**A Performance Assessment of NASA's Heliophysics Program**

Committee on Heliophysics Performance Assessment; National Research Council

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# A Performance Assessment of NASA's Heliophysics Program

Committee on Heliophysics Performance Assessment
Space Studies Board
Division on Engineering and Physical Sciences
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# Preface

In Section 301(a) of the NASA Authorization Act of 2005, the Congress directed the National Aeronautics and Space Administration to have "[t]he performance of each division in the Science directorate . . . reviewed and assessed by the National Academy of Sciences at 5-year intervals." The first two of these assessments, for NASA's Astrophysics Division and NASA's Planetary Science Division, were started in 2006 and 2007, respectively. In late 2007, NASA asked the National Research Council (NRC) to conduct such an assessment for the agency's Heliophysics Division. The statement of task (see Appendix A) for the Committee on Heliophysics Performance Assessment was to study the alignment of NASA's Heliophysics Division strategy with previous NRC advice—primarily the relevant decadal survey report, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*.[1] More specifically, the statement of task asked the committee to address the following:

- How well NASA's current program addresses the strategies, goals, and priorities outlined in the heliophysics decadal survey and other relevant National Research Council reports;
- Progress toward realizing these strategies, goals, and priorities; and
- Any actions that could be taken to optimize the science value of the program in the context of current and forecasted resources available to it.

In the letter from the associate administrator for NASA's Science Mission Directorate, the committee was told that "[t]he review should not revisit or alter the scientific priorities or mission recommendations provided in the 2002 decadal survey, but may provide guidance about implementing the recommended mission portfolio in preparation for the next decadal survey."[2]

The committee held three meetings, in April, June, and August 2008. At the April and June meetings, the committee received presentations from members of the decadal survey, members of the astrophysics and planetary mid-decade assessments, the NRC's Committee on Solar and Space Physics, NASA headquarters staff, NOAA staff, participants in the relevant NASA mission operating working groups, mission scientists, and other members of the research community. Because this was a congressionally directed study, the committee also asked relevant congressional staff for input on what kind of report would be most relevant to their work. In addition, committee representatives visited the NASA Goddard Space Flight Center and the Johns Hopkins University Applied Physics Laboratory to hear from their scientists and managers about the programs reviewed in this report.

The committee thanks those who made formal presentations at its meetings and expresses appreciation to the hosts of and presenters at the site visits. The conversations were sincere, informative, and invaluable to the assessment. The committee also thanks the NASA Headquarters staff who provided the budget figures used in this report.

[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] Alan Stern, Associate Administrator for the Science Mission Directorate, to Lennard Fisk, Chair, Space Studies Board, November 15, 2007.

## Acknowledgment of Reviewers

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 (NRC'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 participation in the review of this report:

Craig DeForest, Southwest Research Institute,
Janet Kozyra, University of Michigan,
Louis J. Lanzerotti, New Jersey Institute of Technology,
John Leibacher, National Solar Observatory,
Robert P. Lin, University of California, Berkeley,
William H. Matthaeus, University of Delaware, and
Mark Miesch, National Center for Atmospheric Research.

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 Peter M. Banks, Astrolabe Venture Partners. Appointed by the NRC, 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.

# Contents

# Summary

Since the 1990s, the pace of discovery in the field of solar and space physics has accelerated, largely owing to prior and continuing NASA investments in its Heliophysics Great Observatory fleet of spacecraft.[1] These enable researchers to investigate connections between events on the Sun and in the space environment by combining multiple points of view. The field of solar and space physics comprises the phenomenology and physics of space plasmas and neutral gases, both individually and as coupled, nonlinear interacting systems driven from the Sun to Earth, to other members of the solar system, and out to the very edge of the heliosphere. Through NASA's current Heliophysics Great Observatory, researchers use 12 spacecraft to address the basic science of variable solar outputs, their transmission to the geospace environment and beyond, and their impacts on technological systems.

Solar and space physics requires synergy between observational and theoretical initiatives, and between basic research and targeted research programs. Investments by NASA, the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Department of Defense (DOD) in space weather instruments, ground-based observatories, research, technology, and education have been important to sustaining progress. Collectively, they enable humanity's deepest understanding of our nearest star and its interactions with all members of the heliosphere, including the technologies that sustain and nurture our presence in geospace and beyond.

Recognizing the importance of distributed observations of all elements of the Sun-to-Earth system and the synergies between observation and theory and between basic and targeted research, the National Research Council's (NRC's) 2003 solar and space physics decadal survey[2] laid out the Integrated Research Strategy, which sought to extend and augment what has now become the Heliophysics Great Observatory as well as to enhance NASA, NOAA, NSF, and DOD's other solar and space physics research activities. The Integrated Research Strategy provided a prioritized list of flight missions and theory and modeling programs that would advance the relevant physical theories, incorporate those theories in models that describe a system of interactions between the Sun and the space environment, obtain data on the system, and analyze and test the adequacy of the theories and models. As directed by Congress in the NASA Authorization Act of 2005, the purpose of this report is to assess the progress of NASA's Heliophysics Division at the 5-year mark against the NASA goals and priorities laid out in the decadal survey.

In addition to the Integrated Research Strategy, the decadal survey also considered non-mission-specific initiatives to foster a robust solar and space physics program. The decadal survey set forth driving science challenges as well as recommendations devoted to the need for technology development, collaborations and cooperation with other disciplines, understanding the effects of the space environment on technology and society, education and public outreach, and steps that could strengthen and enhance the research enterprise.

**Unfortunately, very little of the recommended NASA program priorities from the decadal survey's Integrated Research Strategy will be realized during the period (2004-2013) covered by the survey. Mission cost growth, reordering of survey mission priorities, and unrealized budget assumptions have delayed or deferred nearly all of the NASA spacecraft missions recommended in**

[1] See Box 1.1 of this report for a detailed description of NASA's Heliophysics Great Observatory.

[2] 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 (hereinafter called the "decadal survey" or the "2003 decadal survey").

**the survey. As a result, the status of the Integrated Research Strategy going forward is in jeopardy, and the loss of synergistic capabilities in space will constitute a serious impediment to future progress.**

Some of these factors were largely outside NASA's control, but as the assessments in Chapter 2 of this report detail, many factors were driven by subsequent NASA decisions about mission science content, mission size, and mission sequence. Overcoming these challenges, as well as other key issues like launch vehicle availability, will be critical if NASA is to realize more of the decadal survey's priorities over the next 5 years as well as priorities in solar and space physics research in the long term. Chapter 3 of this report provides recommendations about how NASA can better fulfill the 2003 decadal survey and improve future decadal surveys in solar and space physics.

## ASSESSMENT

In Chapter 2 of this report the Committee on Heliophysics Performance Assessment evaluates NASA's progress against the 2003 decadal survey recommendations. To make its assessment, the committee employed the following grading system:

A—Achieved or exceeded the goal established in the decadal survey.
B—Made significant progress toward the goal.
C—Made some progress toward the goal.
D—Made little progress toward meeting the decadal goal.
F—Made no progress toward meeting the decadal goal or actually regressed from it.

The committee developed a summary finding to support each grade in this report. Chapter 2 provides additional information supporting each grade, including restatements of the specific recommendations from the decadal survey and a more detailed assessment of the NASA program response to those recommendations.

Table S.1 summarizes the committee's assessment, which consists of 21 grades, divided into seven area assessments covering each chapter of the 2003 decadal survey and 14 program assessments covering the NASA program priorities recommended in the decadal survey.

### Area Assessments

Seven of the committee's grades correspond to the seven chapters in the decadal survey, which covered the following areas:

1. Milestones and Science Challenges
2. Integrated Research Strategy
3. Technology Development
4. Connections Between Solar and Space Physics and Other Disciplines,
5. Effects of the Solar and Space Environment on Technology and Society
6. Education and Public Outreach (E/PO)
7. Strengthening the Solar and Space Physics Research Enterprise.

TABLE S.1 Committee Assessment of NASA Progress Over 5 Years Against Recommendations Made in the 2003 Solar and Space Physics Decadal Survey

| Area or Program | Grade |
|---|---|
| Area[a] | |
| Milestones and Science Challenges | B |
| Integrated Research Strategy | C |
| Technology Development | C |
| Connections Between Solar and Space Physics and Other Disciplines | F |
| Effects of the Solar and Space Environment on Technology and Society | C |
| Education and Public Outreach | C |
| Strengthening the Solar and Space Physics Research Enterprise | C |
| Program[b] | |
| Solar Probe | A |
| Magnetospheric Multiscale | B |
| Geospace Network | D |
| Jupiter Polar Mission | B |
| Suborbital Program | B |
| Explorer Program | C |
| Small Programs | A |
| Vitality Programs | B |
| Supporting Research and Technology | C |
| Coupling Complexity Initiative | C |
| Solar and Space Physics Information System | A |
| Guest Investigator Program | A |
| Theory and Data Analysis Program | B |
| Virtual Sun | B |

[a]Decadal survey chapters and areas in which recommendations were made.
[b]NASA programs recommended in Chapter 3, "Integrated Research Strategy for Solar and Space Physics," of the decadal survey.

The committee provided a summary grade of NASA's progress against the recommendations made in each chapter of the decadal survey. The grades and findings for each of these areas are as follows:

**Milestones and Science Challenges**
**Grade: B**

***Finding:*** The highest-level objectives and research focus areas in the NASA Heliophysics Roadmap align with the decadal survey science challenges. However, there are several science questions in the decadal survey—most notably, coronal heating, magnetospheres and ionospheres of other planets, and interaction with the interstellar medium—that receive little or no attention in the roadmap.

**Integrated Research Strategy**
**Grade: C**

***Finding:*** Progress in almost all the programs is seriously compromised by mission cost growth and rescoping and by reductions in funding for programs that provide regular mission opportunities. In addition, decisions to reorder the mission sequence recommended in the decadal survey undermined the Integrated Research Strategy set forth in the decadal survey, which was built around a set of spacecraft missions coordinated to afford opportunities to examine complex, interacting Sun-Earth subsystems from different regions simultaneously. The originally conceived program cannot be recovered before the next decadal survey. Thus, the status of the Integrated Research Strategy going forward is in jeopardy with the potential for loss of synergistic space research capabilities.

**Technology Development**
**Grade: C**

***Finding:*** NASA is planning to add new small and medium launch capabilities and has made some progress in developing advanced spacecraft systems and command-and-control and data acquisition technologies for spacecraft constellations. But NASA's progress in developing solar sails is limited, and NASA has only recently begun studying the feasibility of advanced space nuclear power systems and the availability of the necessary radioactive isotopes. These technologies have been identified as strategic needs for upcoming missions. It is also unclear if the rate of technological progress in spacecraft systems can be sustained in the absence of a replacement for NASA's canceled New Millennium Program, which provided a testbed for new technologies. NASA has also not followed up on decadal survey recommendations regarding advanced scientific instrumentation.

**Connections Between Solar and Space Physics and Other Disciplines**
**Grade: F**

***Finding:*** NASA has taken no specific action on the connections recommendations, which remain valid. However, community interest in interdisciplinary interactions remains strong, and supporting research and technology programs continue to elicit interdisciplinary interest.

**Effects of the Solar and Space Environment on Technology and Society**
**Grade: C**

***Finding:*** NASA/NOAA/NSF joint efforts on modeling and simulations are excellent examples of successful and close interagency coordination. However, the use of scientific spacecraft like NASA's Advanced Composition Explorer for operational purposes by other agencies at L1 is ill-advised and is a potential obstacle to an independent space weather monitoring program.

**Education and Public Outreach**
**Grade: C**

***Finding:*** NASA's E/PO programs are regarded as generally successful, with several notable successes among the mission-associated programs. However, NASA programs have emphasized elementary school and public education despite the decadal survey recommendation that educational efforts should focus on college and university-level training, a goal that remains poorly addressed.

