress together. Finally, containing cost is an important consideration because the recommended program must be affordable within the anticipated budgets of the various federal agencies.

Finding 4. The committee concurs with the principles that were employed for setting priorities in the decadal survey report and believes that those principles remain appropriate and relevant today.

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[1] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.

[2] By "targeted basic" research the committee means research that is conducted at a relatively fundamental level but that is intended to provide the scientific basis for specific future applications. The term "strategic research" has sometimes been used synonymously.

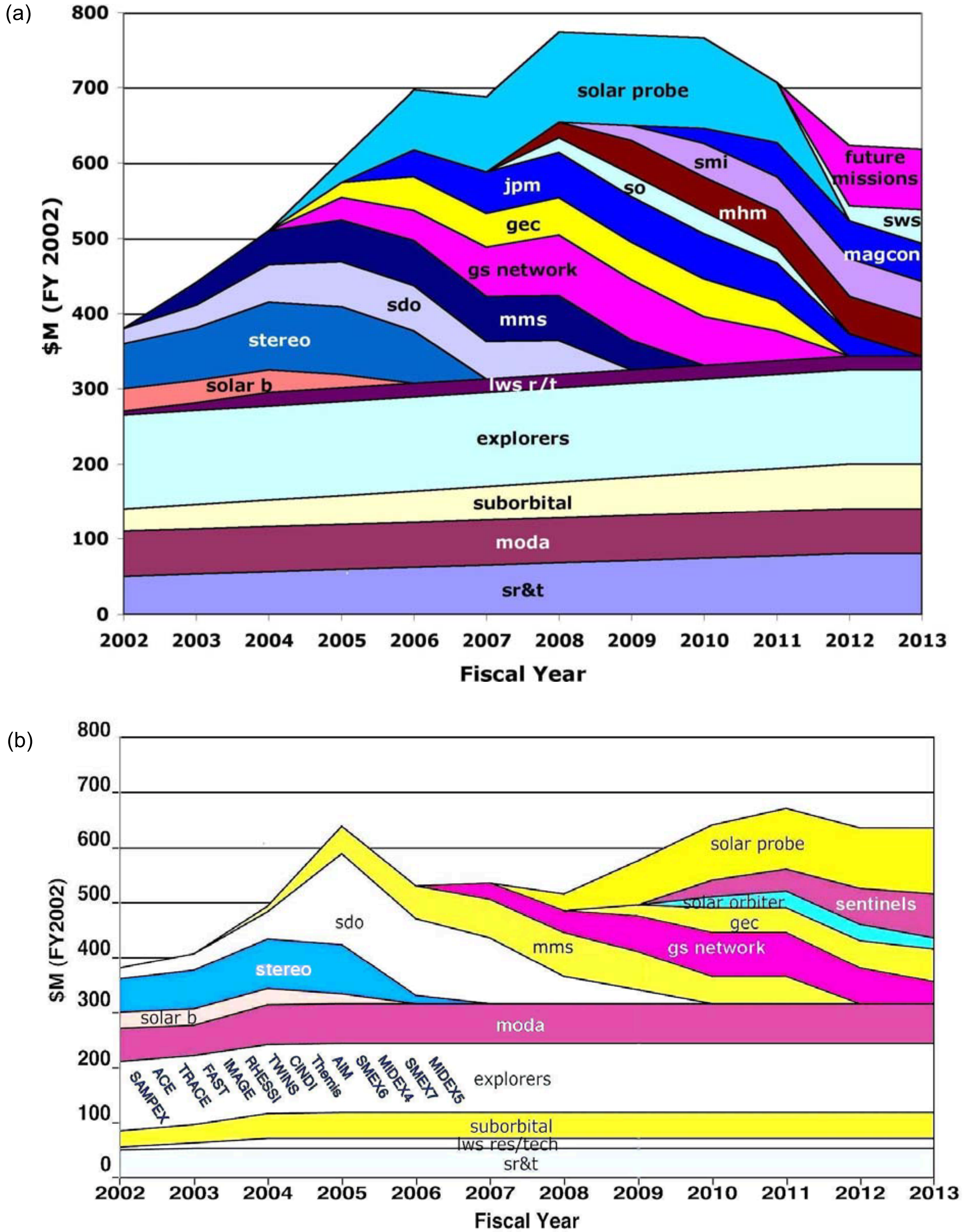

FIGURE 3.1 (a) SEC sample budget as presented in the decadal survey report. SOURCE: Adapted from National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, p. 8, The National Academies Press, Washington, D.C., 2003. (b) Sample budget that accommodates the new vision for exploration. The overlap between MMS and SDO was recommended in the decadal survey report. The fiscal plans are presented in constant FY2002 dollars. The additional cost associated with the application of full-cost accounting to these programs is not included. SOURCE: Committee discussions with NASA representatives.

With those principles in mind, the decadal survey report recommended a specific sequence of high-priority programs as a strategy for solar and space physics in the next decade. To accomplish this task, the survey report presented an assessment of candidate projects in terms of their potential scientific impact (both in their own subdisciplines and for the field as a whole) and potential societal benefit (i.e., with respect to space weather). The survey report also took into consideration the optimum affordable sequence of programs, what programs would benefit from being operational simultaneously, the technical maturity of missions in a planning phase, and what programs should have the highest priority in the event of budgetary limitations or other unforeseen circumstances that might limit the scope of the overall effort.

Finding 5. The committee concludes that, for an SEC program that properly fulfills its dual role of scientific exploration and of enabling future exploration of the solar system, the prioritized sequence recommended in the decadal survey report remains important, timely, and appropriate.

Although the recommendations and schedule presented in the decadal survey were formulated in 2002 before the adoption by NASA of the new exploration vision, the essential reasoning behind the conclusions of the survey report remain valid: to explore and characterize the solar system and to understand and predict the solar-planetary environment within which future exploration missions will take place requires a scientific approach that treats the environment as a complex, coupled system. There is not yet a sufficient understanding of how the system works to be able to rely only on empirical models based on simple monitoring of solar or other inputs. To properly support the exploration vision, the SEC program must continue to develop the understanding of basic physical processes that control the variations in hazardous penetrating radiation in space.

Recommendation 1. To achieve the goals of the exploration vision there must be a robust SEC program, including both the LWS and the STP mission lines, that studies the heliospheric system as a whole and that incorporates a balance of applied and basic science.

MO&DA, Explorer and suborbital flights, and SR&T activities are the lifeblood of SEC research because they provide core research, flexibility, innovative technologies, and invaluable training for the next generation of workers for our nation's space enterprise.[3] The Explorer program provides innovative, fast-response missions to fill critical gaps. The Suborbital program (sounding rockets, balloon payloads) provides low-cost access to space, yielding compelling science, a platform for testing instrumentation, and a vital opportunity to educate the next generation of scientists and engineers at the nation's universities. MO&DA resources ensure that missions continue to produce valuable data, sometimes even decades after launch. In addition, continued operation of existing missions are cost-effective ways to provide measurements of space weather in a severely constrained budgetary environment. The research and analysis program provides smaller grants for basic research, data analysis, and the development of new techniques so as to foster innovative approaches, new ideas, and combined analysis of multiple data sources not envisioned in original mission proposals. This range of activities is vitally important to the basic structure and diversity of SEC activities.

Recommendation 2. The programs that underpin the LWS and STP mission lines—MO&DA, Explorers, the Suborbital program, and SR&T—should continue at a pace and a level that will ensure that they can fill their vital roles in SEC research.

