The Sun to the Earth —and Beyond

A Decadal Research Strategy in Solar and Space Physics

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Preface

The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics is the product of an 18-month effort that began in December 2000, when the National Research Council (NRC) approved a study to assess the current status and future directions of U.S. ground- and space-based programs in solar and space physics research. The NRC's Space Studies Board and its Committee on Solar and Space Physics organized the study, which was carried out by five ad hoc study panels and the 15-member Solar and Space Physics Survey Committee, chaired by Louis J. Lanzerotti, Lucent Technologies. The work of the panels and the committee was supported by the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the Office of Naval Research (ONR), and the Air Force Office of Scientific Research (AFOSR).

The Sun to the Earth—and Beyond is the report of the Solar and Space Physics Survey Committee. It draws on the findings and recommendations of the five study panels, as well as on the committee's own deliberations and on previous relevant NRC reports. The report identifies broad scientific challenges that define the focus and thrust of solar and space physics research for the decade 2003 through 2013, and it presents a prioritized set of missions, facilities, and programs designed to address those challenges.

In preparing this report, the committee has considered the technologies needed to support the research program that it recommends as well as the policy and programmatic issues that influence the conduct of solar and space physics research. The committee has also paid particular attention to the applied aspects of solar and space physics—to the important role that these fields play in a society whose increasing dependence on space-based technologies renders it ever more vulnerable to "space weather." The report discusses each of these important topics—technology needs, applications, and policy—in some detail. *The Sun to the Earth—and Beyond* also discusses the role of solar and space physics research in education and examines the productive cross-fertilization that has occurred between solar and space physics and related fields, in particular astrophysics and laboratory plasma physics.

Each of the five study panels was charged with surveying its assigned subject area and with preparing a report on its findings. The first three panels focused on the important scientific goals within their respective disciplines and on the missions, facilities, programs, technologies, and policies needed to achieve them. In contrast, the Panel on Theory, Modeling, and Data Exploration addressed basic issues that transcend disciplinary boundaries and that are relevant to all of the subdisciplines of solar and space physics. The Panel on Education and Society examined a variety of issues related to both formal and informal education, including the incorporation of solar and space physics content in science instruction at all levels, the training of solar and space physicists at colleges and universities, and public outreach. The reports of the panels are published in a separate volume titled *The Sun to the Earth—and Beyond: Panel Reports* (2003, in press).

In addition to the input from the five study panels, the committee also received information at a 2-day workshop convened in August 2001 to examine in detail issues relating to the transition from research models to operational models. Participants in the workshop included members of the committee and representatives from the Air Force, the Navy, NOAA, NSF, NASA, the U.S. Space Command, academia, and the private sector.

The committee undertook its work intending to provide a community assessment of the present state and future directions of solar and space physics research. To this end, the committee and the panels engaged in a number of efforts to ensure the broad involvement of all segments of the solar and space physics communities. These efforts included town-meeting-like events held at the May 2001 joint meeting of the American Geophysical Union (AGU) and the American Astronomical Society's (AAS's) Solar Physics Division[1] and at spring and summer 2001 workshops of the following programs: International Solar-Terrestrial Physics (ISTP), Solar, Heliospheric, and Interplanetary Environment (SHINE), Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR), and Geospace Environment Modeling (GEM). Each of these outreach events was well attended

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[1] The AGU and the Solar Physics Division of the AAS are the two principal scientific organizations representing the solar and space physics community.

and provided the committee and panels with valuable guidance, suggestions, and insights into the concerns of the solar and space physics community. Additional community input came from presentations on science themes, missions, and programs at panel meetings, from direct communication with individual panel and committee members by phone and e-mail, and through Web sites and Web-based bulletin boards established by two of the panels. Reports in the electronic newsletters of the AGU's Space Physics and Aeronomy section and of the AAS's Solar Physics Division kept those communities informed of the progress of the study and encouraged their continued involvement in the study process.

Each of the study panels met at least twice during the spring and summer of 2001. The Panel on the Sun and Heliospheric Physics and the Panel on Education and Society met three times. The committee met five times, three times in 2001 and twice in 2002. The panel chairs and vice chairs participated in two of those meetings, during which they presented their panels' recommendations and received comments and suggestions from the committee. The final set of scientific and mission, facility, and program priorities and other recommendations was established by consensus at the committee's last meeting, in May 2002.

The committee's final set of priorities and recommendations does not include all of the recommendations made by the study panels, although it is consistent with them.[2] Each panel worked diligently to identify the compelling scientific questions in its subject area and to set program priorities to address these questions. All of the recommendations offered by the panels merit support; however, the committee took as its charge the provision of a strategy for a strong, balanced national program in solar and space physics for the next decade that could be carried out within what is currently thought to be a realistic resource envelope. Difficult choices were inevitable, but the recommendations presented in this report reflect the committee's best judgment, informed by the work of the panels and discussions with the scientific community, about which programs are most important for developing and sustaining the solar and space physics enterprise.

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

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[2] The recommendations of each panel can be found in the companion volume to this report, *The Sun to the Earth—and Beyond: Panel Reports*, 2003, in press.

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:

Claudia Alexander, California Institute of Technology,
Lewis Allen, California Institute of Technology (retired),
George Field, Harvard University,
Peter Gilman, National Center for Atmospheric Research,
Gerhard Haerendel, International University, Bremen, Germany,
Thomas Hill, Rice University,
W. Jeffrey Hughes, Boston University,
Ralph Jacobson, The Charles Stark Draper Laboratory (retired),
Robert Lin, University of California, Berkeley,
Nelson Maynard, Mission Research Corporation,
Atsuhiro Nishida, Japan Society for the Promotion of Science,
William Radasky, Metatech Corporation, and
Donald Williams, Johns Hopkins University Applied Physics Laboratory.

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 Robert A. Frosch, Harvard University, and Lennard Fisk, University of Michigan. Appointed by the National Research Council, they were 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.

Louis J. Lanzerotti, *Chair*
Solar and Space Physics Survey Committee

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Executive Summary

SCIENCE CHALLENGES

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, which produces a termination shock wave and, finally, the outer boundary of the heliosphere. This distant region is the final frontier of solar and space physics.