**Strengthening the Solar and Space Physics Research Enterprise**
**Grade: C**

***Finding:*** Some initiatives to strengthen the solar and space physics enterprise have made progress. NASA has processes in place to capitalize on existing research assets, has allocated funding to revitalize the Suborbital Program, includes space physics instruments in Planetary Division missions, and continues to have an open door data policy. However, there has been limited or no progress on other initiatives. Launch capabilities continue to be inadequate, NASA has not undertaken an independent review of its relationship with academia, and some Announcements of Opportunity could better tailor mission rules to mission scope. Moreover, International Traffic in Arms Regulations (ITAR) continue to hamper international cooperation on missions.

## Program Assessments

In its chapter on the Integrated Research Strategy, the decadal survey recommended a prioritized list of programs. The present committee graded NASA's progress on 14 of the recommended programs that have entered formulation or implementation. For NASA programs that were recommended by the decadal survey but have not entered formulation, the committee provided no grade.

**Solar Probe**
**Program Grade: A**

***Finding:*** NASA is to be commended for reconstituting the Solar Probe science definition team and producing a Solar Probe Plus mission implementation plan that could be conducted with a restricted cost profile. Although its mission design is promising, Solar Probe Plus sequencing is in conflict with the decadal survey, which conditioned Solar Probe implementation on the implementation of all the moderate missions recommended in the survey or on a budget augmentation to accelerate Solar Probe implementation. Neither condition has been met. Solar Probe received the highest possible grade due to efforts to control cost via intelligent mission redefinition. However, NASA has compromised the decadal survey's mission sequence by advancing Solar Probe ahead of the fourth (Multi-Heliospheric Probes), fifth (Geospace Electrodynamic Connections), and seventh (Magnetospheric Constellation) moderate-mission priorities identified in the survey, an approach that has reduced the overall grade given to the Integrated Research Strategy.

**Magnetospheric Multiscale**
**Program Grade: B**

***Finding:*** Magnetospheric Multiscale (MMS) is the number-one-priority moderate mission, with a *science focus on reconnection as a fundamental plasma physical process.* MMS is scheduled for launch in 2014 and has an estimated cost of $990 million. The launch date places it outside the timeframe addressed by the decadal survey (2004-2013), and the cost places it well outside the moderate mission category of the decadal survey. Changes in payload capability, launch vehicles, and project requirements have all contributed to the increases in time and cost. Although it is encouraging to see MMS moving forward, its problems have necessitated the re-programming of subsequent moderate missions.

**Geospace Network**
**Program Grade: D**

***Finding:*** As originally conceived, the Geospace Network mission *aimed at exploring the synergy and coupling between the radiation environment in the inner magnetosphere and the underlying ionosphere and thermosphere, key regions for space weather effects.* It has not been implemented, and the present plan essentially eliminates it from consideration.

**Jupiter Polar Mission**
**Program Grade: B**

***Finding:*** Although there are some limitations due to mission design, instrumentation on the recently selected New Horizons Juno mission will allow the main objectives of the decadal survey Jupiter Polar Mission to be accomplished.

**Suborbital Program**
**Program Grade: B**

***Finding:*** NASA significantly increased its funding request for the Suborbital Program in FY 2009 in response to multiple findings over the years from the community. If passed, this increase appears to be sufficient to bring the support level back above the critical threshold for a viable program. This increased support for operational engineering, infrastructure, and inventory is in line with the relevant recommendation from the decadal survey. Meeting the decadal survey recommendation for a revitalized Suborbital Program will also require an increase in science investigations to take advantage of the increased flight rate.

**Explorer Program**
**Program Grade: C**

***Finding:*** The Explorer Program is characterized by high science return and a minimum of cost overruns and mission expansion. However, reductions in Explorer Program funding have reduced the mission flight rate from one or more missions per year at the time of the decadal survey to one mission every 4 years, with serious implications for the vitality and balance of programs within the Heliophysics Division. The reinstatement of the Small Explorer and Mission of Opportunity competition in 2007 reversed a downward trend but has not restored funding to levels assumed by the decadal survey.

**Small Programs**
**Program Grade: A**

***Finding:*** Significant enhancements to scientific productivity in heliophysics are being achieved with relatively small resource commitments, including NASA cooperation on the European Space Agency's Solar Orbiter mission.

**Vitality Programs**
**Program Grade: B**

***Finding:*** Although some of the specific initiatives recommended by the decadal survey were not undertaken, NASA's Research and Analysis budget has effectively addressed the needs of present and future flight programs while continuing to foster new ideas and innovation.

**Supporting Research and Technology**
**Program Grade: C**

***Finding:*** The decadal survey recommended that funding for the Supporting Research and Technology (SR&T) program be increased to maximize the productivity of existing resources and ensure a sound foundation for the development of future programs. However, funding for this key activity was severely cut in FY 2006. In FY 2008, funding amounts have only recovered to their levels at the time of the decadal survey.

**Coupling Complexity Initiative**
**Program Grade: C**

***Finding:*** No federal agency has led the way in creating new, interagency theory and modeling programs, such as the Coupling Complexity Initiative recommended by the decadal survey. However, within constrained budgets, NASA has supported the development of some portion of these activities through existing programs, such as its Targeted Research and Technology (TR&T) and its Community Coordinated Modeling Center (CCMC).

**Solar and Space Physics Information System**
**Program Grade: A**

***Finding:*** The capabilities of a Solar and Space Physics Information System are being realized through the CCMC and the emerging capabilities of virtual observatories. However, these projects are in their infancy, and continuous, careful examination should be undertaken to identify needed capabilities and specific weaknesses that could hamper their productivity.

**Guest Investigator Program**
**Program Grade: A**

***Finding:*** The importance of the Guest Investigator Program *in maximizing scientific returns from mission data sets and from the Heliophysics Great Observatory by broadening the types and range of scientific* *investigations* is well recognized by NASA, and funding has been increased to maximize the program's effectiveness.

**Theory and Data Analysis Program**
**Program Grade: B**

***Finding:*** The Heliophysics Theory and Data Analysis Program has labored under an inflationary funding profile. To fulfill its mission of supporting groups of critical mass without increasing resources, the number of awards made every 3 years has been decreased. While such funding at least stems deterioration of capabilities in theory and modeling, it cannot foster the bold advances envisioned by the decadal survey.

**Virtual Sun**
**Program Grade: B**

***Finding:*** While no new program element has been created in response to the Virtual Sun recommendation, which proposes an interagency program to develop the theoretical and modeling framework to represent the major elements of the Sun-Earth system, some of the recommendation's objectives have been achieved through existing programs. Living With a Star (LWS) TR&T, for example, supports elements of Virtual Sun that will eventually lead to improvements in space weather applications.

## RECOMMENDATIONS

In addition to assessing NASA's progress against the decadal survey recommendations, the committee was charged with delivering recommendations that can optimize the value of NASA's heliophysics programs without altering the priorities and recommendations of the 2003 decadal survey and that can improve the next decadal survey. Based on the information and grades provided in Chapters 1 and 2 of this report, the committee makes nine recommendations and offers eight guidelines.

### Recommendations to Fulfill the Integrated Research Strategy

The central recommendation of the decadal survey was the Integrated Research Strategy. Although it would be extremely difficult now to restore all of the content anticipated in the Integrated Research Strategy, the committee makes five recommendations that could help restore key features before the end of the decade.

**Recommendation 1:** (a) If no budget augmentation is forthcoming that is large enough to support the planned Solar Probe launch date of 2017 without impacting other Heliophysics Division missions, NASA should consult with the community through a formal review mechanism (such as committees of the NASA Advisory Council or other independent, external, community priority-setting bodies) to determine Solar Probe's priority relative to that of other decadal survey recommendations and its launch date.
(b) An implementation plan for the science objectives of the Geospace Network that includes both ionosphere-thermosphere and magnetosphere components should be developed as soon as possible in advance of lower-ranked moderate missions in the 2003 decadal survey's recommended mission queue.

**Recommendation 2:** Funding for the Heliophysics Explorer Program should be restored to recommended levels as rapidly as possible. The ramp-up in the current 5-year-projection budget is encouraging and should be accelerated as soon as possible.

**Recommendation 3:** Funding for the Solar-Terrestrial Probes flight program should be restored to enable the recommended coordination of investigations.

**Recommendation 4:** Future Solar-Terrestrial Probes and Living With a Star missions should reduce mission requirements that exceed those assumed in the decadal survey to match resource constraints.

**Recommendation 5:** The mission management mode (principal-investigator-led versus center-led) on future Solar-Terrestrial Probe and Living With a Star missions should match resource constraints. Changes in management mode and in associated overhead costs that depart from the original decadal survey should be matched by changes in mission budgets.

## Other Recommendations to Fulfill the Decadal Survey

In addition to the Integrated Research Strategy, the 2003 decadal survey provided guidance on science challenges and made other recommendations on technology development, societal effects, education and public outreach, and supporting activities. The committee makes four recommendations to improve NASA's execution of the decadal survey recommendations in these areas.

**Recommendation 6:** NASA's mission roadmapping activities should seek to retain the balance and synergy of the decadal survey's Integrated Research Strategy.

**Recommendation 7:** NASA should continue to aggressively pursue the recovery of a range of launch capabilities, including replacement or restoration of the Delta II medium-lift launch vehicle, secondary payload capabilities, and access to foreign launch capabilities.

**Recommendation 8:** The future of key measurements at L1 needs to be resolved between NASA and NOAA at the earliest possible time.

**Recommendation 9:** NASA should emphasize the involvement of undergraduate and graduate students in educational outreach grants. NASA should also consider restoring facilitator positions for coordinating educational outreach efforts between researchers, and NASA and should improve the coordination of education efforts between NASA's Heliophysics Division and its Office of Education.

## Guidance to Improve the Next Decadal Survey

The committee provides eight guidelines to improve the quality of the next decadal survey in solar and space physics. These guidelines are not formal recommendations to NASA, but they do give important advice for negotiating the statement of task for the next decadal survey and its committee.

**Guideline 1:** Schedules for future NASA roadmapping exercises should be phased to follow future NRC decadal surveys and midterm assessments.

**Guideline 2:** The next decadal survey should reconsider any missions from the 2003 decadal survey that have not begun development at the time of the next decadal survey.

**Guideline 3:** The next decadal survey should incorporate cost thresholds beyond which NASA must consult with the community through a formal mechanism (such as committees of the NASA Advisory Council or other independent, external, community priority-setting bodies) to review a mission's continued priority.

**Guideline 4:** The next decadal survey should develop a methodology to preserve mission coordination when the importance of mission coordination is equal to or greater than the importance of the missions themselves.

**Guideline 5:** In addition to refining cost estimates for mission development, the next decadal survey should improve cost estimates for mission operations and data analysis.

**Guideline 6:** The next decadal survey should explicitly budget for all recommendations, not just those associated with missions, MO&DA, and research.

**Guideline 7:** The next decadal survey should maintain the practice of providing a prioritized consensus list of program recommendations.

**Guideline 8:** The next decadal survey should include a sufficient number of scientists with spaceflight investigation experience from each of the relevant subdisciplines.

# 1

# Introduction and Background

## THE FIELD OF SOLAR AND SPACE PHYSICS

Understanding the origins and manifestations of solar variability and the influence of the Sun on Earth's atmosphere and geospace is a scientific pursuit driven both by intellectual inquiry and by societal needs. From ancient records of solar eclipses to medieval observations of sunspots and solar prominences during eclipse to Renaissance estimates of the Sun's mass, solar physics has been a human endeavor for thousands of years, satisfying curiosity about how our nearest star works. Studies of Earth and its environment occurred in parallel, from ancient to modern times, with speculations and later key discoveries about the terrestrial magnetic field, the aurora, and meteors as atmospheric phenomena. While linkages between solar physics and geophysics were made in the nineteenth century, the physics-based field of solar-terrestrial relationships was born early in the twentieth century. At mid-century, the first space age satellites were launched and space physics changed forever our view of geospace.