The scientific rationale that supported the decadal survey report's recommendations and mission sequencing remains valid, but the committee recognizes that adjustment of the implementation schedule may become necessary to respond to evolving resource constraints. The preceding chapters have outlined the relevance, scientific validation, and prioritization of the SEC missions, research, and research support activities. The implementation of the near-term SEC mission should remain in the order recommended by the decadal survey report: i.e., MMS (with a 2010 launch), Geospace Network, GEC, and MHM/Sentinels with as much overlap as feasible within available resources.

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[3] See National Research Council, *The Sun to the Earth—and Beyond: Panel Reports*, Chapter 5, The National Academies Press, Washington, D.C., 2003.

A sample SEC resource allocation through FY2009 as presented in the decadal survey report is shown in Figure 3.1(a). To demonstrate the recommended mix of missions and how these missions can be accomplished within realistic SEC cost constraints, Figure 3.1(b) presents a composite schedule and fiscal projection in keeping with this committee's recommendations. The revised plan represents a significant decrease in annual funding and a delay of mission start dates relative to the plan recommended in the decadal survey report. The recommended plan includes a balance of missions addressing the interrelated research areas of solar physics, heliospheric processes, and solar-planetary interactions. This mix of missions supports the exploration vision with a balance of applied and basic science. This mix also will provide the key data resources needed to support human and robotic exploration, including the underlying physical understanding needed to make these data resources relevant.

MMS remains the highest-priority new moderate mission recommended by the committee. The need for overlap of MMS and the Geospace Network probes with the SDO mission indicates a 2006 start date for Geospace Network and the maintenance of a 2010 launch for MMS. The balanced approach that underlies the program plan indicates starts of the Solar Orbiter, GEC, and MHM/Sentinels investigations in 2009 and shortly thereafter. The decadal survey report recommended Solar Probe as the highest-priority large mission, with a new start in 2006 in the survey report's preferred program. The survey report also presented a more constrained profile in which Solar Probe would slip to a start in 2011. This committee recommends that even in a more constrained resource environment Solar Probe should start by 2008 because of its importance for enabling exploration.

The committee has considered whether a reordering of the mission sequence would provide better support for the exploration vision. The information currently available on the proposed missions does not warrant a change in the near-term missions in the plan developed in the decadal survey report. The timing of MHM/Sentinels and other later missions should be reconsidered after further planning of these missions occurs so that they can be properly prioritized in light of the exploration goals.

Recommendation 3. The near-term priority and sequence of solar, heliospheric, and geospace missions should be maintained as recommended in the decadal survey report both for scientific reasons and for the purposes of the exploration vision.

In the new, "stretched" schedule that accommodates the expanded scope of exploration, the scientific goals for solar and space physics are compromised, particularly in the loss of synergy among missions that will no longer overlap unless missions are extended beyond their nominal lifetime. For example, the Geospace Network is devoted to studying the response of the near-space environment and the radiation belts. The near-space environment is dramatically influenced by the solar extreme ultraviolet (EUV) spectral flux. A significant science objective of the missions is to uncover the relative influence of EUV radiation and magnetospheric and solar particles in controlling the storm time evolution of the atmosphere. Detailed measurements of the solar EUV spectrum on SDO and overlap between SDO and the Geospace Network ionosphere-thermosphere storm probes would allow this question to be fully resolved. Such an accomplishment will now require an extended mission for SDO. Similarly a critical overlap between MMS and the Geospace Network radiation belt storm probes was envisaged to relate storm time energization of the inner-zone electrons to reconfiguration of magnetic and electric fields in the magnetosphere and therefore more directly to solar activity. Such a study will now require an extended mission for MMS.

In addition to the losses of scientific synergy that will arise from delaying the pace at which missions are executed there will be other important consequences. A number of missions that were recommended in the decadal survey report will be deferred beyond the 10-year planning horizon. This could be the case for the Jupiter Polar Mission, Stereo Magnetospheric Imager, Magnetospheric Constellation, Solar Wind Sentinels, and Mars Aeronomy Probe. These issues will demand careful attention as NASA develops its overall plan for science in the exploration vision. The committee concurs with the views expressed in the decadal survey report that there should be opportunities to leverage contributions from both inter-agency and international partners in a way that will permit a more robust program in a constrained resource environment.

The Jupiter Polar Mission, which was given a high priority in the decadal survey report, is an important exploration science mission in its own right. The Mars Aeronomy Probe, which was recommended in the solar system exploration survey[4] but deferred in the solar and space physics decadal survey report, now takes on heightened significance because of its role as both an enabling mission and a scientific exploration mission. Both missions deserve serious consideration in the overall context of solar system exploration priorities.

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[4] National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.

Appendixes

A

Statement of Task

Background The 2002 NRC decadal strategy study for solar and space physics, *The Sun to the Earth—and Beyond,* recommended a robust research program for NASA and NSF that would also address the operational needs of NOAA and DOD. The report includes a recommended suite of activities at NASA, which were ordered by priority, presented in an appropriate sequence, and selected to fit within expected resources during the next decade. In early 2004 NASA proposed to adopt major new goals for human and robotic exploration of the solar system that will depend, in part, on basic and applied research in solar and space physics. In view of the fact that the 2002 NRC strategy did not reflect the new exploration goals, a review of the strategy and of the roles that the solar and space physics program should play in support of the new goals is needed.

NASA's solar and space physics program is conducted by the Sun-Earth Connection (SEC) Division of the Office of Space Science. At the time of the decadal survey, the SEC program included two ongoing mission lines--the Solar-Terrestrial Probes (STP) and the longstanding series of smaller Explorer missions--plus a new series of missions that were planned to create the "Living With a Star" (LWS) program. Following introduction of the new space exploration goals, NASA plans to move forward with the LWS initiative, which focuses on aspects of space weather. However, elements of the STP and Explorer programs may be deferred in view of their being assigned a lower priority in the context of preparations for human missions to the Moon and Mars. The more applied LWS program is seen as necessary to supply information on the environment of space travel between Earth and the Moon and Mars and on how it is controlled by solar activity. The STP and Explorer missions address more basic scientific questions that are not viewed as being as immediately relevant to human exploration.

Nevertheless, OMB and NASA recognize that a strong basic research program is essential to the existence and growth of any applied science, and they have asked the NRC to provide advice on how and where the basic research aspects of the SEC program are needed to ensure that the applications needs of the exploration program are solidly grounded. The need to describe the connection to Exploration was not foreseen during the decadal survey.

The 2002 solar and space physics decadal survey report summarized the state of knowledge about the physics of the Sun, the interplanetary medium, and the space environments of Earth and other solar system bodies, and it posed key scientific questions for further research. The report also set out an integrated research strategy, with prioritized initiatives, for the next decade. The recommended strategy embraced both basic research programs and applied research activities that will enhance knowledge and prediction of space weather effects on Earth. While the report's attention to space weather issues elaborated on needs and strategies for addressing effects on terrestrial systems and on both civilian and defense spacecraft in Earth orbit, the effects of space weather on future human missions beyond Earth orbit were not addressed.

Radiation exposure in space will be a significant and serious hazard during any human mission to the Moon or Mars. There are two major sources of radiation: sparse penetrating galactic cosmic radiation, which varies over the solar cycle on time scales of years, and infrequent but intense solar particle events associated with solar storms, which develop over periods of minutes to days. The radiation can lead to both acute and chronic effects, both of which can be life-threatening.

One major challenge to reducing the risk to humans in space from radiation is the need to develop a fundamental understanding of the physical processes at the Sun and in interplanetary space that control the generation and propagation of the radiation. Researchers have made considerable strides in recent years in tackling these problems, but they still remain far from having a reliable capability to model the changing radiation environment, especially from solar events. Having the right mix of basic research aimed at developing the fundamental science and applied research aimed at developing advanced models and forecast tools will be essential.