During the 1990s, space physicists peered inside the Sun with Doppler imaging techniques to obtain the first glimpses of mechanisms responsible for the solar magnetic dynamo. Further, they imaged the solar atmosphere from visible to x-ray wavelengths to expose dramatically the complex interaction between the ionized gas and the magnetic field, which drives both the solar wind and energetic solar events such as flares and coronal mass ejections that strongly affect Earth. An 8-year tour of Jupiter's magnetosphere, combined with imaging from the Hubble Space Telescope, has revealed completely new phenomena resident in a regime dominated by planetary rotation, volcanic sources of charged particles, mysteriously pulsating x-ray auroras, and even an embedded satellite magnetosphere.

The response of Earth's magnetosphere to variations in the solar wind was clearly revealed by an international flotilla of more than a dozen spacecraft and by the first neutral-atom and extreme-ultraviolet imaging of energetic particles and cold plasma. At the same time, computer models of the global dynamics of the magnetosphere and of the local microphysics of magnetic reconnection have reached a level of sophistication high enough to enable verifiable predictions.

While the accomplishments of the past decades have answered important questions about the physics of the Sun, the interplanetary medium, and the space environments of Earth and other solar system bodies, they have also highlighted other questions, some of which are long-standing and fundamental. This report organizes these questions in terms of five challenges that are expected to be the focus of scientific investigations in solar and space physics during the coming decade and beyond:

- *Challenge 1: Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.* Why does solar activity vary in a regular 11-year cycle? Why is the solar corona several hundred times hotter than its underlying visible surface, and how is the supersonic solar wind produced?
- *Challenge 2: Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.* What is the nature of the interstellar medium, and how does the heliosphere interact with it? How do energetic solar events propagate through the heliosphere?
- *Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.* How does Earth's global space environment respond to solar variations? What are the roles of planetary ionospheres, planetary rotation, and internal plasma sources in the transfer of energy among planetary ionospheres and magnetospheres and the solar wind?
- *Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.* How is magnetic field energy converted to heat and particle kinetic energy in magnetic reconnection events?
- *Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and ionosphere.* What is the probability that specific types of space weather phenomena will occur over periods from hours to days?

An effective response to these challenges will require a carefully crafted program of space- and ground-based observations combined with, and guided by, comprehensive theory and modeling efforts. Success in this endeavor will depend on the ability to perform high-resolution imaging and in situ measurements of critical regions of the solar system. In addition to advanced scientific instrumentation, it will be necessary to have affordable constellations of spacecraft, advanced spacecraft power and propulsion systems, and advanced computational resources and techniques.

This report summarizes the state of knowledge about the total heliospheric system, poses key scientific questions for further research, and presents an integrated research strategy, with prioritized initiatives, for the next decade. The recommended strategy embraces both basic research programs and targeted basic research activities that will enhance knowledge and prediction of space weather effects on Earth. The report emphasizes the importance of understanding the Sun, the heliosphere, and planetary magnetospheres and ionospheres as astrophysical objects and as laboratories for the investigation of fundamental plasma physics phenomena. The recommendations presented in the main report are listed also in this Executive Summary.

AN INTEGRATED RESEARCH STRATEGY FOR SOLAR AND SPACE PHYSICS

The integrated research strategy proposed by the Solar and Space Physics Survey Committee is based on recommendations from four technical study panels regarding research initiatives in the following subject areas: solar and heliospheric physics, solar wind-magnetosphere interactions, atmosphere-ionosphere-magnetosphere interactions, and theory, computation, and data exploration. Because it was charged with recommending a program that will be feasible and responsible within a realistic resource envelope, the committee could not adopt all of the panels' recommendations. The committee's final set of recommended initiatives thus represents a prioritized selection from a larger set of initiatives recommended by the study panels. (All of the panel recommendations can be found in the second volume of this report, *The Sun to the Earth—and Beyond: Panel Reports*, 2003, in press.)

The committee organized the initiatives that it considered into four categories: large programs, moderate programs, small programs, and vitality programs. Moderate and small programs comprise both space missions and ground-based facilities and are defined according to cost, with moderate programs falling in the range from $250 million to $400 million and small programs costing less than $250 million. The committee considered one large (>$400 million) program, a Solar Probe mission, and gave it high priority for implementation in the decade 2003-2013. The programs in the vitality category are those that relate to the infrastructure for solar and space physics research; they are regarded by the committee as essential for the health and vigor of the field. The cost estimates used by the committee for all four categories are based either on the total mission cost or, for level-of-effort programs, on the total cost for the decade 2003-2013. FY 2002 costs are used in each case.

In arriving at a final recommended set of initiatives, the committee prioritized the selected initiatives according to two criteria—scientific importance and societal benefit. The ranked initiatives are listed and described briefly in Table ES.1. As discussed in Chapter 2, the rankings in Table ES.1, cost estimates, and judgments of technical readiness were then used to arrive at an overall program that could be conducted in the next decade while remaining within a reasonable budget. Nearly all of the recommended missions and facilities either are already planned or were recommended in previous strategic planning exercises conducted by the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF).

The committee's recommended phasing of NASA missions and initiatives is shown in Figures ES.1 and ES.2; its recommended phasing of NSF initiatives is shown in Figure ES.3. While the committee did not find a need to create completely new mission or facility concepts, some existing programs are recommended for revitalization and will require stepwise or ramped funding increases. These programs include NASA's Suborbital Program, its Supporting Research and Technology (SR&T) program, and the University-Class Explorer (UNEX) program, as well as guest investigator initiatives in the NSF for national facilities. In the vitality category, new theory and modeling initiatives, notably the Coupling Complexity initiative (discussed in the report of the Panel on Theory, Modeling, and Data Exploration) and the Virtual Sun initiative (discussed in the report of the Panel on the Sun and Heliospheric Physics), are recommended.

> **Recommendation: The committee recommends the approval and funding of the prioritized programs listed in Table ES.1.**

The committee developed its national strategy based on a systems approach to understanding the physics of the coupled solar-heliospheric environment. Ongoing NSF programs and facilities in solar and space physics, two complementary mission lines in the NASA Sun-Earth Connection program—the Solar Terrestrial Probes (STP) for basic research and Living With a Star (LWS) for targeted basic research—and applications and operations activities in the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense (DOD) facilitate such an approach.