Today, the once separate fields of *solar physics* and *space physics* now strive jointly to understand how changes in the Sun and the solar wind cause changes in the ionospheres, thermospheres, and magnetospheres surrounding Earth and other planets, as well as the heliosphere that marks the boundaries of our solar system. While changes in the total solar radiative output are small, the energetic photons (x rays and extreme ultraviolet light) and the highly variable particles and fields that escape the Sun can have profound effects on the space environment. Together, solar and space physics offer a pathway to the critical understanding of this highly coupled natural system. In addition, it addresses how the Sun's radiation and space plasmas can affect life and technology on Earth, as well as the health of human and robotic space explorers beyond Earth.

The interdisciplinary, interagency, and international enterprise of modern solar and space physics involves observing platforms in space, in the atmosphere, and on the ground that support a range of research, from fundamental, curiosity-driven investigations to predictive space weather applications. The field draws on the expertise of research physicists, instrument builders, technologists, and spacecraft engineers. In the United States, the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) support the field's space- and ground-based research, while the National Oceanic and Atmospheric Administration (NOAA) applies these and other resources to deliver space weather forecasts for users in the government and private sector. Research teams often include international contributions, with foreign instruments mounted on U.S. research platforms and vice versa. By drawing on this large set of talent and resources, the research community is able to make progress in understanding the complex and highly nonlinear phenomena that comprise solar and space physics.

## NASA'S HELIOPHYSICS DIVISION

NASA's Heliophysics Division, one of four divisions that make up NASA's Science Mission Directorate (SMD), is responsible for managing NASA's solar and space physics activities. In fiscal year (FY) 2008, SMD had a total budget of $4.7 billion, of which $561 million (or 12 percent) was allocated to the Heliophysics Division. The Heliophysics Division is responsible for operating 18 space-based research missions, the ongoing development of another five space-based research missions, a program of suborbital rocket- and balloon-borne research missions, and sound theoretical programs, data analysis, research, and technology development to motivate and support these missions.

The Heliophysics Division manages these assets and activities through four programs:

- *Living With a Star.* Living With a Star (LWS) is an applied research program that seeks to understand how and why the Sun varies; how Earth, the solar system, and the heliosphere respond; and how this variability and response affect humanity. Through improved understanding of solar variability and its effects, LWS seeks to create a reliable, predictive capability for space weather. The Solar Dynamics Observatory (SDO) and a Radiation Belt Storm Probes (RBSP) mission, both under development, and Solar Probe Plus, under design, are the first three missions in the LWS program.
- *Solar-Terrestrial Probes.* Solar-Terrestrial Probes (STP) is a directed research program that seeks to understand the Sun-Earth connection, targeting the least understood links in the chain of plasma processes that operate from the Sun to Earth's environment. The first STP mission, the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission, launched in 2001, followed by the Solar Terrestrial Relations Observatory (STEREO) and Hinode (Solar-B) missions in 2006. They will be followed by the Magnetospheric Multiscale (MMS) mission, still under development.
- *Heliophysics Explorer Program.* The Heliophysics Explorer Program funds competitively selected, principal investigator–managed missions to provide frequent, relatively low-cost flight opportunities for world-class investigations across the entire range of fundamental solar and space physics research. The Explorer Program is NASA's oldest space science program, with dozens of successful missions starting with Explorer 1, the first successful U.S. satellite. Recent Heliophysics Explorer missions include the Two Wide-angle Imaging Neutral-atom Spectrometers B (TWINS-B); the Aeronomy of Ice in the Mesosphere (AIM) mission; the Interstellar Boundary Explorer (IBEX); and the Coupled Ion Neutral Dynamics Investigation (CINDI), a mission of opportunity instrument flown on a DOD satellite mission (see Box 2.1).
- *Heliophysics Research Program.* The Heliophysics Research Program undertakes scientific investigations using operational space-based platforms developed under the LWS, STP, and Explorer Programs, as well as suborbital platforms managed by the Research Program, including rockets, balloons, and aircraft. The Research Program also supports the ongoing operations of Heliophysics Division spacecraft, research and analysis grants (including theory), supporting research and technology, sounding rockets, and science data archiving and computing.

## THE DECADAL SURVEY

The solar and space physics research community and its major supporters at NASA, NOAA, and NSF have worked together over the decades to determine the science goals and direction of the field. Adopting the model of decadal surveys used successfully by the astronomy and astrophysics community since the 1960s, the National Research Council (NRC) through the Space Studies Board produced in 2003 the first 10-year strategy for solar and space physics, *The Sun to the Earth—and Beyond: A Decadal*

*Research Strategy in Solar and Space Physics*[1] (hereinafter the "decadal survey"). The 2003 decadal survey was derived from the deliberations of five discipline panels:

- The Sun and the heliosphere,
- The solar wind and magnetosphere interactions,
- Atmosphere-ionosphere-magnetosphere interactions,
- Theory, modeling, and data exploration, and
- Education and society.

For the decade 2003 to 2013, the survey identified five science challenges that would advance understanding of solar and space physics.

- *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.
- *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.
- *Challenge 3.* Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.
- *Challenge 4.* Understanding the basic physical principles manifest in processes observed in solar and space plasmas.
- *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.

To address these challenges, the decadal survey developed an integrated strategy to advance the relevant physical theories, incorporate those theories in models that describe a system of interactions between the Sun and the space environment, obtain data on the system, and analyze and test the adequacy of the theories and models. This integrated strategy was embodied by the core recommendation in the second chapter of the decadal survey—a prioritized list of flight missions and theory and modeling programs.

NASA's responsibilities under the integrated strategy included launching three space-based research missions (Solar B, STEREO, and the SDO), launching or starting development of 10 new space-based research missions during the upcoming decade (MMS, Geospace Network, Global Electrodynamic Connection, Jupiter Polar Mission (JPM), Solar Orbiter, Multi-Heliospheric Probes, Stereo Magnetospheric Imager, Magnetospheric Constellation (MagCon), Solar Probe, and Solar Wind Sentinels), and continuing investments in small space-based (Explorer Program) and suborbital research missions, mission operations and data analysis, and supporting research and technology. The integrated research strategy categorized these activities by cost into large, moderate, small, and vitality categories and prioritized activities within and across each category (see Table 1.1). The decadal survey generated a budget based on NASA's cost estimates for these activities that was phased to maximize opportunities for concurrent observations of the same solar and space physics phenomena by multiple spacecraft. These coordinated investigations were a key aspect of the decadal survey's integrated research strategy, later termed the "Heliophysics Great Observatory" by NASA (see Box 1.1).

The decadal survey also considered non-mission-specific initiatives that foster the development of a robust program in solar and space physics. Chapters 3 through 7 of the decadal survey set forth recommendations devoted, respectively, to the need for technology development, the advantages that

[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.

accrue through collaborations and cooperation with other disciplines, the effects of the space environment on technology and society, the need for education and public outreach for solar and space physics, and steps that could strengthen and enhance the program.

TABLE 1.1 Priority Order of Programs Recommended in the 2003 Solar and Space Physics Decadal Survey

| Type of Program | Rank | Program | Responsible Agency |
|---|---|---|---|
| Large | 1 | Solar Probe | NASA |
| Moderate | 1 | Magnetospheric Multiscale | NASA |
| | 2 | Geospace Network | NASA |
| | 3 | Jupiter Polar Mission | NASA |
| | 4 | Multispacecraft Heliospheric Mission | NASA |
| | 5 | Geospace Electrodynamic Connections | NASA |
| | 6 | Suborbital Program | NASA |
| | 7 | Magnetospheric Constellation | NASA |
| | 8 | Solar Wind Sentinels | NASA |
| | 9 | Stereo Magnetospheric Imager | NASA |
| Small | 1 | Frequency-Agile Solar Radiotelescope | NSF |
| | 2 | Advanced Modular Incoherent Scatter Radar | NSF |
| | 3 | L1 Monitor | NOAA |
| | 4 | Solar Orbiter | NASA |
| | 5 | Small Instrument Distributed Ground-Based Network | NSF |
| | 6 | University-Class Explorer | NASA |
| Vitality | 1 | NASA Supporting Research and Technology | NASA |
| | 2 | National Space Weather Program | NSF-led/multiagency |
| | 3 | Couple Complexity | NASA/NSF |
| | 4 | Solar and Space Physics Information System | Multiagency |
| | 5 | Guest Investigator Program | NASA/NSF |
| | 6 | SEC Theory and LWS Data, Analysis, Theory and Modeling | NASA/NSF |
| | 7 | Virtual Sun | Multiagency |

**BOX 1.1**
**NASA's Heliophysics Great Observatory and the Decadal Survey's Integrated Research Strategy**

The investigation of solar system plasmas as coupled nonlinear systems requires synergy between observational and theoretical initiatives and between basic research and targeted research programs. NASA recognized this in establishing the fleet of twelve missions—consisting of Advanced Composition Explorer (ACE), Solar and Heliospheric Observatory (SOHO), and Wind in L1 orbit and Cluster, Transition Region and Coronal Explorer (TRACE), Ramaty High-Energy Solar Spectroscopic Imager (RHESSI), Geotail, Fast Auroral Snapshot Explorer (FAST), Polar, and Thermospere Ionosphere Mesosphere Energetics and Dynamics (TIMED) in Earth orbit, and Ulysses and the Voyager probes—that NASA's Heliophysics Division would later call its Heliophysics Great Observatory. SOHO, TRACE, and RHESSI observe the variable outputs of the Sun; ACE and Wind provide advance information on the disturbances traveling to Earth; Cluster, Geotail, FAST, POLAR, and TIMED observe the resulting space weather responses in the geospace environment; and Ulysses and Voyager measure responses in the heliosphere. The Heliophysics Great Observatory enabled the coordinated investigation of space plasmas as complex coupled systems driven from the Sun to Earth and into the heliosphere, as demonstrated by the observation and analysis of the famous "Halloween" solar storms of 2003.

The decadal survey clearly recognized the mission synergies and balance that underpin the Heliophysics Great Observatory approach: mission selections and priorities in the Integrated Research Strategy were chosen in order to most efficiently maintain and augment such a research approach. The decadal survey anticipated a midterm period where Solar-B, Solar Terrestrial Relations Observatory (STEREO), and Solar Dynamics Observatory (SDO) would be providing more detailed information on the propagation of solar disturbances to Earth, while the Magnetospheric Multiscale (MMS) mission, the Geospace Network, and the Geospace Electrodynamic Connections (GEC) mission would be providing the information needed to understand how the disturbances were processed within the geospace system. Throughout this period the Explorer Program was expected to play a pivotal role in addressing new inquiries and strategic initiatives that would emerge during the conduct of the program. A revitalized sounding rocket program would also continue to provide unique capabilities associated with access to critical regions and diagnosis of small-scale features. However as of this writing, the only two strategic missions to have been successfully implemented are Solar-B (Hinode) and STEREO. SDO and MMS are in development, and the Geospace Network and GEC have not received starts. Only one of the 10 large and moderate missions called for in the decadal survey, Jupiter Polar Mission, (Table 1.1) will be launched by 2013, the end of the 10-year period covered by the strategy. Thus, one of the foremost findings of this report is that the status of the Integrated Research Strategy is in jeopardy and that the loss of synergistic capabilities in space will seriously impede progress in the division.

## THE MIDTERM ASSESSMENT

In the NASA Authorization Act of 2005, the Congress directed NASA, through the National Academy of Sciences, to review and assess each division in the Science Mission Directorate at 5-year intervals. In 2007, the NRC created the Committee on Heliophysics Performance Assessment to study the alignment of NASA's Heliophysics Division with the decadal survey. The committee was specifically tasked with answering three questions, which are addressed in Chapters 2 and 3 of this report:

- How well does NASA's current program address the strategies, goals, and priorities outlined in the decadal survey and other relevant NRC reports? See Section 2.1. The committee has interpreted NASA's "current program" to mean its recommended Heliophysics Roadmap, issued in 2005.[2]
- What progress has been made toward realizing these strategies, goals, and priorities? See Sections 2.2 to 2.7.
- Can any actions be taken to optimize the science value of the program in the context of current and forecasted resources available to it? See Chapter 3.