The 2002 NRC report provides a strong starting point for such a strategic assessment, and OMB and NASA have turned to the NRC to apply that study to planning for future human exploration missions.

Plan In a meeting on April 2, 2004, with the chair of the SSB Committee on Solar and Space Physics, James Burch, and SSB staff officer Art Charo, the chief of the OMB Science and Space Branch, David Radzanowski, and William Jeffreys of OSTP asked that the SSB organize an independent assessment of how the recommendations of the recent NRC report, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* would be relevant to NASA's new space exploration initiative. In subsequent discussions with Richard Fisher, director of NASA's Sun-Earth Connection division, Fisher agreed that such an assessment was needed.

NASA's new space exploration goals include plans for an integrated program of human and robotic exploration of the Moon, Mars, and beyond. To prepare for these new challenges, the NRC will provide an independent assessment of the alignment of the agency's Sun-Earth Connection (SEC) program with the space exploration initiative, especially with respect to the capability of planned space missions to provide data that are needed to improve scientific understanding, monitoring, modeling, and prediction of the hazardous space environment.

An ad hoc committee of the Space Studies Board will be formed to address this request. Specifically, the committee will:

1. Analyze the missions and programs that were recommended by the 2002 NRC Solar and Space Physics Survey and assess their relevance to the space exploration initiative; and
2. Recommend an effective strategy for high-priority missions that will:
   —provide a basic scientific foundation for future space weather prediction capabilities,
   —support the needs of the space exploration initiative,
   —address the scientific and operational needs of NASA, NOAA, and the DOD, and
   —be feasible within realistic resource projections and time scales.

Schedule An ad hoc committee, which includes some members of the authoring committee of the 2002 solar and space physics decadal survey report, will be formed to conduct the study. The committee will prepare a brief report for delivery to NASA in the third quarter of 2004.

B

Sun-Earth Connection Missions and Exploration

The following one-page summaries describe key elements of the NASA Sun-Earth Connection program, including planned and recommended future Living With a Star and Solar Terrestrial Probe mission lines, the Explorer program, and critical supporting activities. The summaries utilize program information from NASA and the committee's assessment of the relevance of the projects and activities to the NASA exploration vision.

EXPLORERS

Status

Ongoing line of scientifically focused principal-investigator-led missions

Mission

The Explorer program has, since the beginning of the space age, been the bedrock of space-based solar and space physics research through a series of small- and medium-sized missions. Present-day Explorers like SAMPEX, ACE, TRACE, FAST, IMAGE, and RHESSI have enabled ground-breaking research on space plasma phenomena found in the Sun and interplanetary space as well as in Earth's own magnetosphere and upper atmosphere. Explorer missions recently selected for flight will investigate the aeronomy of ice in the mesosphere and the onset mechanisms of magnetospheric substorms. Potential future Explorer missions may perform remote sensing of planetary magnetospheres, heliospheric boundaries, and termination shocks. The Explorer program's strength lies in its ability to respond rapidly to new concepts and developments in science as well as in the program's synergistic relationship with ongoing strategic missions. For example, ACE and IMAGE contributed solar-wind data and magnetospheric imaging, respectively, to the ISTP missions Polar and Cluster. Similarly, spectrally selective imaging by TRACE and RHESSI supplemented the comprehensive measurements of the USTP SOHO mission. Run according to NASA's "faster, better, cheaper" management principles, Explorer missions are relatively low-budget and require little technology development, so they have the ability to adapt to the ever-changing, immediate needs of the space science community.

Science Objectives

Explorer missions are currently providing:

- Data on the triggering of coronal mass ejections (TRACE) and the source of solar energetic particles (RHESSI),
- Early warning of the arrival of interplanetary disturbances (ACE),
- Global imaging of space weather effects in the magnetosphere (IMAGE), and
- Monitoring of Earth's radiation belts (SAMPEX).

Relevance to Exploration

By nature of their quick and cost-effective design and operation, Explorer missions are well suited to meet the needs of whatever scientific questions or space weather issues may arise in conjunction with exploration. Explorer missions can work in tandem with other space science missions as well as with strategic exploration missions to fill gaps in space physics or astronomical knowledge and thereby pave the way for future discovery.

THEMIS
TIME HISTORY OF EVENTS AND MACROSCALE INTERACTIONS DURING SUBSTORMS

Status

Phase C, hardware fabrication; launch October 2006

Mission

THEMIS answers fundamental outstanding questions regarding the magnetospheric substorm instability, a dominant mechanism of transport and explosive release of solar wind energy within geospace. THEMIS will elucidate which magnetotail process is responsible for substorm onset at the region where substorm auroras map (~10 R_e): (1) a local disruption of the plasma sheet current or (2) that current's interaction with the rapid influx of plasma emanating from lobe flux annihilation at ~25 R_e. Correlative observations from long-baseline (2 to 25 R_e) probe conjunctions will delineate the causal relationship and macroscale interaction between the substorm components. THEMIS's five identical probes will measure particles and fields on orbits that optimize tail-aligned conjunctions over North America. Ground observatories time auroral breakup onset. Three inner probes at ~10 R_e monitor current disruption onset, while two outer probes, at 20 and 30 R_e, respectively, remotely monitor plasma acceleration due to lobe flux dissipation. In addition to addressing its primary objective, THEMIS will answer critical questions in radiation belt physics and solar wind-magnetosphere energy coupling. THEMIS's probes use flight-proven instruments and subsystems, yet demonstrate spacecraft design strategies ideal for constellation class missions. THEMIS is complementary to MMS and a science and a technology pathfinder for future STP missions.

Science Objectives

- Establish when and where substorms start,
- Determine how the individual substorm components interact macroscopically,
- Determine how substorms power the aurora, and
- Identify how the substorm instability couples dynamically to local current disruption modes.

Relevance to the Exploration Initiative

THEMIS addresses two of NASA's primary SEC themes: How does our planet respond to solar variations? and, How does solar variability affect society? THEMIS will play a key role in understanding Earth's space environment and a prerequisite to understanding space weather. Specifically, the coupling of energy from the magnetosphere to the ionosphere is dominated by substorms, and if the time and place of substorm initiation can be predicted accurately, then better predictions of the resulting effects on the upper atmosphere and ionosphere can be made.

THEMIS is a macroscale mission, with objectives and orbits complementary to those of the micro- and mesoscale mission MMS.

SOLAR-B

Status

JAXA (Japan)/PPARC (UK)/NASA, instrumentation built, in system integration stage, launch 2006

U.S. Involvement

NASA will provide the focal plane package (FPP) for the optical telescope as well as components of the X-ray telescope and Extreme Ultraviolet Imaging Spectrometer. NASA has selected three U.S. teams to participate in the development of these scientific instruments.

Mission

Solar-B will provide a new comprehensive view of the dynamic solar atmosphere and enable a unique and timely interaction between theory and observations. The Solar-B international collaboration is based on the very successful Japan/UK/U.S. Yohkoh mission that observed x-ray and gamma-ray solar phenomena. Using a combination of optical, EUV, and x-ray instrumentation, Solar-B will study the Sun's outer atmosphere, surface, and near-surface layers as a magnetically linked system. This approach will shed light on the way that the Sun's magnetic field modulates solar luminosity and generates the million-degree corona and supersonic solar wind, and also how the magnetic field contributes to the explosive release of solar flares and coronal mass ejections into the solar system. Solar-B will provide the first space-based observations of the Sun's vector magnetic fields, gathering continuous high-spatial- and high-temporal-resolution measurements over active-region scale fields of view. Such observations help determine the extent to which free energy stored in sheared or twisted (i.e., non-potential) magnetic fields heats the corona and powers solar flares and coronal mass ejections.