As a key first element of its systems-oriented strategy, the committee endorsed three approved NASA missions: Solar-B and the Solar Terrestrial Relations Observatory (STEREO), both part of STP, and the Solar Dynamics Observatory (SDO), part of LWS. Together with ongoing NSF-supported solar physics programs and facilities as well as the start of the Advanced Technology Solar Telescope (ATST), these missions constitute a synergistic approach to the study of the inner heliosphere that will involve coordinated observations of the solar interior and atmosphere and the formation, release, evolution, and propagation of coronal mass ejections toward Earth. Later in the decade covered by the survey, overlapping investigations by the SDO, the ATST, and Magnetospheric Multiscale (MMS) (part of STP), together with the start of the Frequency-Agile Solar Radiotelescope (FASR), will form the intellectual basis for a comprehensive study of magnetic reconnection in the dense plasma of the solar atmosphere and the tenuous plasmas of geospace.

The committee's ranking of the Geospace Electrodynamic Connections (GEC; STP) and Geospace Network (LWS) missions acknowledges the importance of studying Earth's ionosphere and inner magnetosphere as a coupled system. Together with a ramping up of the launch opportunities in the Suborbital Program and the implementation of both the Advanced Modular Incoherent Scatter Radar (AMISR) and the Small Instrument Distributed Ground-Based Network, these missions will provide a unique opportunity to study the local electrodynamics of the ionosphere down to altitudes where energy is transferred between the magnetosphere and the atmosphere, while simultaneously investigating the global dynamics of the ionosphere and radiation belts. The implementation of the L1 Monitor (NOAA) and of the vitality programs will be essential to the success of this systems approach to basic and targeted basic research. Later on in the committee's recommended program, concurrent operations of a Multispacecraft Heliospheric Mission (MHM; LWS), Stereo Magnetospheric Imager (SMI; STP), and Magnetospheric Constellation (MagCon; STP) will provide opportunities for a coordinated approach to understanding the large-scale dynamics of the inner heliosphere and Earth's magnetosphere (again with strong contributions from the ongoing and new NSF initiatives).

TABLE ES.1 Priority Order of the Recommended Programs in Solar and Space Physics

Type of Program	Rank	Program	Description
Large	1	Solar Probe	Spacecraft to study the heating and acceleration of the solar wind through in situ measurements and some remote-sensing observations during one or more passes through the innermost region of the heliosphere (from ~0.3 AU to as close as 3 solar radii above the Sun's surface).
Moderate	1	Magnetospheric Multiscale	Four-spacecraft cluster to investigate magnetic reconnection, particle acceleration, and turbulence in magnetospheric boundary regions.
	2	Geospace Network	Two radiation-belt-mapping spacecraft and two ionospheric mapping spacecraft to determine the global response of geospace to solar storms.
	3	Jupiter Polar Mission	Polar-orbiting spacecraft to image the aurora, determine the electrodynamic properties of the Io flux tube, and identify magnetosphere-ionosphere coupling processes.
	4	Multispacecraft Heliospheric Mission	Four or more spacecraft with large separations in the ecliptic plane to determine the spatial structure and temporal evolution of coronal mass ejections (CMEs) and other solar-wind disturbances in the inner heliosphere.
	5	Geospace Electrodynamic Connections	Three to four spacecraft with propulsion for low-altitude excursions to investigate the coupling among the magnetosphere, the ionosphere, and the upper atmosphere.
	6	Suborbital Program	Sounding rockets, balloons, and aircraft to perform targeted studies of solar and space physics phenomena with advanced instrumentation.
	7	Magnetospheric Constellation	Fifty to a hundred nanosatellites to create dynamic images of magnetic fields and charged particles in the near magnetic tail of Earth.
	8	Solar Wind Sentinels	Three spacecraft with solar sails positioned at 0.98 AU to provide earlier warning than L1 monitors and to measure the spatial and temporal structure of CMEs, shocks, and solar-wind streams.
	9	Stereo Magnetospheric Imager	Two spacecraft providing stereo imaging of the plasmasphere, ring current, and radiation belts, along with multispectral imaging of the aurora.
Small	1	Frequency-Agile Solar Radiotelescope	Wide-frequency-range (0.3-30 GHz) radiotelescope for imaging of solar features from a few hundred kilometers above the visible surface to high in the corona.

TABLE ES.1 Continued

Type of Program	Rank	Program	Description
	2	Advanced Modular Incoherent Scatter Radar	Movable incoherent scatter radar with supporting optical and other ground-based instruments for continuous measurements of magnetosphere-ionosphere interactions.
	3	L1 Monitor	Continuation of solar-wind and interplanetary magnetic field monitoring for support of Earth-orbiting space physics missions. Recommended for implementation by NOAA.
	4	Solar Orbiter	U.S. instrument contributions to European Space Agency spacecraft that periodically corotates with the Sun at 45 solar radii to investigate the magnetic structure and evolution of the solar corona.
	5	Small Instrument Distributed Ground-Based Network	NSF program to provide global-scale ionospheric and upper atmospheric measurements for input to global physics-based models.
	6	University-Class Explorer	Revitalization of University-Class Explorer program for more frequent access to space for focused research projects.
Vitality	1	NASA Supporting Research and Technology	NASA research and analysis program.
	2	National Space Weather Program	Multiagency program led by the NSF to support focused activities that will improve scientific understanding of geospace in order to provide better specifications and predictions.
	3	Coupling Complexity	NASA/NSF theory and modeling program to address multiprocess coupling, nonlinearity, and multiscale and multiregional feedback.
	4	Solar and Space Physics Information System	Multiagency program for integration of multiple data sets and models in a system accessible by the entire solar and space physics community.
	5	Guest Investigator Program	NASA program for broadening the participation of solar and space physicists in space missions.
	6	Sun-Earth Connection Theory and LWS Data Analysis, Theory, and Modeling Programs	NASA programs to provide long-term support to critical-mass groups involved in specific areas of basic and targeted basic research.
	7	Virtual Sun	Multiagency program to provide a systems-oriented approach to theory, modeling, and simulation that will ultimately provide continuous models from the solar interior to the outer heliosphere.