The committee was directed not to alter the scientific priorities or mission recommendations provided in the 2003 decadal survey but was asked to provide guidance (see Chapter 3) for implementing the recommended mission portfolio in preparation for the next decadal survey. The decadal survey is a positive and welcome development for the field, and this midterm assessment reinforces its recommendations.

## ACCOMPLISHMENTS SINCE THE DECADAL SURVEY

Since the release of the decadal survey, NASA's Heliophysics Division and the solar and space physics community have advanced on all of the major fronts of the research enterprise, including solar, ionospheric/thermospheric/mesospheric, magnetospheric, and heliospheric physics. Four examples of many notable accomplishments over the past 5 years are as follows:

- *Hinode, SOHO, and STEREO Missions Identify Origins of the Solar Wind.* The solar atmosphere consists of closed magnetic loops anchored to the solar surface at both ends and of open flux tubes extending from the Sun into space. Early models proposed that the solar wind was heated and accelerated strictly within the regions of open magnetic field. An unprecedented complement of spacecraft instrumentation, including NASA's SOHO and its STEREO and the Japanese Hinode mission, has recently revealed that some jets originate from the interfaces between the open and closed magnetic fields, driven by a process called magnetic reconnection (see Figure 1.1).
- *CINDI Mission Maps Baseline for Earth's Equatorial Ionosphere.* CINDI is a NASA mission of opportunity flown on the DOD's Communication/Navigation Outage Forecast System (C/NOFS) satellite, which launched in 2008. The CINDI instruments measure neutral wind and ion drift vectors along with the total ion density, composition, and temperature. Initial data were taken during a time of extremely low solar activity when most of the atmosphere lay below the satellite's altitude. Measurements made by CINDI during that time have revealed the daily expansion and contraction of the ionosphere, using the height at which the densities of the constituent species $O^+$ and $H^+$ were equal as a key ionospheric marker. This information, together with measurements of the ion temperature, provides a baseline from which future variations in solar activity can be recorded (see Figure 1.2.).
- *THEMIS Mission Determines Auroral Brightening Sequence (Magnetosphere).* In 2008, NASA's Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission, part of NASA's Heliospheric Explorer Program, determined the sequencing of magnetic substorms in Earth's magnetotail that are responsible for sudden brightening and expansion of Earth's aurora. The five-spacecraft mission, in combination with ground-based observations, found that magnetic reconnection in the near-tail initiates the substorm and is followed by tailward ejection of plasma and rapid auroral brightening and poleward expansion (see Figure 1.3).
- *Voyager Missions Cross the Termination Shock and Enter Heliosheath (Heliosphere).* In 2004 and 2007, respectively, NASA's Voyager 1 and Voyager 2 missions crossed the heliospheric termination shock, where the solar wind begins interacting with the interstellar medium. The Voyager

[2] NASA, *The New Science of the Sun-Solar System Connection: Recommended Roadmap for Science and Technology 2005-2035,* Washington, D.C., 2005.

spacecraft discovered the termination shock's location at 84 (Voyager 2) and 94 (Voyager 1) astronomical units (AU) from the Sun and ascertained that the termination shock's overall shape is blunt and that it is not a source of anomalous cosmic rays, as had been expected. Instead, the Voyagers identified a new, lower-energy population of particles at the termination shock. Beyond the termination shock, the Voyagers started providing the first data ever on the largest structure in our solar system, the heliosheath, where the solar wind slows to the speed of the interstellar medium. NASA's IBEX mission, launched in 2008, will start providing remote imaging of the termination shock and heliosheath. In coming years, the Voyagers will cross the Sun's hypothesized bow shock and enter interstellar space proper (see Figure 1.4).

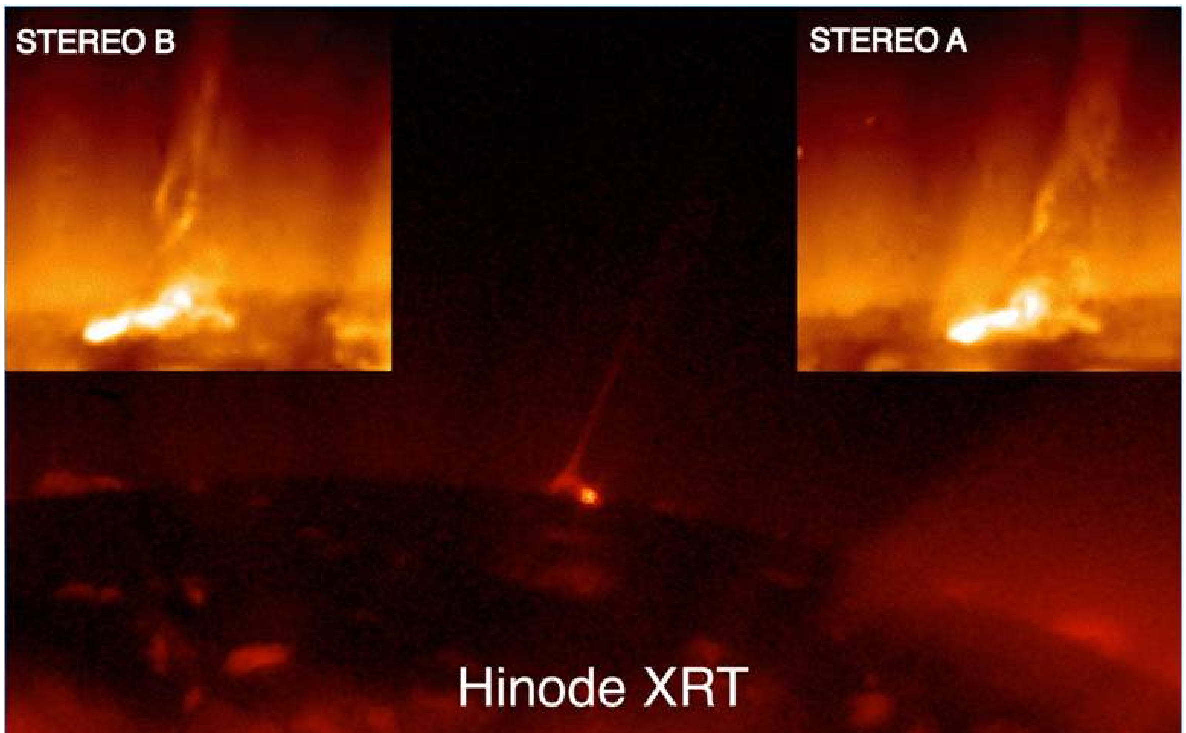


FIGURE 1.1 Coronal jets, a key contributor to the solar wind, observed from different spacecraft. The bottom image, from the X-ray Telescope (XRT) on Hinode, shows jets as small triangular features populating the most northerly latitudes of the Sun. In this region, formerly believed to consist of only open field, reconnection between open and closed fields produces jets in numbers far greater than and with outflow speeds far greater than previously suspected. The two top images show one large jet produced by magnetic reconnection from two different perspectives. The left top image is from the STEREO A spacecraft orbiting the Sun ahead of Earth and the right top image is from the STEREO B spacecraft orbiting the Sun behind Earth. These images of coronal plasma jetting upward reveal its twisted structure as only multiple views truly can. SOURCE: Courtesy of Jonathan Cirtain, NASA Marshall Space Flight Center.

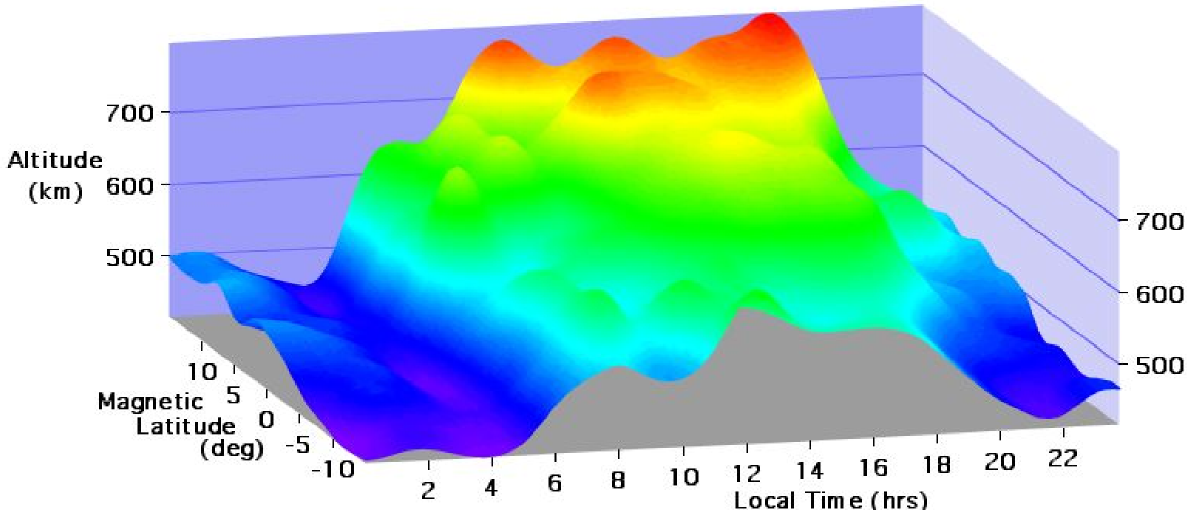


FIGURE 1.2 Spatial distribution of the oxygen/hydrogen ion transition height observed by CINDI during May and June 2008, showing the daily expansion and contraction of the ionosphere. SOURCE: Courtesy of Rod Heelis, William B. Hanson Center for Space Sciences, University of Texas at Dallas.

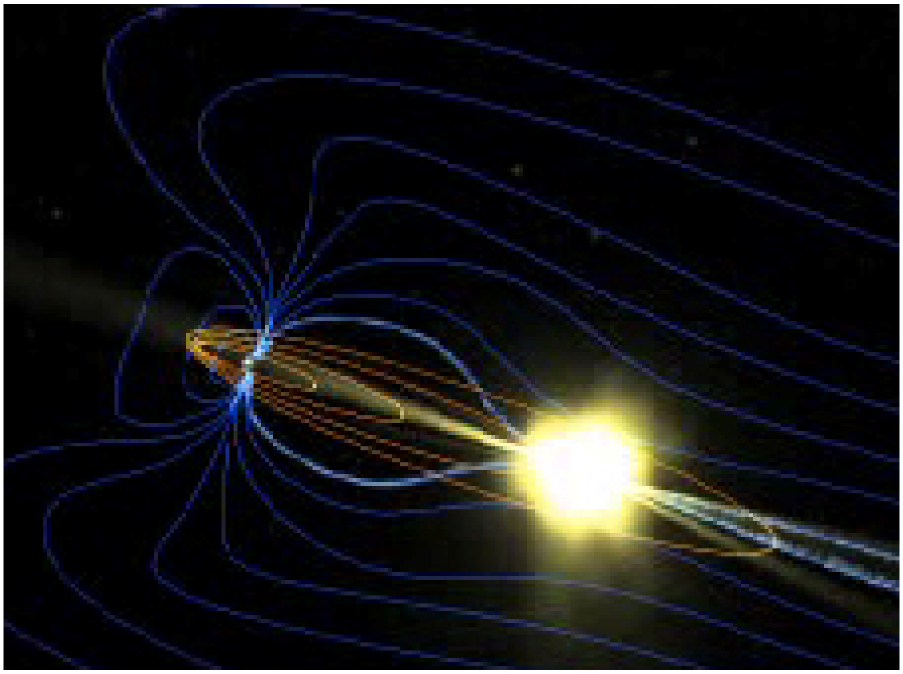

FIGURE 1.3 Artist's concept showing the explosive release of energy generated by magnetic reconnection processes, which are responsible for sudden increases in the brightness and movement of the Northern Lights. SOURCE: Courtesy of NASA.