Science Objectives

Solar-B will seek to understand:

- The creation and destruction of the Sun's magnetic field,
- Solar magnetic explosions,
- The generation of EUV and x-ray radiation in the Sun, and
- Modulation of the Sun's luminosity.

Relevance to Exploration

Solar activity is the primary driver of the space weather. By quantitatively understanding the solar physics that causes processes such as flares and CMEs (i.e., the relationship between the release of magnetic energy and the magnitude of the resulting flare), scientists will be able to more accurately predict major solar eruptions that significantly affect space weather. Knowledge of the three-dimensional magnetic structure of the eruptive material is also important for predicting its propagation through and interaction with the solar wind and its time of arrival at an interplanetary spacecraft. Solar-B will provide EUV and x-ray observations of unprecedented spatial resolution, wavelength coverage, and temporal continuity that will reveal the mechanisms of energetic particle acceleration in solar flares.

STEREO
SOLAR-TERRESTRIAL RELATIONS OBSERVATORY

Status

NASA STP, Phase C/D, launch 2006

Mission

STEREO is designed to develop an understanding of the fundamental nature and origin of coronal mass ejections—the most energetic eruptions on the Sun and the primary cause of major geomagnetic storms. Using remote sensing instruments, STEREO will image the three-dimensional evolution of CMEs from birth at the Sun's surface through the corona and interplanetary medium. Using in situ instruments, STEREO will measure properties of particles and vector magnetic fields of both CMEs and the ambient solar wind at 1 AU. These observations will occur at two locations in solar orbit: one spacecraft in orbit in front of Earth and one behind. The resulting stereoscopic vision will help to construct a global picture of the Sun and its influences on the space environment.

Science Objectives

STEREO will attempt to:

- Understand the causes and mechanisms triggering coronal mass ejections,
- Characterize the propagation of coronal mass ejections through the heliosphere,
- Discover the mechanisms and sites of energetic particle acceleration in the low corona and the interplanetary medium, and
- Develop a three-dimensional, time-dependent model of the magnetic topology, temperature, density, and velocity structure of the ambient solar wind.

Relevance to Exploration

By revealing the physics behind the mechanisms that cause coronal mass ejections as well as the trajectories and properties of the ejections as they propagate through the heliosphere, STEREO will be able to generate unique alerts for Earth-directed events as well as alerts for events directed at the Moon, Mars, or an interplanetary spacecraft. STEREO's study of energetic particle acceleration will enable predictions of the occurrence and intensity of particle events, necessary ingredients for evaluating their potential hazard to astronauts. A comprehensive model of the ambient solar wind will also enable better understanding of its short- and long-term impacts on Earth, nearby planets, and exploration initiative spacecraft. True predictive power necessitates an understanding of both sporadic solar events and the ambient solar wind—and especially their interaction—which STEREO is designed to investigate.

SDO
SOLAR DYNAMICS OBSERVATORY

Status

NASA LWS, Phase B, launch 2008

Mission

SDO is the first mission in NASA's Living With a Star program and is being designed to understand, driving toward a predictive capability, the solar variations that influence life on Earth and humanity's technological systems. From geosynchronous orbit, SDO will study how the Sun's magnetic field is generated and structured and how this stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind, energetic particles, and variations in the solar irradiance.

Science Objectives

SDO will study:

- The mechanisms driving the quasi-periodic, 11-year cycle of solar activity;
- The synthesis, concentration, and dispersion across the solar surface of the active region magnetic flux;
- The relation between magnetic reconnection on small scales and the reorganization of large-scale field topology as well as magnetic reconnection's significance in heating the corona and accelerating the solar wind;
- The origins of the observed variations in the Sun's EUV spectral irradiance and their relation to magnetic activity cycles;
- The magnetic field configurations that lead to coronal mass ejections, filament eruptions, and flares that produce energetic particles and radiation;
- The degree to which the structure and dynamics of the solar wind near Earth can be determined from the magnetic field configuration and atmospheric structure near the solar surface; and
- The possibility of making accurate and reliable forecasts of space weather and climate.

Relevance to Exploration

Because solar activity is the primary driver of a range of potentially hazardous space weather effects, SDO's observations of the magnetic causes and dynamic repercussions of events such as coronal mass ejections and flares will, in conjunction with realistic models, greatly improve the accuracy of space weather forecasts. In particular, it will provide solar surface vector magnetic field observations that, in combination with coronal plasma observations, will guide interpretation of the magnetic reconnection processes believed to be intrinsic to solar activity. SDO helioseismology observations can be used to monitor the evolution of active regions on the unobservable opposite face of the Sun, providing additional warnings of potential solar activity. Since space weather involves the interaction between sporadic ejecta from the Sun and the ambient solar wind through which the ejecta propagate, true predictive power necessitates an understanding of both. SDO will provide crucial information about the source of the ambient solar wind which can be combined with observations of dynamic solar processes to gain insight into the global heliospheric environment experienced by exploring astronauts and spacecraft. The EUV irradiance monitor on board SDO will also improve our ability to understand the effect of the Sun's irradiance on Earth's and Mars's upper atmospheres, critical for maintaining good communications.

MMS
MAGNETOSPHERIC MULTISCALE

Status

NASA STP, Phase A, launch 2010

Mission

The overall objective of the MMS mission is to obtain a detailed understanding of the physics of the magnetic reconnection process and the associated phenomena of plasma turbulence and charged particle acceleration. MMS will employ four identically instrumented spacecraft orbiting in tetrahedral formation to conduct definitive investigations of reconnection in key boundary regions of Earth's magnetosphere. Reconnection is fundamental to our understanding of astrophysical and solar system plasma phenomena such as coronal mass ejections, solar flares, magnetospheric substorms, and the acceleration of relativistic particles throughout the cosmos. It is only in Earth's magnetosphere, however, that reconnection is readily accessible for sustained study through the in situ measurement of plasma properties and the electric and magnetic fields that govern its behavior. MMS will acquire high-resolution measurements of Earth's magnetosphere by its cluster of spacecraft whose separations can be varied from 10 km to a few thousands of kilometers.

Science Objectives

MMS will:

- Probe the crucial microscopic physics involved in reconnection;
- Determine the three-dimensional geometry of the plasma, field, and current structure associated with it; and
- Relate the microscale processes to phenomena occurring at larger scales in adjacent regions.

Relevance to Exploration

Safe interplanetary travel will ultimately depend on the ability to predict the planetary and heliospheric environments through which the exploration spacecraft will have to pass. Magnetic reconnection is considered to be the main driver of the most energetic phenomena within the solar system plasma environment (e.g., solar flares, coronal mass ejections, and magnetic storms), and the ability to predict these phenomena to ensure the safety of astronauts and interplanetary spacecraft hinges on acquiring sound scientific understanding of magnetic reconnection, which MMS is designed to obtain.

GEOSPACE NETWORK

Status

NASA LWS, Pre-Phase A, GS-ITSP Probes launch 2010, GS-RBSP Probes launch 2012

Mission

Two radiation belt probes (GS-RBSP) and two ionosphere-thermosphere probes (GS-ITSP) will study the effects of solar-driven storms on regions of geospace that profoundly influence the operation of critical technological systems. Strong synergism exists with SDO (described above) and between the two Geospace Network components. Scientific and programmatic closure will be achieved by comparisons with geospace models.

Science Objectives

The Geospace Network will seek to understand and characterize:

- Radiation belt dynamics and underlying physical mechanisms including the acceleration, global distribution, and variability of radiation belt electrons and ions that produce the harsh space environment for spacecraft and humans;
- Mid-latitude ionospheric variability and the irregularities that affect communications and navigation systems as well as space assets; and
- The energetic and dynamical coupling between the mid-latitude ionosphere/thermosphere, the plasmasphere, and the ring current.