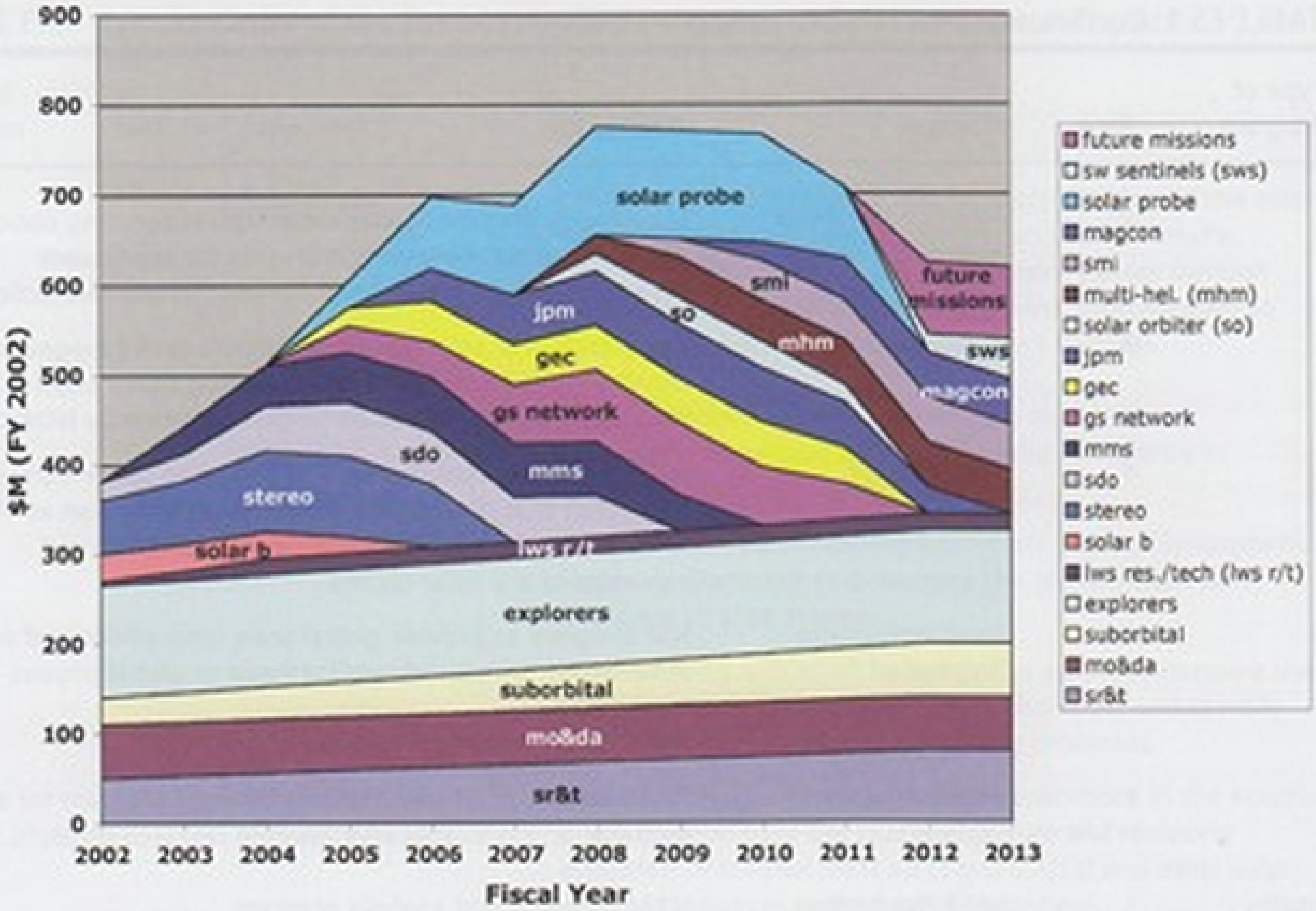

FIGURE ES.1 Recommended phasing of the highest-priority NASA missions, assuming an early implementation of a Solar Probe mission. Solar Probe was the Survey Committee's highest priority in the large mission category, and the committee recommends its implementation as soon as possible. However, the projected cost of Solar Probe is too high to fit within plausible budget and mission profiles for NASA's Sun-Earth Connection (SEC) Division. Thus, as shown in this figure, an early start for Solar Probe would require funding above the currently estimated SEC budget of $650 million per year for fiscal years 2006 and beyond. Note that mission operations and data analysis (MO&DA) costs for all missions are included in the MO&DA budget wedge.

To understand the genesis of the heliospheric system, it is necessary to determine the mechanisms by which the solar corona is heated and the solar wind is accelerated and to understand how the solar wind evolves in the innermost heliosphere. These objectives will be addressed by a Solar Probe mission. Because of the importance of these objectives for the overall understanding of the solar-heliosphere system, as well as of other stellar systems, a Solar Probe mission[1] should be implemented as soon as possible within the coming decade. The Solar Probe measurements will be comple-