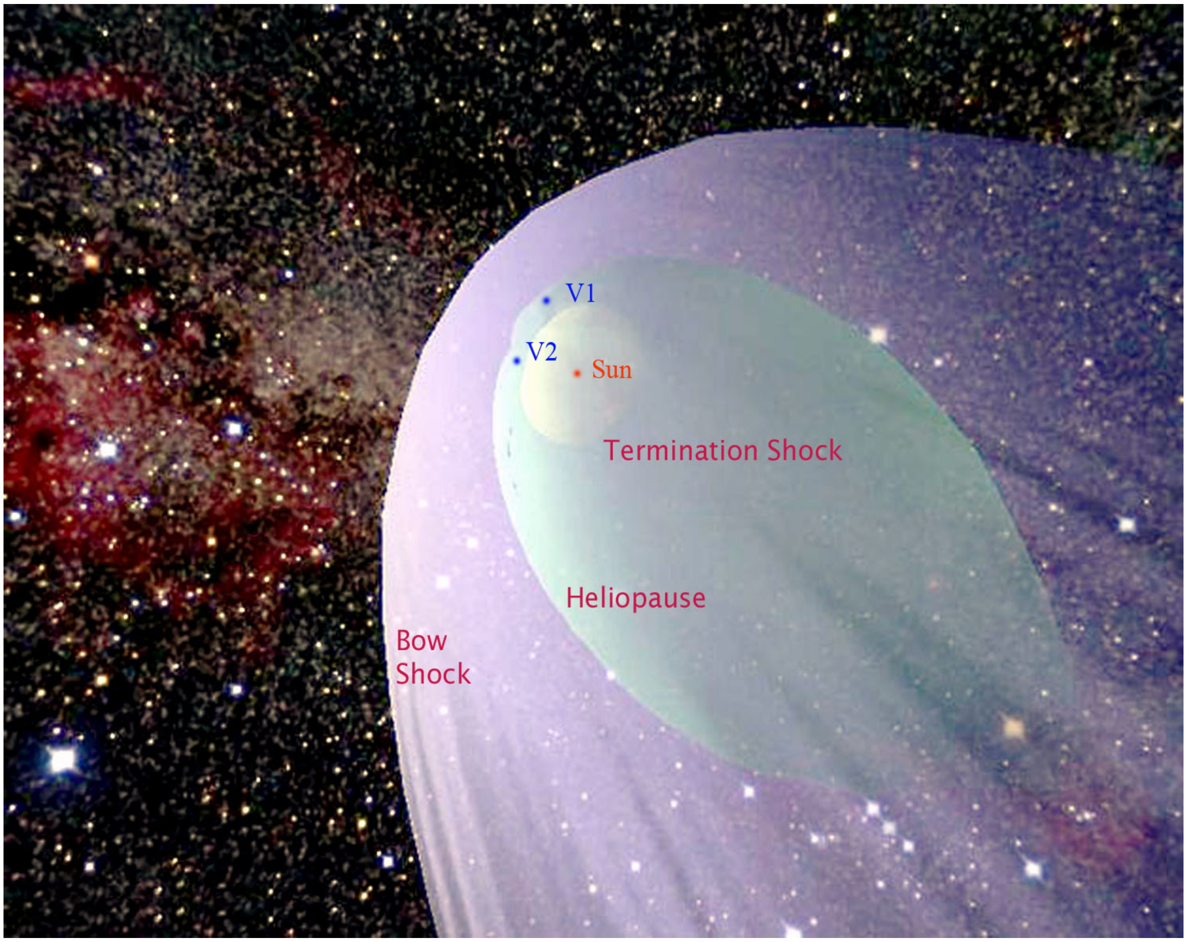


FIGURE 1.4 A schematic of the position of the Voyager 1 and 2 spacecraft (V1 and V2 in the illustration above) as they leave our heliosphere, relative to the termination shock, heliosheath, heliopause, and bow shock.
SOURCE: Courtesy of Jack R. Jokipii, University of Arizona.

## BUDGET CHANGES SINCE THE DECADAL SURVEY

A number of budget-related factors, some within and NASA's control and some outside, have altered NASA's implementation of the decadal survey's recommendations. When assessing the progress of NASA's Heliophysics Division, it is important to understand how the costs and budgets of NASA's solar and space physics programs have changed over the 5 years since the decadal survey was prepared.

Figure 1.5 is the recommended 2003-2013 budget for priority NASA programs in the decadal survey, based on a level Heliophysics Division budget of approximately $650 million per year.[3] The decadal survey anticipated that by early FY 2009, NASA would have made progress as follows:

- Development complete for Solar B, STEREO, and SDO.
- Development of MMS nearly complete.
- Development of the Geospace Network largely complete.

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[3] 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, p. 8.

- Development of Geospace Electrodynamic Connections (GEC) and Jupiter Polar Mission over half complete.
- Development of Solar Orbiter, Multispacecraft Heliospheric Mission (MHM), and SMI well under way.
- Development of MagCon just under way.

Unfortunately, the actual program and budget have not matched the anticipated program or budget. Figure 1.6 is the actual 2003-2008 budget and projected 2009-2013 budget for the same NASA Heliophysics Division programs.

Over the past 6 years, a number of budgetary and cost factors, both within and outside NASA's control, have affected implementation of the integrated research strategy recommended by the decadal survey.

### Cost Growth in Missions Under Development at the Time of the Survey

The 2003 decadal survey endorsed completion of three major NASA missions under development in 2003: Solar-B, STEREO, and SDO. The budget totals for completing Solar-B and STEREO are close to the budgets in the decadal survey. However, the decadal survey assumed that SDO could be completed in 2008 for an additional $315 million. In reality, SDO will require at least $700 million more before its launch in late 2009 or in 2010.

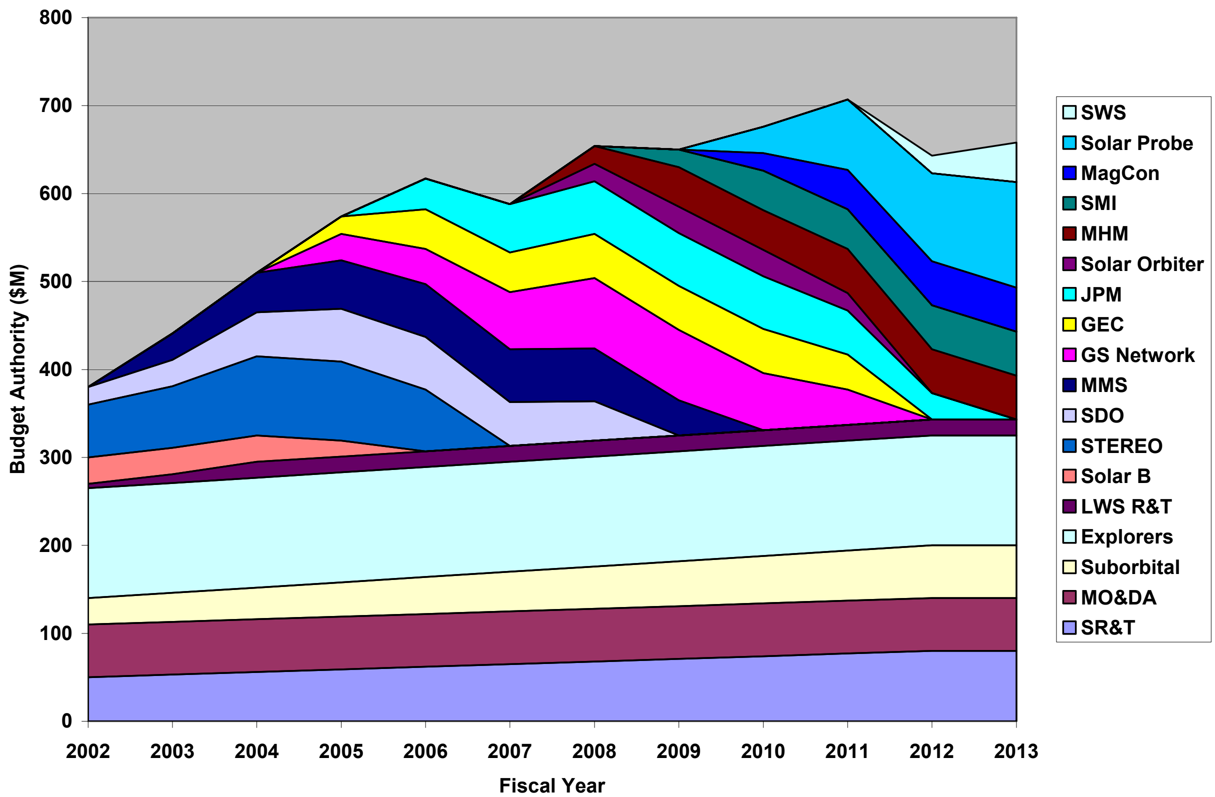


FIGURE 1.5 Recommended budget phasing of NASA programs from the solar and space physics decadal survey. SOURCE: National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* The National Academies Press, Washington, D.C., 2003, p. 8.

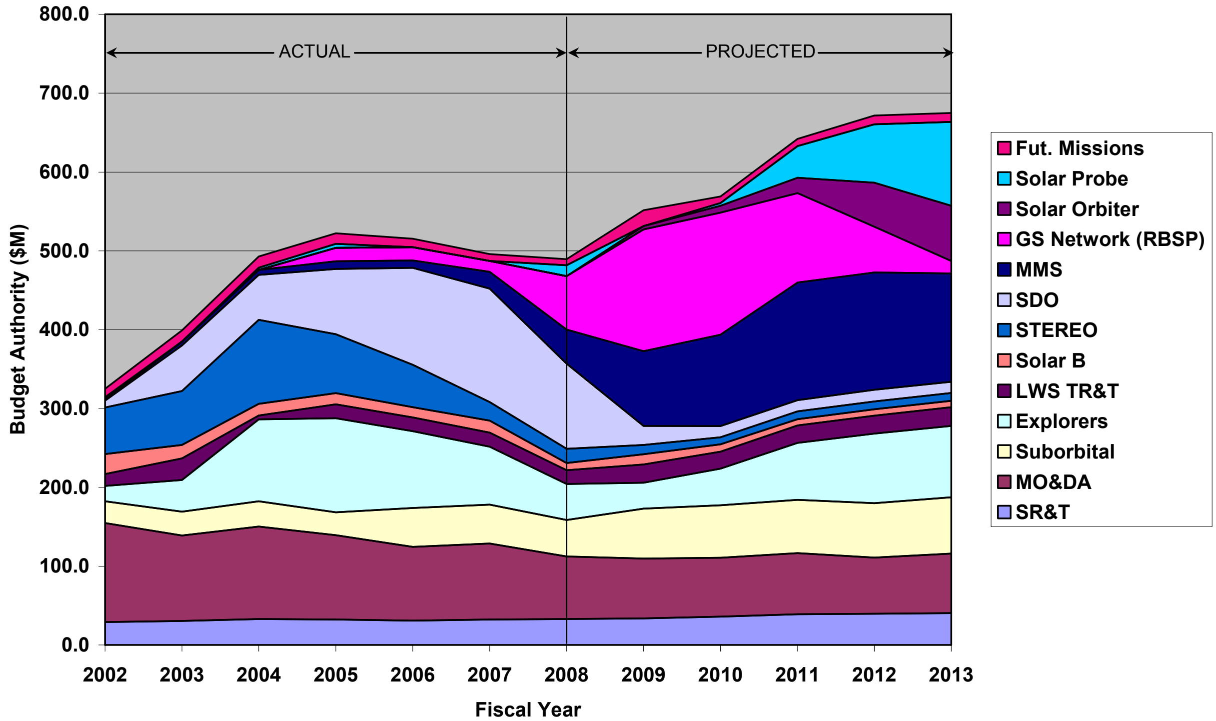


FIGURE 1.6 NASA Heliophysics Division actual and projected budget implementation. SOURCE: Data courtesy of NASA.