Relevance to Exploration

The Geospace Network addresses two fundamental processes of space physics—particle acceleration and ionosphere-thermosphere-magnetosphere coupling—each of which plays important roles in space weather. Energetic particles in the radiation belts pose a serious radiation hazard to astronauts and spacecraft systems alike, especially during magnetic storms. These particles can have a detrimental impact on communications satellites and on astronauts who remain closer to Earth in the early exploration phase. Understanding of particle acceleration derived from the Geospace Network will contribute to basic knowledge of processes occurring in solar flares and in the radiation belts of other planets. Understanding of ionosphere-thermosphere-magnetosphere coupling is directly relevant to questions about how space weather effects influence a planet's upper atmosphere.

GEC
GEOSPACE ELECTRODYNAMIC CONNECTIONS

Status

NASA STP, Pre-AO, launch 2015

Mission

The overall objective of the GEC mission is to understand the electrodynamic processes in Earth's lower ionosphere and thermosphere. The mission consists of four spacecraft that will fly in formation at altitudes as low as 135 km and can independently change orbit to directly measure electrical currents that connect from high altitudes to denser regions in the lower ionosphere. The mission seeks to determine the extent and nature of the magnetosphere-ionosphere-thermosphere coupling. While primarily targeted at terrestrial processes, the science of GEC is applicable to neutral/ionospheric boundaries throughout the solar system.

Science Objectives

The GEC mission will investigate:

- Energy transfers from the magnetosphere to the ionosphere and thermosphere, and
- Ionosphere-thermosphere coupling, revealed by measurements of the dissipation of the transferred magnetospheric energy.

Relevance to Exploration

Current understanding and modeling of the upper atmospheres of planets is based on terrestrial observations and processes. The basic physics of magnetosphere-ionosphere-thermosphere coupling is common to other planetary systems, specifically terrestrial planets such as Mars, and is best studied in the more readily accessible terrestrial environment. GEC will significantly improve our understanding of space weather processes in the lower ionosphere that are particularly relevant to NASA's research support to the DOD.

SOLAR PROBE

Status

Under study, NASA Science and Technology Definition Team

Mission

Solar Probe is a mission of exploration through the heliosphere and into the Sun's outer corona (4-10 solar radii), the latter being a region never before directly explored and a region where many of the fundamental physical processes that drive the Sun-Earth system are generated. The solar wind is an extension of the solar corona that carves out the heliosphere and shapes planetary magnetospheres. A comprehensive knowledge of our space environment depends on a detailed understanding of the basic local physics as well as global morphology and the dynamics behind this interplay. The Solar Probe mission includes both in situ and remote sensing instruments on the spacecraft to fully characterize and understand the source regions and mechanisms governing the generation and flow of the solar wind, which links the Sun's magnetic field to the Earth and beyond.

Science Objectives

Solar Probe will seek to determine:

- The origin of the solar wind;
- Why the hot corona exists around the Sun;
- How the solar wind is accelerated;
- The mechanisms that store, accelerate, and transport energetic particles;
- The role of the plasma turbulence near the Sun;
- The quantitative relation between remote observations and the underlying fundamental physics of the corona; and
- The coronal magnetic field strength.

Relevance to Exploration

Solar Probe is clearly linked to the exploration initiative in two ways. First, it is itself a mission of exploration to study the solar system frontier of the local environment of the Sun. Second and more generally, it is relevant since the Sun is the main driver of the space environment that future piloted and robotic missions must traverse. A main goal of the LWS mission line is a linked operational model system of the entire inner heliosphere in order to predict and characterize space weather. Solar Probe will directly explore the solar atmosphere where solar flares and CMES are formed and propagate, and where energetic particles are accelerated, thus providing unique information about the plasma close to the Sun as well as throughout the heliosphere. Solar Probe is also driving innovative technology development that might later be applicable to exploration missions, in particular, technology that will allow spacecraft to survive extreme temperature conditions (>2000 kelvin near the Sun).

MHM
MULTISATELLITE HELIOSPHERIC MISSION
(SENTINELS)

Status

NASA LWS, recommended in the solar and space physics decadal survey report

Mission

The Multisatellite Heliospheric Mission, designated as the Inner Heliospheric Sentinels mission in the 2003 SEC Roadmap document, consists of four spacecraft in different elliptical orbits around the Sun such that, during various phases of the mission, two diamond-shaped configurations sense simultaneously both radial and azimuthal structure within interplanetary solar disturbances. These solar sentinels will study the formation and evolution of eruptions and flares from the Sun to Earth's magnetosphere, and they will try to explore and characterize the connection between solar events and geospace disturbances.

Science Objectives

The Multisatellite Heliospheric Mission is intended to determine:

- How the global character of the inner heliosphere changes with time,
- How geo-effective structures (coronal mass ejections, shocks, corotating interaction regions) propagate and evolve from the Sun to 1 AU,
- Which solar dynamic processes are responsible for the release of energetic particles and geoeffective events, and
- Heliospheric models.

Relevance to Exploration

Solar interplanetary disturbances drive interplanetary shock waves that energize charged particles, which ultimately impact planetary environments and spacecraft. The Multisatellite Heliospheric Mission/Sentinels will lead to better understanding of the role of the interplanetary disturbances in modifying the radiation environment that poses dangers to the astronauts, spacecraft, and instruments of the exploration initiative.

SOLAR ORBITER

Status

European Space Agency mission, confirmed, launch October 2013

U.S. Involvement

U.S. scientists are members of the ESA Science Definition Team and Payload Working Group; U.S. contribution to the science payload is foreseen; Solar Orbiter is a key element of International LWS.

Mission

By approaching as close as 48 solar radii, the Solar Orbiter will view the solar atmosphere with unprecedented spatial resolution and will measure in situ properties of the inner heliosphere, a region hitherto not directly explored. Over extended periods, the Solar Orbiter will deliver images and data of the solar polar regions and the side of the Sun not visible from Earth. The Solar Orbiter will co-rotate with solar active regions and be able to view the dynamic processes of flares and coronal mass ejections with very high precision.

Science Objectives

The Solar Orbiter will investigate:

- The in situ properties and dynamics of plasma, fields, and particles in the near-Sun heliosphere;
- The fine detail of the Sun’s magnetized atmosphere using a camera capable of detecting solar features as small as 35 kilometers across;
- The links between activity on the Sun’s surface and the resulting evolution of the corona and inner heliosphere using solar co-rotation passes; and
- The Sun’s polar regions and equatorial corona from high latitudes.

Relevance to Exploration

The Solar Orbiter will explore the inner heliosphere where many of the processes critically affecting the exploration initiative occur. For example, by directly measuring the acceleration and transport of solar energetic particles, scientists hope to be able to make accurate predictions as to their occurrence and intensity. Moreover, Solar Orbiter will be able to gain a unique view of the origins of solar activity, and, by combining co-rotating remote sensing views with in situ observations of subsequent inner heliospheric processes, Solar Orbiter will help to characterize the consequences of solar activity and enable accurate prediction of space weather.

MAP
MARS AERONOMY PROBE

Status

Mission concept, recommended in the solar and space physics decadal survey report

Mission

MAP will address the question of how the upper atmosphere of Mars is affected by solar variability. The interaction of the martian atmosphere with the solar wind is uniquely complicated by the absence of a global magnetic field and the presence of patchy crustal remnant fields on Mars. MAP will be a low-altitude, circular polar orbiter with a minimum mission duration of one martian year. The mission will probe Mars's upper atmosphere, ionosphere, and the interactions of Mar's atmosphere and strong, patchy magnetic field with the solar wind.