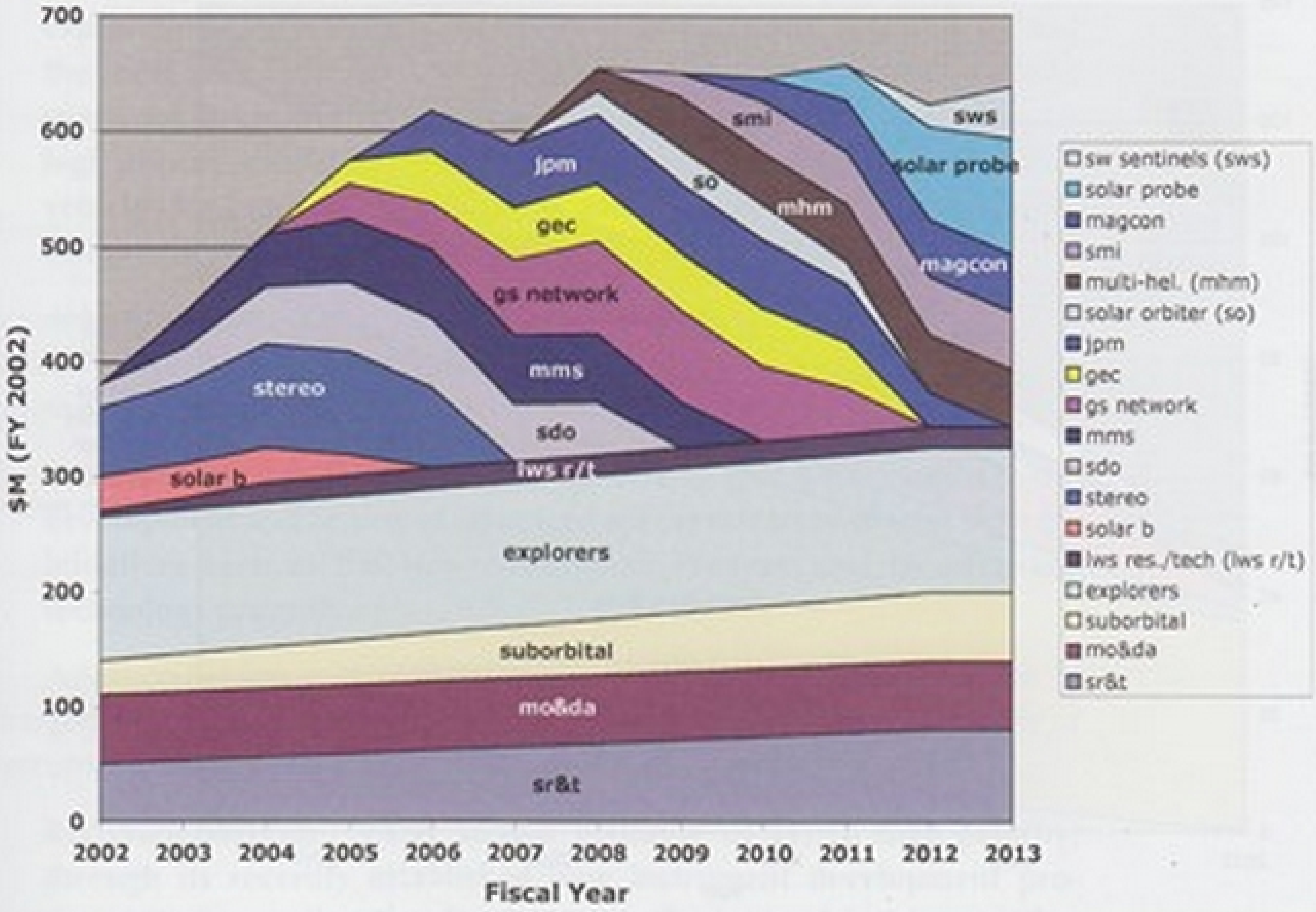

FIGURE ES.2 Recommended phasing of the highest-priority NASA missions if budget augmentation for Solar Probe is not obtained. MO&DA costs for all missions are included in the MO&DA budget wedge.

mented by correlative observations from such initiatives as Solar Orbiter, SDO, ATST, and FASR.

Similarly, because comparative magnetospheric studies are important for advancing the understanding of basic magnetospheric processes, the committee has assigned high priority to a Jupiter Polar Mission (JPM), a space physics mission to study high-latitude electrodynamic coupling at Jupiter. Such a mission will provide both a means of testing and refining theoretical concepts developed largely in studies of the terrestrial magnetosphere and a means of studying in situ the electromagnetic redistribution of angular momentum in a rapidly rotating system, with results relevant to such astrophysical questions as the formation of protostars.

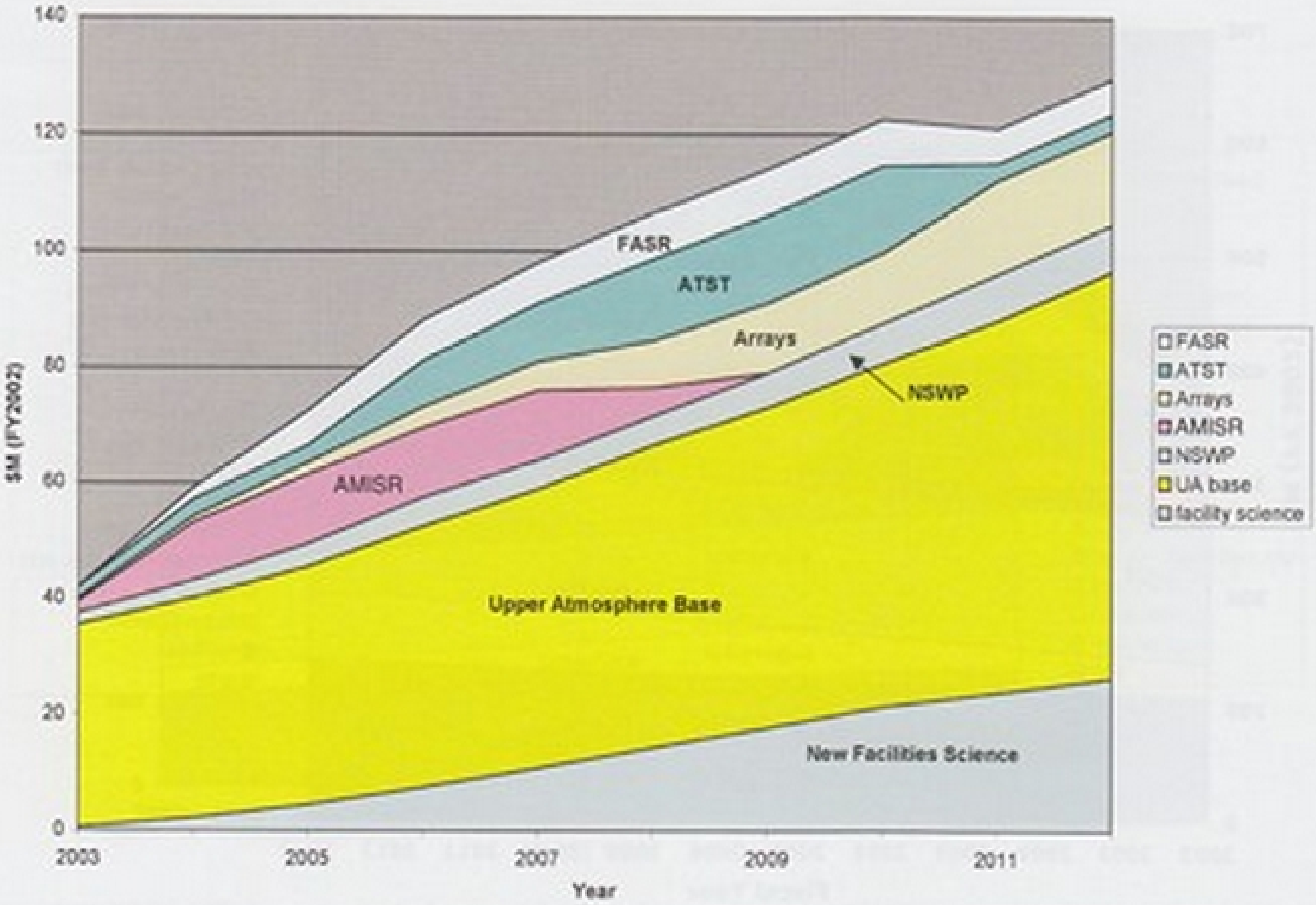

FIGURE ES.3 Recommended phasing of major new and enhanced NSF initiatives. The budget wedge for new facilities science refers to support for guest investigator and related programs that will maximize the science return of new ground facilities to the scientific community. Funding for new facilities science is budgeted at approximately 10 percent of the aggregate cost for new NSF facilities.