### Cost Growth in Development of Missions Recommended in the Survey

The first new NASA mission recommended by the decadal survey, MMS, and an RBSP mission have experienced significant cost growth.

The decadal survey allocated $350 million for MMS development and characterized the level of technical concern associated with its completion as “low.” The latest estimate for MMS is $990 million. Factors leading to MMS’s cost escalation are described in detail in Section 2 of Chapter 2.

Decadal survey costs for the Geospace Network, a mission to investigate energy transfer within and between Earth’s ionosphere and radiation belts, were estimated at $400 million. NASA has yet to start development of the mission as originally intended. Rather an RBSP mission, which by itself does not constitute a complete Geospace Network mission, has been started with an expected cost of more than $600 million. Factors leading to RBSP’s cost escalation are described in detail in Section 2 of Chapter 2.

### Underestimation of Decadal Survey Costs for Mission Operations and Data Analysis

The decadal survey assumed an annual budget of $60 million for Heliophysics Division mission operations and data analysis (MO&DA). Actual costs from FY 2004 to FY 2008 have ranged between approximately $80 million and $120 million and are projected to remain between $70 million and $80 million from FY 2009 to FY 2013.

## Budgets for NASA's Heliophysics Division Did Not Meet Projections

Figure 1.7 shows the actual budget for NASA's Heliophysics Division from FY 2002 to FY 2008, as well as the 5-year projections from the President's FY 2004, FY 2005, and FY 2009 budgets. At the time of the decadal survey, the 5-year profile in the President's FY 2004 budget projected growth from about $800 million in FY 2004 to about $1,250 million in FY 2008. The actual appropriated budget for NASA's Heliophysics Division varied between approximately $710 million and $840 million over the same years, including about $250 million per year in Deep Space Network (DSN) costs that were transferred out of the Heliophysics Division budget starting in FY 2009. Approximately $1.3 billion of the projected growth in the Heliophysics Division budget was eliminated in the President's FY 2005 budget to help fund new human space exploration programs under the Vision for Space Exploration.

The decadal survey did not take the FY 2004 budget projection on faith and instead constructed priorities based on a budget of approximately $650 million per year for FY 2006 and beyond. This budget level included responsibility for funding one decadal survey priority, the JPM, which is now part NASA's Planetary Science Division. After backing out DSN costs, in terms of program content, actual appropriations have been quite close to the $650 million assumed in the survey.

## Reductions in Budgets for Regular Flight Opportunities

The decadal survey assumed an annual budget of $125 million for the Heliophysics Explorer Program to sustain a regular series of opportunities for competitively selected mission investigations. As Figure 1.8 shows the annual budget for Heliophysics Explorers ranged between approximately $50 million and $120 million from FY 2004 to FY 2008. The FY 2008 funding of $50 million is projected to grow to $90 million by FY 2013, including both selected Heliophysics Explorer missions and half of the future Explorer budget for upcoming Explorer competition selections.

The Solar-Terrestrial Probes (STP) budget has undergone similar large swings in funding. In Figure 1.9, it can be seen that the STP budget rose to a level of approximately $140 million in FY 2004, then dropped to approximately $70 million in FY 2008. The STP budget is projected to grow to between $160 million and $170 million by FY 2011 to FY 2013.

These swings in funding have reduced the frequency of Explorer, STP, and overall Heliophysics Division spacecraft missions, decreasing opportunities for scientific investigations. Figure 1.10 shows the launch rate for NASA Heliophysics Division spacecraft missions, which peaked at two to four missions per year in 2006 to 2008 but is projected to decrease to between zero and one mission per year in the 2009 to 2013 timeframe. (Under an ongoing competition whose outcome is not available at the time of this report, NASA may select one or more Heliophysics Small Explorer missions in early 2009 that may launch before 2013.)

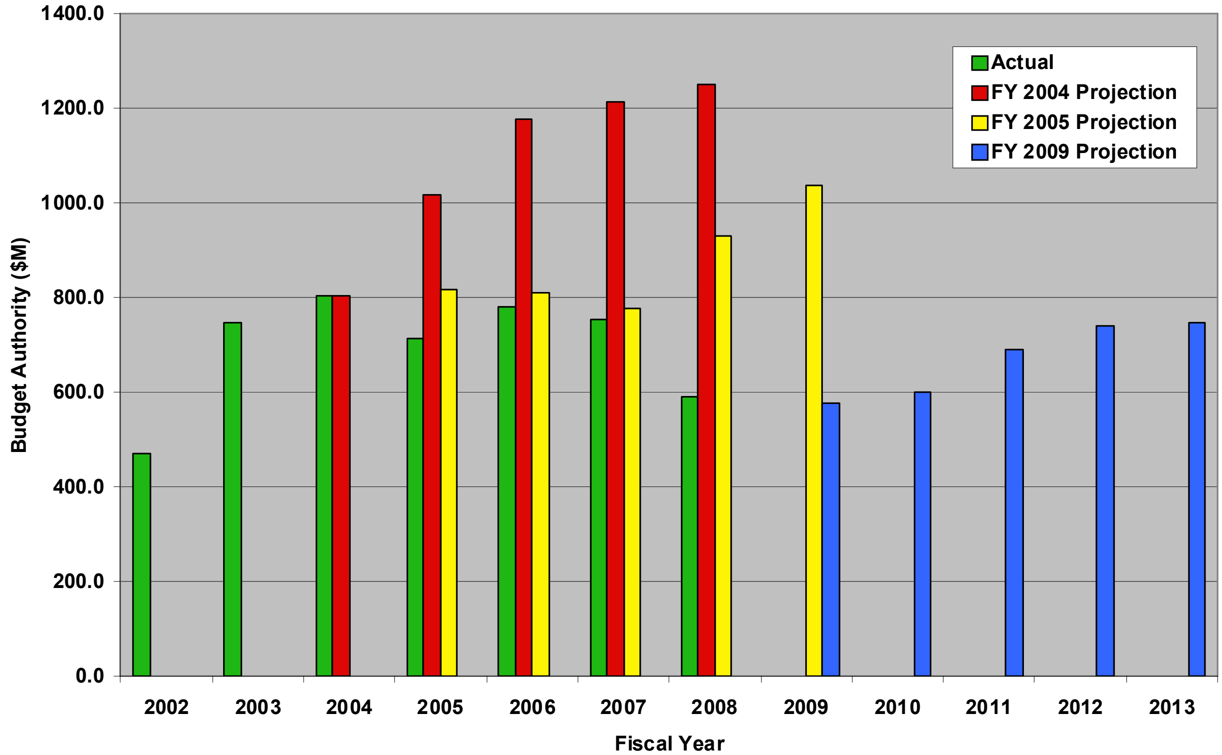


FIGURE 1.7 NASA Heliophysics Division budgets. NOTE: This figure (but not Figures 1.5 and 1.6) has not been normalized for year-to-year changes in full cost accounting methods and includes funding for NASA's Astrophysics Explorer missions. SOURCE: Data courtesy of NASA.

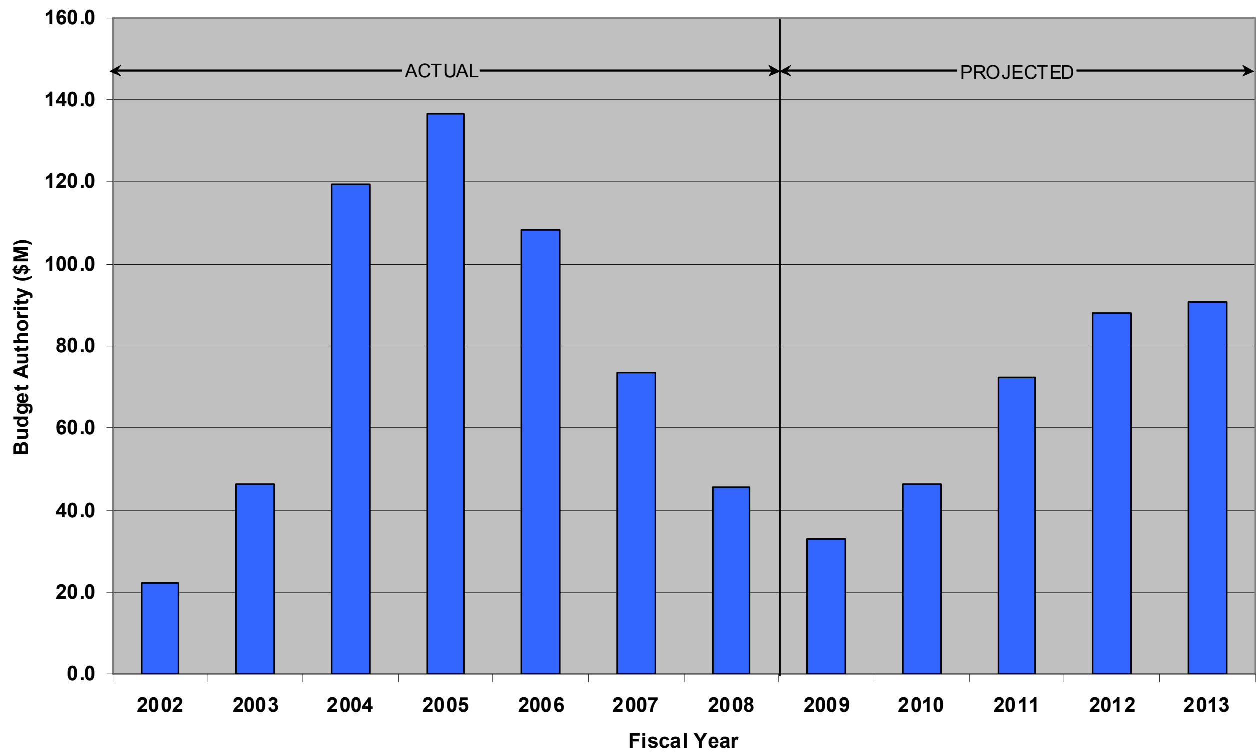


FIGURE 1.8 Heliophysics Explorer Program actual and projected budget, assuming that heliophysics proposals win half of future Explorer Program funding. SOURCE: Data courtesy of NASA.

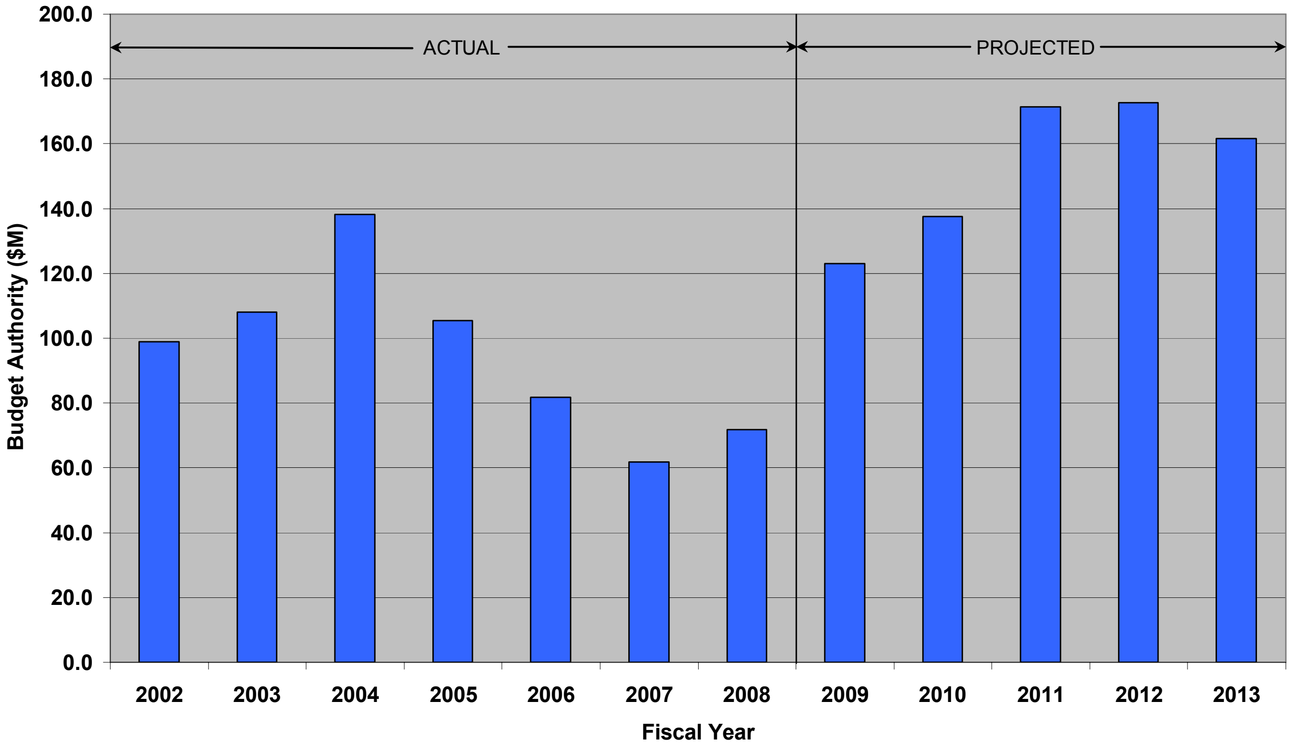


FIGURE 1.9 Solar-Terrestrial Probes actual and projected budget. SOURCE: Data courtesy of NASA.