Science Objectives

The MAP mission will determine:

- Upper martian atmospheric composition, thermal profile, and global circulation;
- The properties of the martian ionosphere, its sources and sinks, its electrodynamic response to the solar wind, and its variability; and
- The response of the upper martian atmosphere to solar activity.

Relevance to Exploration

The landing of larger and more complex payloads—and eventually humans—on Mars will require ever more sophisticated entry, descent, and landing systems and will place increasing demands on the predictability of upper atmospheric properties like the thermospheric density profile. Both "aero-capture" at low altitudes (~30-80 km) and "aero-braking" at somewhat higher altitudes are currently envisioned for Mars exploration. The successful implementation of these orbital insertion and modification techniques will yield large savings in fuel and will increase the total payload delivered to the planet's surface. However, they will require mature models of the martian upper atmosphere, validated by measurements from the Mars Aeronomy Probe. The atmospheric structure and dynamics and, in particular, the density profile are affected by variations in inputs from the Sun such as flares and coronal mass ejections, by inputs from the lower atmosphere like gravity waves, and by underlying crustal magnetic fields. The measurements to be returned by the Mars Aeronomy Probe and the subsequent modeling and data analysis will lead directly to predictive models for these important upper atmospheric effects.

JPM
JUPITER POLAR MISSION

Status

NASA STP, recommended in the solar and space physics decadal survey report

Mission

Jupiter has a giant magnetosphere that has morphological similarities to Earth's magnetosphere, but Jupiter's strong magnetic field, high rotation rate, and the strong volcanic mass loading from Io create an intense outward centrifugal force that stretches the magnetic field into a disk-like configuration. Previous flyby missions and the Galileo orbiter have explored only the equatorial region of the jovian magnetosphere. From a polar orbit, a Jupiter Polar Mission can study the plasma dynamics and moon-ionosphere electromagnetic coupling, processes that transfer angular momentum from the spinning central object to the surrounding plasma and have implications for the early phases of the formation of solar and planetary systems.

Science Objectives

The Jupiter Polar Mission can identify:

- The relative contributions of planetary rotation and the solar wind to the energy budget of the jovian magnetosphere,
- How the plasma circulates in the magnetosphere,
- The role of Io's volcanism in providing mass that drives the circulation process,
- The charged particles responsible for the jovian aurora and how those particles become energized, and
- The electrodynamic processes that couple the jovian moons to the planet's high-latitude ionosphere.

Relevance to Exploration

The objective to explore Jupiter's moons and understand the history of the solar system makes a Jupiter Polar Mission important to the exploration initiative. A Jupiter Polar Mission would provide estimates of the angular momentum loss through the planet's coupling to the magnetosphere, a process that is important in all giant-planet magnetospheres and that may have played a major role in the early evolution of the solar system. From a space physics perspective, Jupiter is an excellent test bed of fundamental magnetospheric processes (plasma transport, auroral emissions, particle acceleration, wave generation, and so on) under conditions very different from those experienced at Earth. A Jupiter Polar Mission will study the processes that establish the environments within which the Galilean satellites, such as Europa, reside. In turn, those environments are critical to establishing the suitability of these satellites as incubators for life. Furthermore, Jupiter's moons are major sources of magnetospheric plasma and are electrodynamically coupled to the planet, triggering radio emissions and auroras in Jupiter's polar regions.

MO&DA
MISSION OPERATIONS AND DATA ANALYSIS

Status

Ongoing programs, active, prime missions and extended missions with multiple launches per year

Mission

After commissioning (typically 30 days after launch), all missions are transferred from a development phase to a mission operations and data analysis (MO&DA) phase. The duration of the MO&DA phase varies, but it typically extends through the prime mission—one to several years—and often through an extended mission, sometimes lasting many more years. The prime mission funding is guaranteed under the mission budget, and the extended mission funding is competitively awarded through periodic review of all ongoing missions. During the prime mission, an average of approximately 25 to 33 percent of the MO&DA budget is spent on missions operations, and the remainder is spent on science data analysis. As a percentage of total costs, the mission operations costs decrease during the extended mission. Part of the MO&DA budget goes to a Guest Investigator program that allows additional scientists to participate in exciting science from ongoing missions. The number of funded Guest Investigator proposals is a direct measure of the value of a mission to the community.

Science Objectives

MO&DA is the lifeblood of the solar and space physics flight program. Furthermore, optimum science return in the connected Sun-heliosphere-planetary system often requires the extension of compelling sciences missions beyond their prime-mission lifetime both to exploit the continuing capabilities of the instruments and to take advantage of synergy that may arise with data from a more recently launched mission. The new science achieved during an extended mission is typically cutting-edge, providing measurements and comprehensiveness that would cost considerably more to produce in new hardware missions.

Relevance to Exploration

MO&DA is the vehicle through which data from all missions are returned to Earth, analyzed, archived, and made available for public use.

RESEARCH AND ANALYSIS PROGRAMS

THEORY, MODELING, TARGETED RESEARCH AND DEVELOPMENT, INSTRUMENT DEVELOPMENT

Status

Ongoing programs

Mission

Research and Analysis programs include the Supporting Research and Technology (SR&T) program, the Sun-Earth Connection (SEC) Theory program, the Living With a Star (LWS) Targeted Research and Technology program, and the Sun-Earth Connection Instrument Development program.

Science Objectives

Each of these Research and Analysis programs makes major contributions to many aspects of Sun-Earth Connection science:

- SR&T programs support individual research projects that use a wide variety of techniques including theory and modeling, analysis and interpretation of space data, development of new instrument concepts, and laboratory measurements of relevant atomic and plasma parameters.
- The SEC Theory program supports efforts to use relatively large “critical mass” groups of investigators to tackle SEC program-related problems that are beyond the scope of the nominally smaller SR&T projects.
- The LWS Targeted Research and Technology program is similar in scope to the SR&T program, but its goal is to address specifically those aspects of the connected Sun-Earth system that affect life and society on Earth.
- The Sun-Earth Connection Instrument Development program supports spacecraft-based instrument technologies that show promise for use in scientific investigations on future SEC missions.

Relevance to Exploration

The Research and Analysis programs contribute significantly to the knowledge base needed to pursue the exploration initiative. Theoretical and modeling studies provide a conceptual foundation for interpreting measurements and observations in the Sun-heliosphere-planetary system, including those related to martian aeronomy, the jovian system, empirical data in Earth’s near-space environment, and other regions relevant to the exploration initiative. Research and Analysis programs provide important support for innovative ideas and technology development, and they are especially well suited for training students at both undergraduate and graduate levels.

SUBORBITAL
SOUNDING ROCKETS AND BALLOONS
(LOW COST ACCESS TO SPACE)

Status

Ongoing program, active, multiple launches per year

Mission

The Suborbital program provides a wide range of cutting-edge science that enables some of the highest-resolution measurements ever made. Many of the instruments used on satellites were first developed on sounding rockets. For example, the "top-hat" electrostatic analyzer—a staple for determining particle distributions on virtually every space plasma physics mission currently flying—was first validated on sounding rocket flights. More recent examples include new detectors for dust particles in space and wave-particle correlators. Development of new instruments using the Suborbital program provides a cost-effective way of achieving high technical readiness levels with actual spaceflight heritage.

Science Objectives

The Suborbital program provides investigations into:

- Mesosphere/ionosphere interactions,
- Auroral physics,
- Equatorial ionosphere investigation of the electrojet and spread-F phenomena,
- Polar cusp studies,
- High-resolution solar coronal imaging, and
- Magnetic reconnection.