TECHNOLOGY DEVELOPMENT

Technology development is required in several critical areas if a number of the future science objectives of solar and space physics are to be accomplished.

Traveling to the planets and beyond. New propulsion technologies are needed to rapidly propel spacecraft to the outer fringes of the solar system and into the local interstellar medium. Also needed are power systems to support future deep-space missions.

Recommendation: NASA should assign high priority to the development of advanced propulsion and power technologies required for the

exploration of the outer planets, the inner and outer heliosphere, and the local interstellar medium. Such technologies include solar sails, space nuclear power systems, and high-efficiency solar arrays. Equally high priority should be given to the development of lower-cost launch vehicles for Explorer-class missions and to the reopening of the radioisotope thermoelectric generator (RTG) production line.

Advanced spacecraft systems. Highly miniaturized spacecraft and advanced spacecraft subsystems will be critical for a number of high-priority future missions and programs in solar and space physics.

Recommendation: NASA should continue to give high priority to the development and testing of advanced spacecraft technologies through initiatives such as the New Millennium Program and its advanced technology program.

Advanced science instrumentation. Highly miniaturized sensors of charged and neutral particles and photons will be essential elements of instruments for new solar and space physics missions.

Recommendation: NASA should continue to assign high priority, through its recently established new instrument development programs, to supporting the development of advanced instrumentation for solar and space physics missions and programs.

Gathering and assimilating data from multiple platforms. Future flight missions include multipoint measurements to resolve spatial and temporal scales that dominate the physical processes that operate in solar system plasmas.

Recommendation: NASA should accelerate the development of command-and-control and data acquisition technologies for constellation missions.

Modeling the space environment. Primarily because of the lack of a sufficient number of measurements, it has not been necessary until quite recently for the solar and space physics community to address data assimilation issues. However, it is anticipated that within 10 years vast arrays of data sets will be available for assimilation into models.

Recommendation: Existing NOAA and DOD facilities should be expanded to accommodate the large-scale integration of space- and ground-based data sets into physics-based models of the geospace environment.

Observing geospace from Earth. The effects of temperature, moisture, and wildly varying solar insolation have posed serious problems for arrays of ground-based sensor systems that are critical for solar and space physics studies.

> **Recommendation: The relevant program offices in the NSF should support comprehensive new approaches to the design and maintenance of ground-based, distributed instrument networks, with proper regard for the severe environments in which they must operate.**

Observing the Sun at high spatial resolution. Recent breakthroughs in adaptive optics have eliminated the major technical impediments to making solar observations with sufficient resolution to measure the pressure scale height, the photon mean free path, and the fundamental magnetic structure size.

> **Recommendation: The NSF should continue to fund the technology development program for the Advanced Technology Solar Telescope.**

CONNECTIONS BETWEEN SOLAR AND SPACE PHYSICS AND OTHER DISCIPLINES

The fully or partially ionized plasmas that are the central focus of solar and space physics are related on a fundamental level to laboratory plasma physics, which directly investigates basic plasma physical processes, and to astrophysics, a discipline that relies heavily on understanding the physics unique to the plasma state. Moreover, there are numerous points of contact between space physics and atmospheric science, particularly in the area of aeronomy. Knowledge of the properties of atoms and molecules is critical for understanding a number of magnetospheric, ionospheric, solar, and heliospheric processes. Understanding developed in one of these fields is thus in principle applicable to the others, and productive cross-fertilization between disciplines has occurred in a number of instances.

> **Recommendation: In collaboration with other interested agencies, the NSF and NASA should take the lead in initiating a program in laboratory plasma science that can provide new understanding of fundamental processes important to solar and space physics.[2]**

> **Recommendation: The NSF and NASA should take the lead and other interested agencies should collaborate in supporting, via the proposal and funding processes, increased interactions between researchers in**

solar and space physics and those in allied fields such as atomic and molecular physics, laboratory fusion physics, atmospheric science, and astrophysics.

SOLAR AND SPACE ENVIRONMENT EFFECTS ON TECHNOLOGY AND SOCIETY

The space environment of the Sun-Earth system can have deleterious effects on numerous technologies that are used by modern-day society. Understanding this environment is essential for the successful design, implementation, and operation of these technologies.

National Space Weather Program. A number of activities under way in the United States aim to better understand and to mitigate the effects of solar activity and the space environment on important technological systems. The mid-1990s saw the creation of the National Space Weather Program (NSWP), an interagency effort whose goal is to achieve, within a 10-year period, "an active, synergistic, interagency system to provide timely, accurate, and reliable space environment observations, specifications, and forecasts."[3] In 1999, NASA initiated an important complementary program, Living With a Star, which over the next decade and beyond will carry out targeted basic research on space weather. Crucial components of the national space weather effort continue to be provided by the operational programs of the Department of Defense and NOAA. Moreover, in addition to governmental activities, a number of private companies have, over the last decade, become involved in developing and providing space weather products.

Monitoring the solar-terrestrial environment. Numerous research instruments and observations are required to provide the basis for modeling interactions between the solar-terrestrial environment and technical systems and for making sound technical design decisions that take such interactions into account. Transitioning of programs and/or their acquisition platforms or instruments into operational use requires strong and effective coordination efforts among agencies. Imaging of the Sun and of geospace will play a central role in operational space forecasting in the future.

Recommendation: NOAA and DOD, in consultation with the research community, should lead in an effort by all involved agencies to jointly assess instrument facilities that contribute key data to public

and private space weather models and to operational programs. They should then determine a strategy to maintain the needed facilities and/or work to establish new facilities. The results of this effort should be available for public dissemination.