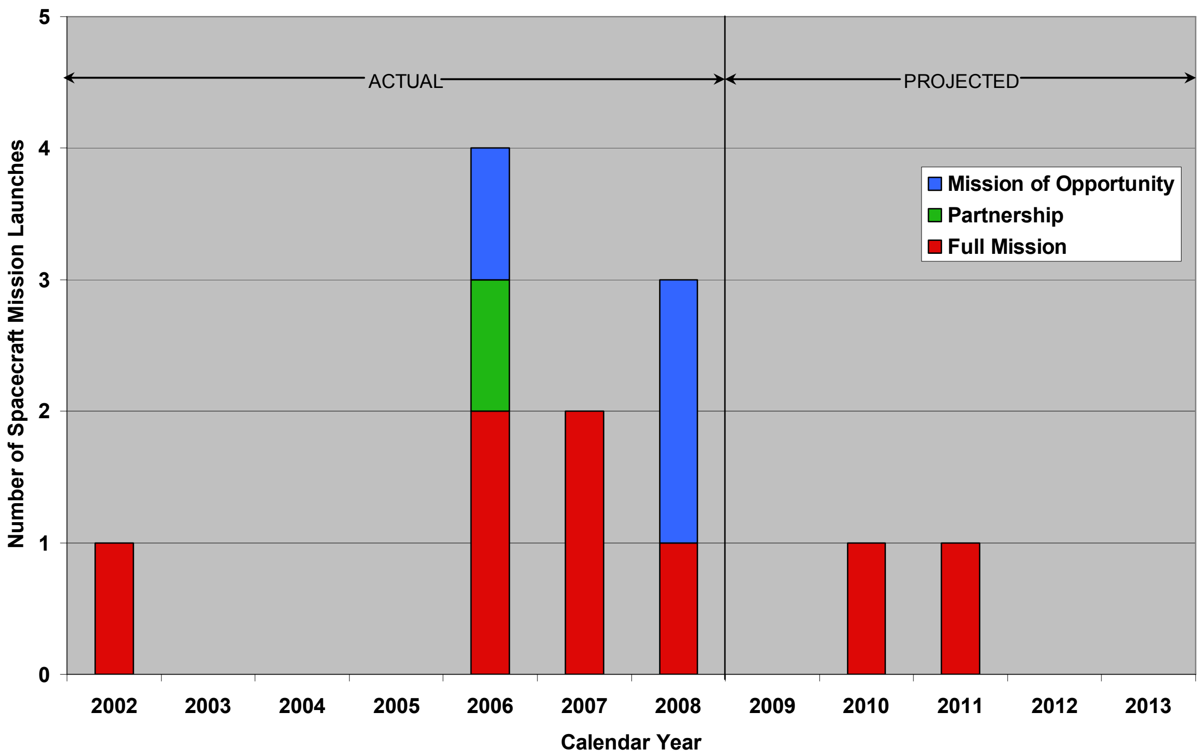


FIGURE 1.10 NASA Heliophysics Division spacecraft mission launch rate. NOTE: In this figure, the 2010 mission is SDO and the 2011 mission is RBSP. SOURCE: Data courtesy of NASA.

## OTHER PROGRAM CHANGES SINCE THE DECADAL SURVEY

In addition to cost growth, underestimated costs, and budget changes, changes in mission priorities, schedules, and launch vehicles have altered NASA's implementation of the decadal survey's recommendations and may continue to do so in the future.

### Reordering of the Mission Sequence Recommended in the Decadal Survey

In the President's FY 2009 budget, NASA proposed advancing the Solar Probe mission ahead of other missions in the 2003 decadal survey's recommended mission sequence. The decadal survey recommended starting Solar Probe, the only mission priority in the large program category, only after additional funding for NASA's Heliophysics Division materialized.[4] NASA has compromised the survey's mission sequence by advancing Solar Probe ahead of the fourth, MHM, the fifth, GEC, and the seventh, MagCon, moderate mission priorities identified in the survey, none of which has begun development. NASA has also begun an apparent reformulation of MHM and Solar Wind Sentinels (SWS), the eighth-ranked moderate mission priority in the survey, ahead of a clear execution plan for MHM, GEC, and MagCon.

### Schedules Delays and Deferments for Missions Recommended in the Survey

Nearly all of moderate NASA space missions recommended in the decadal survey have seen multiyear delays (MMS from 2010 to 2014) or have been indefinitely deferred (Geospace Network, MHM, GEC, MagCon, and Stereo Magnetospheric Imager [SMI]). These delays and deferrals reduce opportunities for concurrent and synergistic observations, seriously compromising the decadal survey's integrated strategy, especially in terms of the Heliophysics Great Observatory.

### Reduction in Range of Available Launch Vehicles

Historically, the Heliophysics Division has relied heavily on small and medium-sized spacecraft launched on small- (Pegasus) and medium-class (Delta II) launch vehicles. The decadal survey's moderate spacecraft mission recommendations assumed availability of a medium-class launch capability. In the past, MIDEX missions in the Explorer Program, such as the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) and THEMIS, have also used medium-class launches.

With the migration of the Air Force's Global Positioning Satellite spacecraft from the Delta II launch vehicle to the Evolved Expendable Launch Vehicles, the long-term outlook for the Delta II launch vehicle line is in doubt, and it could be retired as early as 2012. Unless a means of extending its life or replacing the Delta II line at reasonable cost is found, the Heliophysics Division will have no capability for launching medium-sized spacecraft. This will either force a migration of these missions to larger launch vehicles, with associated increases in launch and mission costs, or force a dramatic change in the implementation plan for the presently recommended program.

[4] 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, p. 8.

### Division Name Change

Since the decadal survey, the title of the division within NASA's Science Mission Directorate responsible for carrying out the survey changed, from the Solar and Space Physics Division to the Heliophysics Division. Both the decadal survey and the work of the Heliophysics Division address the full breadth of the solar and space physics field, including solar, magnetospheric, ionospheric, thermospheric, mesospheric, and heliospheric physics. However, as noted by NASA's Geospace Mission Operations Working Group, the wording "Heliophysics Division" can be misconstrued to mean a more limited emphasis on the study of solar physics. This runs the risk that the field's actual scope and the integrated nature of much of the field's current research will not be well represented to the world at large beyond NASA.

## CHALLENGES TO FUTURE PROGRESS

Over the past 5 years, NASA investments in the missions that would later comprise the Heliophysics Great Observatory and other research activities prior to the decadal survey continue to pay high dividends, enabling breakthrough discoveries that result in a better and deeper understanding of how various coupled, nonlinear systems drive changes in space plasmas from the Sun to Earth and into the heliosphere. The decadal survey built on this model of research and recommended an Integrated Research Strategy that sought to extend and augment the Heliophysics Great Observatory as well as to enhance NASA's other solar and space physics research and supporting activities. But as Chapter 1 has shown, very little of the recommended NASA priorities from the decadal survey will be realized during the period covered by the survey. Mission cost growth, reordering of survey mission priorities, and unrealized budget assumptions have delayed or deferred nearly all of the NASA missions recommended in the survey. Some of these factors were largely outside NASA's control, but as the assessments in Chapter 2 detail, many were driven by subsequent NASA decisions about mission science content, mission size, and mission sequence. Overcoming these challenges, as well as other key issues like launch vehicle availability, will be critical if NASA is to realize more of the decadal survey's priorities over the next 5 years and to succeed in its solar and space physics research enterprise over the long term. Chapter 3 provides recommendations about how NASA can better fulfill the 2003 decadal survey and improve future decadal surveys in solar and space physics.

# 2

# Assessment

Chapter 2 assesses the Heliophysics Division's program to address the strategies, goals, and priorities of the decadal survey and progress toward realizing them. The sections in this chapter match the chapters of the 2003 solar and space physics decadal survey[1] (the "decadal survey"), which contain specific recommendations to NASA. For example, Section 2.1 assesses the contributions that the present program has made to the scientific challenges put forth in Chapter 1 of the decadal survey. The committee has provided an overall grade for each section, followed by a finding that is related to the grade, and then a restatement of specific recommendations in the corresponding decadal survey chapter and a more detailed assessment of the NASA program response to these recommendations. The committee used the following grading system:

A—Achieved or exceeded the goal established in the decadal survey.
B—Made significant progress toward the goal.
C—Made some progress toward the goal.
D—Made little progress toward meeting the decadal goal.
F—Made no progress toward meeting the decadal goal or regressed from it.

## 2.1 MILESTONES AND SCIENCE CHALLENGES

Chapter 1 of the decadal survey contains no specific recommendations but provides five science challenges that drive the priorities and recommendations in the rest of the survey. NASA also employs a more detailed list of scientific objectives from its triennial heliophysics roadmapping exercise to further define missions and other research activities. NASA's last roadmap, released in 2005, is titled *The New Science of the Sun-Solar System Connection: Recommended Roadmap for Science and Technology 2005-2035.*[2] The committee compared the decadal survey and its science challenges with the Roadmap and its objectives and research focus areas (RFAs).

**Grade: B**

***Finding:*** The highest-level objectives and research focus areas in the NASA Heliophysics Roadmap align with the decadal survey science challenges. However, there are several science questions in the

[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] NASA, *The New Science of the Sun-Solar System Connection: Recommended Roadmap for Science and Technology 2005-2035,* Washington, D.C., 2005. Hereinafter referred to as the Heliophysics Roadmap or the Roadmap.

decadal survey—most notably, coronal heating, the magnetospheres and ionospheres of other planets, and interaction with the interstellar medium—that receive little or no attention in the roadmap.

***Background:*** At the top level, the Roadmap's three objectives and 12 research focus areas align with the five science challenges in the decadal survey. Many of the survey's science challenges are purposely framed as broad, cross-cutting, and multidecadal. The survey implies that significant progress should be made in the timeframe of a decade on representative questions that are part of the broader challenges. Thus, the committee looked for correspondence between the Roadmap's RFAs and the key science questions in the decadal survey. It is not expected that the Heliophysics Roadmap would cover all of the questions in the survey. Rather, the committee looked for trends in the Roadmap research focus areas that might indicate exclusion or poor coverage of subsets of questions dealing with similar topics.

### Challenge 1: The Sun's Dynamic Interior and Corona

This challenge focuses on understanding the Sun from its interior out through its atmosphere and solar wind. The science questions focus on the solar cycle and solar dynamo, the solar corona, the fast and slow solar wind, and explosive energy releases like coronal mass ejections (CMEs).