Relevance to Exploration

Suborbital missions stand to produce great technological and human capital benefits for the exploration initiative because of the programs' efficient approach to technology development and the hands-on training of the future workforce that these student-friendly missions enable. Instrument development on suborbital missions provides a key test bed for proving new experimental techniques so that exploration is carried out in the most efficient manner possible. Because these missions are low-cost with higher risk tolerance, students have the opportunity to participate directly in hardware development and operations. The experience gained is pivotal in training effective future principal investigators. Also, the results of studies performed by many suborbital missions will have direct implications on the science and technology necessary to support humans in Earth's orbit during the early years of exploration.

C

A Notional Science Research Agenda

Origins—the beginnings of the universe, our solar system, other planetary systems, and life.

- The Big Bang, the structure and composition of the universe including the formation of galaxies and the origin of dark matter and dark energy.
- Nebular composition and evolution—gravitational collapse and stellar ignition.
- Formation of our solar system and other planetary systems—clues to the origin of the solar system found in meteorites, cosmic dust, asteroids, comets, Kuiper Belt objects, and samples of planetary surfaces.
- Pre-biotic solar system organic chemistry—locations, histories, and processes; emergence of life on Earth; interplay between geological and astronomical processes.

Evolution—how the components of the universe have changed with time, including the physical, chemical, and biological processes that have affected it, and the sequences of major events.

- The universe—processes that influence and produce large-scale structure, from subnuclear to galactic scales.
- Stellar evolution—nucleosynthesis and evolutionary sequences, including the influence of particles and fields on the space environment.
- Planetary evolution—the roles of impact, volcanism, tectonics, and orbital or rotational dynamics in shaping planetary surfaces; structure of planetary interiors.
- Comparative planetology—study of Earth as a terrestrial planet; divergence of evolutionary paths of Earth, Venus, and Mars; comparisons of giant planets and extrasolar planets.
- Atmospheres—early evolution and interaction with hydrospheres; long-term changes and stability.
- Search for habitable environments—identification and characterization of environments potentially suitable for the past existence and present sustenance of biogenic activity.

NOTE: Adapted from *A Journey to Inspire, Innovate, and Discover: Report of the President's Commission on Implementation of United States Space Exploration Policy,* ISBN 0-16-073075-9, U.S. Government Printing Office, Washington, D.C., 2004.

Fate—what the lessons of galactic, stellar, and planetary history tell about the future and our place in the universe.

- Biology of species in space—micro- and fractional gravity, long-term effects of exposure to variable gravity; radiation; avoidance and mitigation strategies.
- Impact threat—cataloguing and classification of near-Earth objects; estimation of the recent impact flux and its variations; flux variation with position in solar system; hazard avoidance and mitigation.
- Natural hazard assessment—advanced space-based characterization of meteorological, oceanic, and solid Earth natural hazards to diminish consequences and advance toward predictive capability.
- Temporal variations in solar output—monitoring and interpretation of space weather as relevant to consequence and predictability.
- Climate change—assessment of recent climatic variations; solar controls on climate change; quantitative modeling and testing of the greenhouse effect; and possible effects on planets and life.
- Long-term variations of solar system environment—galactic rotation and secular variations; local supernovae.

D

Biographies of Committee Members and Staff

FRANCES BAGENAL (*Chair*) is a professor in the Department of Astrophysical and Planetary Sciences and the Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder. The main theme of her research has been the synthesis of data analysis and theory in the study of space plasmas, especially in the fields of planetary magnetospheres and, more recently, the solar corona. Dr. Bagenal is a co-investigator on the Voyager Plasma Science (PLS) experiment and has worked with colleagues at the Massachusetts Institute of Technology in analyzing plasma data obtained in the magnetospheres of Jupiter, Saturn, Uranus, and Neptune. She is an interdisciplinary scientist on the Galileo project, specializing in a study of the Io plasma torus in the magnetosphere of Jupiter using both in situ plasma measurements and spectroscopic remote sensing observations. She has been a member of the NRC Space Studies Board, the Committee on Planetary and Lunar Exploration, and the Committee on International Space Programs. She also served as a member of the Solar and Space Physics Survey Panel on Education and Society.

CLAUDIA J. ALEXANDER is a space plasma physicist at the Jet Propulsion Laboratory. She does research on comets and on the exosphere of Jupiter's moon Ganymede. She serves as both the project scientist and the project manager of the NASA contribution to the International Rosetta Mission, and she has recently served as the project manager of the Galileo Mission (until its demise). She began her research career with a study of the thermal history of Ganymede while an undergraduate at the University of California, Berkeley. She continued research at the University of California, Los Angeles on the solar wind and the solar wind interaction with Venus. She completed a Ph.D. in space plasma physics (gas kinetic theory) at the University of Michigan in 1993, where she wrote a numerical model of the process of expansion of gases from a comet nucleus. Dr. Alexander also has community interests. She contributes to a NASA sponsored, Internet-based, public science learning tool entitled "Windows to the Universe."

JAMES L. BURCH is vice president of the Southwest Research Institute Instrumentation and Space Research Division. As an investigator in a number of spaceflight experiments, Dr. Burch has achieved a prominent reputation in the fields of upper-atmosphere geophysics and space plasma physics. In 1996 he was selected as the principal investigator for the NASA Imager for Magnetopause-to-Aurora Global Exploration investigation, which provided the first-ever global images of key regions of Earth's magnetosphere as they respond to variations in the solar wind. Dr. Burch was elected a fellow of the American Geophysical Union. He has served as chair of the SSB Committee on Solar and Space

Physics and has been a member of the Space Studies Board. He also served on the ad hoc committee that produced the 2004 NRC workshop report on the exploration of the outer heliosphere.

ANTHONY CHAN is an associate professor in the Department of Physics and Astronomy and a member of the Rice Space Institute at Rice University. His area of expertise is in theoretical plasma physics with an emphasis on space and astrophysical plasmas. Dr. Chan's research involves the study of sources, losses, and acceleration mechanisms of relativistic electrons in Earth's magnetosphere as part of the National Space Weather Program and the NSF Geospace Environment Modeling (GEM) program. He is also working in collaboration with NASA astronaut Franklin Chang-Diaz and his team in the Advanced Space Propulsion Laboratory at the Johnson Space Center to develop plasma rocket technology for NASA's interplanetary missions.

JAMES F. DRAKE is a professor in the Department of Physics and the Institute for Physical Science and Technology at the University of Maryland. His work is currently focused on magnetic reconnection with space physics applications and turbulence and transport with applications to the magnetic fusion program. Dr. Drake is a fellow of the American Physical Society and was the recipient of a Humboldt Senior Scientist Research Award. He is currently a member of the SSB Committee on Solar and Space Physics and was a member of the ad hoc committee that produced the 2004 NRC workshop report on exploration of the outer heliosphere.

JOHN C. FOSTER is a group leader with the Atmospheric Sciences Group at the Millstone Hill Observatory, and he is associate director of the Massachusetts Institute of Technology's Haystack Observatory, where he is a principal research scientist. Dr. Foster's research interests are in the physics of the magnetosphere, ionosphere, and thermosphere, especially magnetosphere/ionosphere/atmosphere coupling, incoherent scatter radar, plasma waves and instabilities, and ionospheric convection electric fields, and cleft and high-latitude phenomena. Dr. Foster previously served as a member of the NRC U.S. National Committee for the International Union of Radio Science (ex officio, 1999 to 2002), the SSB Committee on Solar and Space Physics (2001 to 2002), and the BASC Committee on Solar-Terrestrial Research (1988 to 1991).

STEPHEN A. FUSELIER, a researcher at Lockheed Martin Advanced Technology Center, has been involved with the development of the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft since its inception. He is currently a co-investigator on two instruments onboard IMAGE: the Far Ultraviolet (FUV) imager and the Low Energy Neutral Atom (LENA) imager. He is also the lead U.S. investigator on the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the joint European Space Agency/NASA ROSETTA mission. Dr. Fuselier is a fellow of the American Geophysical Union (AGU) and was the 1995 recipient of the AGU James B. Macelwane award.