Recommendation: NOAA should assume responsibility for the continuance of space-based measurements such as solar wind data from the L1 location as well as near Earth and for distribution of the data for operational use.[4]

Recommendation: NASA and NOAA should initiate the necessary planning to transition solar and geospace imaging instrumentation into operational programs for the public and private sectors.

Transition from research to operations. Means must be established for transitioning new knowledge into those arenas where it is needed for design and operational purposes. Creative and cutting-edge research in modeling the solar-terrestrial environment is under way. Under the auspices of the NSWP, models that are thought to be potentially useful for space weather applications can be submitted to the Community Coordinated Modeling Center (currently located at the NASA Goddard Space Flight Center) for testing and validation. Following validation, the models can be turned over to either the U.S. Air Force or the NOAA Rapid Prototyping Center, where the models are used for the objectives of the individual agencies. In many instances, the validation of research products and models is different in the private and public sectors, with publicly funded research models and system-impact products usually being placed in an operational setting with only limited validation.

Recommendation: The relevant federal agencies should establish an overall verification and validation program for all publicly funded models and system-impact products before they become operational.

Recommendation: The operational federal agencies, NOAA and DOD, should establish procedures to identify and prioritize operational needs, and these needs should determine which model types are selected for transitioning by the Community Coordinated Modeling Center and the Rapid Prototyping Centers. After the needs have been prioritized, procedures should be established to determine which of the competing models, public or private, is best suited for a particular operational requirement.

Data acquisition and availability. During the coming decade, gigabytes of data could be available every day for incorporation into physics-based data assimilation models of the solar-terrestrial environment and into system-impact codes for space weather forecasting and mitigation purposes. DOD generally uses data that it owns and only recently has begun to use data from other agencies and institutions, so that not many data sets are available for use by the publicly funded or commercial vendors who design products for DOD. Engineers typically are interested in space climate, not space weather. Needed are long-term averages, the uncertainties in these averages, and values for the extremes in key space weather parameters. The engineering goal is to design systems that are as resistant as possible to the effects of space weather.

> **Recommendation: DOD and NOAA should be the lead agencies in acquiring all the data sets needed for accurate specification and forecast modeling, including data from the international community. Because it is extremely important to have real-time data, both space- and ground-based, for predictive purposes, NOAA and DOD should invest in new ways to acquire real-time data from all of the ground- and space-based sources available to them. All data acquired should contain error estimates, which are required by data assimilation models.**

> **Recommendation: A new, centralized database of extreme space weather conditions should be created that covers as many of the relevant space weather parameters as possible.**

Public and private sectors in space weather applications. To date, the largest efforts to understand the solar-terrestrial environment and apply the resultant gains in knowledge for practical purposes have been mostly publicly funded and have involved government research organizations, universities, and some industries. Recently some private companies both large and small have been devoting their own resources to the development and sale of specialized products that address the design and operation of certain technical systems that can be affected by the solar-terrestrial environment. Such companies often use publicly supported assets (such as spacecraft data) as well as proprietary instrumentation and models. A number of the private efforts use proprietary system knowledge to guide their choice of research directions. Policies on such matters as data rights, intellectual property rights and responsibilities, and benchmarking criteria can be quite different for private efforts and publicly supported ones, including those of universities. Thus, transitioning knowledge and models from one sector to another can be fraught with complications and requires continued attention and discussion by all interested entities.

> **Recommendation: Clear policies should be developed that describe government and industry roles, rights, and responsibilities in space weather activities. Such policies are necessary to optimize the benefits of the national investments, public and private, that are being made.**

EDUCATION AND PUBLIC OUTREACH

The committee's consideration of issues related to education and outreach was focused in two areas: ensuring a sufficient number of future scientists in solar and space physics and identifying ways in which the solar and space physics community can contribute to national initiatives in science and technology education.

Solar and space physics in colleges and universities. Because of its relatively short history, solar and space physics appears only adventitiously in formal instructional programs, and an appreciation of its importance is often lacking in current undergraduate curricula. If solar and space physics is to have a healthy presence in academia, additional faculty members will be needed to guide student research (both undergraduate and graduate), to teach solar and space physics graduate programs, and to integrate topics in solar and space physics into basic physics and astronomy classes.

> **Recommendation: The NSF and NASA should jointly establish a program of "bridged positions" that provides (through a competitive process) partial salary, start-up funding, and research support for four new faculty members every year for 5 years.**

Distance education. Education in solar and space physics during the academic year could be considerably enhanced if the latest advances in information technology are exploited to provide distance learning for both graduate students and postdoctoral researchers. This approach would substantially increase the educational value of the expertise that currently resides at a limited number of institutions.

> **Recommendation: The NSF and NASA should jointly support an initiative that provides increased opportunities for distance education in solar and space physics.**

Undergraduate research opportunities and undergraduate instruction. NSF support for the Research Experiences for Undergraduates program has been valuable for encouraging undergraduates in the solar and space physics research area.

> **Recommendation: NASA should institute a specific program for the support of undergraduate research in solar and space physics at colleges and universities. The program should have the flexibility to support such research with either a supplement to existing grants or with a stand-alone grant.**
>
> **Recommendation: Over the next decade NASA and the NSF should fund groups to develop and disseminate solar and space physics educational resources (especially at the undergraduate level) and to train educators and scientists in the effective use of such resources.**

STRENGTHENING THE SOLAR AND SPACE PHYSICS RESEARCH ENTERPRISE

Advances in understanding in solar and space physics will require strengthening a number of the infrastructural aspects of the nation's solar and space physics program. The committee has identified several that depend on effective program management and policy actions for their success: (1) development of a stronger research community, (2) cost-effective use of existing resources, (3) ensuring cost-effective and reliable access to space, (4) improving interagency cooperation and coordination, and (5) facilitating international partnerships.

Strengthening the solar and space physics research community. A diverse and high-quality community of research institutions has contributed to solar and space physics research over the years. The central role of the universities as research sites requires enhancement, strengthening, and stability.

> **Recommendation: NASA should undertake an independent outside review of its existing policies and approaches regarding the support of solar and space physics research in academic institutions, with the objective of enabling the nation's colleges and universities to be stronger contributors to this research field.**

Recommendation: NSF-funded national facilities for solar and space physics research should have resources allocated so that the facilities can be made widely available to outside users.

Cost-effective use of existing resources. Optimal return in solar and space physics is obtained not only through the judicious funding and management of new assets, but also through the maintenance and upgrading, funding, and management of existing facilities.

Recommendation: The NSF and NASA should give all possible consideration to capitalizing on existing ground- and space-based assets as the goals of new research programs are defined.

Access to space. The continuing vitality of the nation's space research program is strongly dependent on having cost-effective, reliable, and readily available access to space that meets the requirements of a broad spectrum of diverse missions. The solar and space physics research community is especially dependent on the availability of a wide range of suborbital and orbital flight capabilities to carry out cutting-edge science programs, to validate new instruments, and to train new scientists. Suborbital flight opportunities are very important for advancing many key aspects of future solar and space physics research objectives and for enabling the contributions that such opportunities make to education.

Recommendation: NASA should revitalize the Suborbital Program to bring flight opportunities back to previous levels.

Low-cost launch vehicles with a wide spectrum of capabilities are critically important for the next generation of solar and space physics research, as delineated in this report.

Recommendations:

- **NASA should aggressively support the engineering research and development of a range of low-cost vehicles capable of launching payloads for scientific research.**
- **NASA should develop a memorandum of understanding with DOD that would delineate a formal procedure for identifying in advance flights of opportunity for civilian spacecraft as secondary payloads on certain Air Force missions.**
- **NASA should explore the feasibility of similar piggybacking on appropriate foreign scientific launches.**

The comparative study of planetary ionospheres and magnetospheres is a central theme of solar and space physics research.

Recommendation: The scientific objectives of the NASA Discovery program should be expanded to include those frontier space plasma physics research subjects that cannot be accommodated by other spacecraft opportunities.

The principal investigator (PI) model that has been used for numerous Explorer missions has been highly successful. Strategic missions such as those under consideration for the STP and LWS programs can benefit from emulating some of the management approach and structure of the Explorer missions. The committee believes that the science objectives of the solar and space physics missions currently under consideration are best achieved through a PI mode of mission management.

Recommendation: NASA should (1) place as much responsibility as possible in the hands of the principal investigator, (2) define the mission rules clearly at the beginning, and (3) establish levels of responsibility and mission rules within NASA that are tailored to the particular mission and to its scope and complexity.

Recommendation: The NASA official who is designated as the program manager for a given project should be the sole NASA contact for the principal investigator. One important task of the NASA official would be to ensure that rules applicable to large-scale, complex programs are not being inappropriately applied, thereby producing cost growth for small programs.

Interagency cooperation and coordination. Interagency coordination over the years has yielded greater science returns than could be expected from single-agency activities. In the future, a research initiative at one agency could trigger a window of opportunity for a research initiative at another agency. Such an eventuality would leverage the resources contributed by each agency.

Recommendation: The principal agencies involved in solar and space physics research—NASA, NSF, NOAA, and DOD—should devise and implement a management process that will ensure a high level of coordination in the field and that will disseminate the results of such a coordinated effort—including data, research opportunities, and related matters—widely and frequently to the research community.

Recommendation: For space-weather-related applications, increased attention should be devoted to coordinating NASA, NOAA, NSF, and DOD research findings, models, and instrumentation so that new developments can quickly be incorporated into the operational and applications programs of NOAA and DOD.

International partnerships. The geophysical sciences—in particular, solar and space physics—address questions of global scope and inevitably require international participation for their success. Collaborative research with other nations allows the United States to obtain from other geographical regions data that are necessary to determine the global distributions of space processes. Studies in space weather cannot be successful without strong participation from colleagues in other countries and their research capabilities and assets, in space and on the ground.

Recommendation: Because of the importance of international collaboration in solar and space physics research, the federal government, especially the State Department and NASA, should implement clearly defined procedures regarding exchanges of scientific data or information on instrument characteristics that will facilitate the participation of researchers from universities, private companies, and nonprofit organizations in space research projects having an international component.

NOTES

1. The Solar Probe mission recommended by the committee is a generic mission to study the heating and acceleration of the solar wind through measurements as close to the surface of the Sun as possible. NASA's previously announced Solar Probe mission was canceled for budgetary reasons; a new concept study for a Solar Probe was conducted in 2002. The new study built on the earlier science definition team report to NASA and examined, among other issues, the power and communications technologies (including radioisotope thermoelectric generators) needed to enable such a mission within a realistic cost cap. The measurement capabilities considered in the study comprise both instrumentation for the in situ measurement of plasmas, magnetic fields, and waves and a remote-sensing package, including a magnetograph and Doppler, extreme ultraviolet, and coronal imaging instruments.

The committee notes that the Panel on the Sun and Heliospheric Physics recommends as its highest-priority new initiative a Solar Probe mission whose primary objective is to make in situ measurements of the innermost heliosphere. The panel does not consider remote sensing a top priority on a first mission to the near-Sun region, although it does allow as a possible secondary objective remote sensing of the photospheric magnetic field in the polar regions. (See the Solar Probe discussion in the report of the Panel on the Sun and Heliospheric Physics, which is published in *The Sun to the Earth—and Beyond: Panel Reports*, 2003, in press.) While accepting the panel's assessment of the critical importance of the in situ measurements for understanding coronal heating and solar wind acceleration, the committee does not wish to rule out the possibility that some additional remote-sensing capabilities, beyond the remote-sensing experiment to measure the polar photospheric magnetic field envisioned by the panel, can be accommodated on a Solar Probe within the cost cap set by the committee.

2. The establishment of such a laboratory initiative was previously recommended in the 1995 National Research Council report *Plasma Science: From Fundamental Research to Technological Applications* (National Academy Press, Washington, D.C., 1995).

3. Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM), *National Space Weather Program Strategic Plan,* FCM-P30-1995, OFCM, Washington, D.C., August 1995.

4. For example, a NOAA-Air Force program is producing operational solar x-ray data. The Geostationary Operational Environmental Satellite (GOES) Solar X-ray Imager (SXI), first deployed on GOES-M, took its first image on September 7, 2001. The SXI instrument is designed to obtain a continuous sequence of coronal x-ray images at a 1-minute cadence. These images are being used by NOAA's Space Environment Center and the broader community to monitor solar activity for its effects on Earth's upper atmosphere and the near-space environment.

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