SARAH GIBSON is a scientist at the National Center for Atmospheric Research's High Altitude Observatory. Her interests are in the role of the large-scale solar coronal magnetic field in both stable and dynamic coronal structures, and in the connections between the multiple heights and scales on which these structures are observed. Her current research focus is on coronal mass ejections—the eruptions of large amounts of matter from the Sun's outer atmosphere that can affect sensitive electronics systems on and orbiting Earth. Her recent work has focused on sigmoidal magnetic fields.

RODERICK A. HEELIS is a professor and the director of the William B. Hanson Center for Space Sciences at the University of Texas at Dallas. His research specialization covers planetary atmospheres, ionospheres, and magnetospheres and the physical phenomena coupling these regions. He has served on the NASA Sun-Earth Connections Advisory Subcommittee, the NRC Solar and Space Physics Survey Committee (2001 to 2003), and the Committee on Solar and Space Physics (1985 to 1987).

CRAIG KLETZING is an associate professor in the Department of Physics and Astronomy at the University of Iowa. His research interests lie in the area of experimental space plasma physics, especially particle acceleration processes in the auroral zone, and he has been a principal or co-investigator on several sounding rocket and satellite projects. He is currently serving on the NRC ad hoc committee to organize and conduct a workshop on distributed arrays of small instruments for research and monitoring in solar-terrestrial physics. He has also served on the NRC's Committee on Solar and Space Physics, the Solar and Space Physics Survey Panel on Atmosphere-Ionosphere-Magnetosphere Interactions, and the ad hoc committee that produced the 2004 NRC workshop report on the exploration of the outer heliosphere.

LOUIS J. LANZEROTTI is distinguished research professor and a member of the Center for Solar-Terrestrial Research at the New Jersey Institute of Technology, and he is also a consulting physicist to Bell Laboratories-Lucent Technologies, Murray Hill. He has contributed to research that includes studies of space plasmas and geophysics, and also engineering problems related to the impact of space processes on terrestrial technologies, as well as those used in space. He is the principal investigator for the Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies on the Ulysses spacecraft. The American Geophysical Union (AGU) named Dr. Lanzerotti in February of 2003 to be editor of *Space Weather: The International Journal of Research and Applications*. Dr. Lanzerotti is a fellow of the Institute of Electrical and Electronics Engineers, the American Physical Society, the American Geophysical Union, the American Institute of Aeronautics and Astronautics, and the American Association for the Advancement of Science, and a member of the National Academy of Engineering and the International Academy of Astronautics. He has received the NASA Distinguished Scientific Achievement Medal and the NASA Distinguished Public Service Medal. He served as the chair of the NRC Decadal Survey Committee on Solar and Space Physics, and he is chair of the NRC committee that is investigating the potential for extending the life of the Hubble Space Telescope.

GANG LU is a scientist in the Terrestrial Impacts of Solar Output section of the High Altitude Observatory at the National Center for Atmospheric Research. Her primary research covers high-latitude ionospheric electrodynamics and ionosphere-magnetosphere interactions. Dr. Lu serves as the scientific discipline representative to the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). She is a member of NSF's Geospace Environment Modeling (GEM) Steering Committee and a member of the Auroral Plasma Physics Working Group at the International Space Science Institute. She is the associate editor for the *Journal of Geophysical Research*.

BARRY H. MAUK is a physicist and section supervisor in the Applied Physics Laboratory at Johns Hopkins University. His professional service includes study scientist for NASA's Living with a Star Geospace Program, principal investigator for the Auroral Multiscale MIDEX mission, principal investigator for the Energetic Neutral Atom Camera for the Earth Observing System, and co-investigator with NASA's Voyager Low Energy Charged Particles Investigation and NASA's Cassini Magnetospheric Imaging Instrument Investigation. Dr. Mauk has served on the NRC Committee on Planetary and Lunar Exploration and on NASA's Sun-Earth Connections Roadmap Committee.

TERRANCE G. ONSAGER is head of the Solar Terrestrial Models and Theory Group at the NOAA Space Environment Center. His areas of research include solar wind-magnetosphere-ionosphere interactions, mass and energy coupling between the solar wind and the magnetosphere, magnetic reconnection, formation of magnetospheric boundary layers, and Earth's radiation belts. His previous positions include research assistant and associate professor at the University of New Hampshire Physics Department and Institute for the Study of Earth, Oceans, and Space and postdoctoral research fellow at Los Alamos National Laboratory. Dr. Onsager served as a member of the NASA Sun-Earth Connection Advisory Subcommittee and the NRC Solar and Space Physics Survey Panel on Education and Society.

EUGENE N. PARKER is the S. Chandrasekhar Distinguished Service Professor Emeritus in the Departments of Astronomy and Astrophysics and Physics at the University of Chicago. His current research interests include theoretical plasma physics; magnetohydrodynamics; solar and terrestrial physics; basic physics of the active star; application and extension of classical physics to the active conditions found in the astronomical universe (e.g., the stellar x-ray corona); and the solar wind and the origin of stellar and galactic magnetic fields. A recipient of numerous prizes from his peers, he also has extensive NRC service on committees and task groups related to solar physics and astronomy. Dr. Parker is a member of the National Academy of Sciences (NAS) and chaired the NAS's Astronomy Section from 1983 to 1986, and he served as chair of the NRC Task Group on Ground-based Solar Research (1997 to 1998).

Staff

ARTHUR CHARO, study director, received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. Dr. Charo then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a fellow from 1985 to 1988. From 1988 to 1995, he worked in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment (OTA). He has been a senior program officer at the Space Studies Board (SSB) of the National Research Council since OTA's closure in 1995. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and was the American Institute of Physics Congressional Science Fellow from 1988 to 1989. He is the author of research papers in the field of molecular spectroscopy; reports on arms control and space policy; and the monograph, *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990).

THERESA M. FISHER is a senior program assistant with the Space Studies Board. During her 25 years with the National Research Council (NRC) she has held positions in the executive, editorial, and contract offices of the National Academy of Engineering, as well as positions with several NRC boards, including the Energy Engineering Board, the Aeronautics and Space Engineering Board, the Board on Atmospheric Sciences and Climate, and the Marine Board.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board (SSB). She joined SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board, then as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was also a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a bachelor of arts in natural science from St. Mary's College of Maryland.

E

Acronyms

CIR	co-rotating interaction region
CME	coronal mass ejection
DOD	Department of Defense
EUV	extreme ultraviolet
GCR	galactic cosmic ray
GEC	Geospace Electrodynamic Connections
IMAGE	Imager for Magnetopause-to-Aurora for Global Exploration
ISTP	International Solar-Terrestrial Program
ITSP	ionosphere-thermosphere storm probes
JPM	Jupiter Polar Mission
LEO	low Earth orbit
LISM	local interstellar medium
LWS	Living With a Star
MAP	Mars Aeronomy Probe
MHM	Multisatellite Heliosphere Mission
MIDEX	Medium-Class Explorer
MMS	Magnetospheric Multiscale
MO&DA	mission operations and data analysis
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NSWP	National Space Weather Program

RBSP	radiation belt storm probes
SDO	Solar Dynamics Observatory
SEC	Sun-Earth Connection
SMEX	Small Explorer
SOHO	Solar and Heliospheric Observatory
SPE	solar particle event
SR&T	supporting research and technology
SSB	Space Studies Board
STEREO	Solar-Terrestrial Relations Observatory
STP	Solar Terrestrial Probes
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TRACE	Transition Region and Coronal Explorer