For the solar cycle and solar dynamo, there is a Heliophysics Roadmap RFA that is directed at the solar dynamo question (RFA F4.1). This focus area and related questions in the decadal survey should be addressed with the Solar Dynamics Observatory (SDO) mission as well as ongoing research using existing space assets like the Solar and Heliospheric Observatory (SOHO).

For the solar corona, there is only indirect overlap between the decadal science questions and RFAs concerning fundamental processes (e.g., RFA F1.1 and F1.2). Although coronal heating is included in the science objectives of NASA missions like Hinode, SDO, SOHO, and Transition Region and Coronal Explorer (TRACE), the Heliophysics Roadmap does not adequately emphasize important topics related to coronal heating and coronal characteristics.

For the fast and slow solar wind, RFA F2.3 is directed at related decadal science questions. The origin of the fast and slow solar wind has been the focus of recent study of the solar atmosphere by the Hinode spacecraft. It will also be a focus of the SDO mission and is a prime objective of Solar Probe.

For explosive energy releases, there are several RFAs (for example, fundamental processes such as particle acceleration, precursors to solar disturbances and CMEs, and consequences for the near-Earth environment)—that correspond directly to decadal survey questions. The evolution of CMEs and other disturbances is a prime focus of the Solar Terrestrial Relations Observatory (STEREO) mission and existing space assets like the Advanced Composition Explorer (ACE) and Wind missions. Precursor studies and evolution of disturbances are included also in the Hinode mission as well as the future SDO mission.

### Challenge 2: The Heliosphere and its Components

This challenge focuses on understanding the heliosphere as a single, dynamic structure immersed in and interacting with the local interstellar medium. Science questions focus on the propagation of solar events throughout the heliosphere, the nature of the interaction between the interstellar medium and the heliosphere, the location and characteristics of heliospheric boundaries, and the nature of the local interstellar medium.

For propagation of solar events through the heliosphere, there are several Roadmap RFAs that are directly related to these decadal survey questions. The RFAs span all three Roadmap objectives. The propagation of solar events in the heliosphere continues to be researched with an unprecedented fleet of spacecraft, including those located at several longitudes at L1, at Mars, Saturn, and out to the edge of the heliosphere.

For the nature of the interaction between the interstellar medium and the heliosphere, the Roadmap RFAs are only indirectly related to decadal science questions. In particular, there is significant emphasis on propagation of CMEs in the inner heliosphere but much less emphasis on interaction of solar disturbances with the heliospheric boundaries.

For the location of the heliospheric boundaries and the nature of the interstellar medium, Roadmap RFAs are only indirectly related to the decadal science questions. The only discussion of the properties of the interstellar medium is in relation to the sustainability of life in the solar system in RFA H4, and the only discussion of the heliospheric boundaries is a brief mention of the heliospheric termination shock in conjunction with particle acceleration. There is no discussion of the various boundaries of the heliosphere, their location, or their variability, despite one of the most significant accomplishments of the past few years—namely, the encounter of the termination shock by Voyager 1 and 2. Their surprising observations of the termination shock location and structure have magnified the need for a better understanding of the boundary of the solar system. NASA's Interstellar Boundary Explorer (IBEX) spacecraft, a competitively selected, principal investigator-led Explorer Program mission launched in 2008, will be the first mission to follow up on the Voyagers' findings and address decadal survey questions about the heliosphere's boundaries.

### Challenge 3: Space Environments of Earth and Other Solar System Bodies

This challenge focuses on the space environments of solar system bodies, particularly that of Earth, and their dynamical interaction with the Sun and the solar wind. The wide-ranging science questions include these:

- The response of Earth to solar variations and extreme conditions.
- Magnetic reconnection and particle acceleration in magnetospheres.
- Magnetosphere-ionosphere interactions, including auroral displays.
- How planetary mesospheres, ionospheres and internal magnetospheric plasma sources transfer energy among the various regions of space.
- Many questions related to interactions between regions in the Jovian magnetosphere.
- Solar wind interactions with Mars.
- Ionosphere-magnetosphere-solar wind interactions at Mercury.

The science questions for this challenge are broader than those for the four other challenges because all types of solar system bodies are included in one challenge. The Roadmap should not be expected to cover all of the science questions, but there are some overall trends that need to be addressed.

The Roadmap reflects well the science questions that deal with interaction between Earth's magnetosphere, ionosphere, and atmosphere and the Sun and solar wind. Similarly, there is reasonable overlap for Mars space environment interactions. However, the Roadmap science at Jupiter clearly underrepresents the broad science objectives for the planet that are in the decadal survey. The science related to the magnetospheres and ionospheres of Saturn, Venus, and Mercury are even more underrepresented. The Roadmap emphasizes Mars to the near exclusion of the science available at other planets, notwithstanding the recent science accomplishments at Jupiter by the Pluto-Kuiper spacecraft, new discoveries at Saturn by the Cassini spacecraft, exciting new results at Mercury by the Messenger spacecraft, and the Planetary Science Division's upcoming Juno mission, which will conduct Heliophysics Division science at Jupiter.

### Challenge 4: Fundamental Space Plasma Physics

This challenge focuses on the basic physical principles manifest in processes observed in solar and space plasmas. Science questions address magnetic reconnection, turbulence, particle acceleration and transport, and wave-particle interactions.

The Roadmap devotes one its three objectives (and four of its RFAs) to this decadal challenge. Both documents have appropriate focus on magnetic reconnection, turbulence, and particle acceleration. The Roadmap goes further to include coupling to neutral species and planetary atmospheric chemistry. These RFAs correspond better to decadal challenge 3; however, their inclusion here as fundamental processes underscores their importance in the coupled Sun-Earth system. Reconnection processes are the major scientific objective of the Magnetospheric Multiscale (MMS) mission, and aspects of these phenomena are studied by the Cluster, Hinode, Polar, THEMIS (Time History of Events and Macroscale Interactions during Substorms), and Wind missions. Particle acceleration is the focus of the Radiation Belt Storm Probes (RBSP) mission, and aspects of this phenomenon are studied by the Hinode, RHESSI (Ramaty High-Energy Solar Spectroscopic Imager), STEREO, and Wind missions. Other decadal science questions and their associated Roadmap RFAs that focus on ionosphere-thermosphere-mesosphere (ITM) processes await the development of dedicated ITM missions. The uneven emphasis on radiation belt particle acceleration compared to fundamental ionospheric processes is the direct result of the change from the decadal survey Geospace Network mission to the radiation belt and ionospheric missions identified in the Roadmap.

### Challenge 5: Space Weather

This challenge focuses on the development of a near-real-time capability for understanding and predicting the impact on human activities of processes described in the first four challenges. Representative science questions include determining the probability of specific types and levels of space weather occurring on various time scales, determining the measurements and models needed to predict and quantify space weather, and understanding in parallel the risks from space weather on human spaceflight outside of the magnetosphere.

The Roadmap dedicates an entire objective (J) to this challenge. It focuses on predicting solar activity that has significant influence on the near-Earth space environment, particle acceleration at the Sun and within Earth's magnetosphere, aeronomic processes, and solar wind interactions at Mars. This RFA also includes dust and dust-plasma interactions, especially at the Moon. These RFAs and their corresponding decadal science question are the focus of space missions like SDO and RBSP, which have specific objectives to improve modeling and prediction of solar activity and particle acceleration in the magnetosphere.

The decadal survey science challenges are connected through the coupling of the entire Sun-heliosphere-Earth system. This system is rich in complexity arising from nonlinear coupling in plasmas, causing different subsystems to interact over a wide range of scales. This characteristic of plasmas is well described in the Roadmap. Small constellations of spacecraft and multiple spacecraft will have to be used in different regions to understand this coupled system. The Heliophysics Great Observatory, consisting of widely separated but related missions, is the key to achieving many of the science objectives.

However, there are elements in the Heliophysics Great Observatory that have been modified by the Roadmap and no longer correspond to the program recommended by the decadal survey. The most notable of these modifications is the change from the Geospace Network in the decadal survey to individual radiation belt (RBSP) and ionospheric (Ionosphere Thermosphere Storm Probes [ITSP]) missions in the Roadmap, a change that has severely compromised observations of the synergy and coupling aspects of the magnetosphere with the ionosphere. The future development of Heliophysics Great Observatory elements does not appear to have a high priority in the Roadmap.

## 2.2 INTEGRATED RESEARCH STRATEGY

This section addresses the committee's second charge, which is to assess NASA's progress toward realizing the strategies, goals, and priorities put forward in the decadal survey. In its Chapter 2, the decadal survey recommended an integrated research strategy consisting of a sequence of overlapping flight programs, coupled with small and vitality research activities, as the most effective way to address key scientific challenges.

**Grade: C**

***Finding:*** Progress in almost all the programs is seriously compromised by mission cost growth and rescoping and by reductions in funding for programs that provide regular mission opportunities. In addition, decisions to reorder the mission sequence recommended in the decadal survey undermined the Integrated Research Strategy, which was built around a set of spacecraft missions coordinated to afford opportunities to examine complex, interacting Sun-Earth subsystems from different regions simultaneously. The originally conceived program cannot be recovered before the next decadal survey. Thus, the status of the Integrated Research Strategy is in jeopardy and could result in the loss of synergistic space research capabilities.

***Background:*** The balanced and integrated program recommended by the decadal survey includes initiatives in the satellite flight program and in associated theory, modeling, and data analysis. This Integrated Research Strategy prioritized programs in four cost categories (large, moderate, small, and vitality) so that one science initiative would not be undermined by another of different scope. With this organization the decadal survey provided a single overarching recommendation to fund and execute the programs as prioritized in Table 1.1.

The survey recognized not only that understanding the nonlinear behavior of the connected subsystems describing the Sun, the heliosphere, the magnetosphere, and the upper atmosphere would require missions to these specific regions but also that complete understanding would be obtained only when knowledge was advanced across all of these subsystems. The decadal survey integrated findings of panels that included experts from these disciplines to determine the requirements to address specific problems. The priorities assigned to specific missions were tightly coupled to the anticipated schedules and costs of those missions.

The recommended mission execution plan was intended to afford opportunities to examine the complex, interacting components of geospace through simultaneous observations in different regions. Around 2011 opportunities for simultaneous observations of the variable Sun, the outer and inner magnetosphere, and the ionosphere and atmosphere would be afforded by the operations of SDO, MMS, and the Geospace Network. In 2012 the final fate of the electromagnetic energy delivered to Earth would be investigated through coordinated measurements from Geospace Electrodynamic Connections (GEC) and the Geospace Network. By the end of the decadal period investigation of the coupled system would begin anew with observations from Multispacecraft Heliospheric Mission (MHM) and Magnetospheric Constellation (MagCon). The desirability of this coordinated approach to observation was demonstrated most recently during the great Halloween storms of 2003, when the state of all the interacting subsystems was described.

Unfortunately, increases in the cost and complexity of all the moderate missions under development have stretched the schedule such that none of them will be conducted within the decadal period and all of them are likely to be conducted in isolation from the others. Within the period of the decadal survey, only two of the nine moderate missions described in the decadal survey (MMS and JPM) will be under development, and only one (JPM) will be launched. The growing costs of the SDO, MMS, and RBSP missions have pushed all of the missions that follow them within the Solar Terrestrial Probe (STP) and Living With a Star (LWS) lines beyond the decade in which they were anticipated to occur, making a coordinated study of the interacting parts of the system unlikely.

After MMS, the Geospace Network mission called for two spacecraft to map the radiation belt and two to map the ionosphere to determine the global response of geospace to solar storms. SDO, MMS, and Geospace Network would enable key subsystem responses in the overall Sun-Earth system to be studied—from solar activity itself, to solar wind energy coupling to the magnetosphere, to ultimate energy deposition and dissipation in the upper atmosphere. The priority order stressed the importance of a consensus approach to unresolved science issues of recognized importance as well as their application to the needs and concerns of a highly technological society on Earth. Instead, the present course replaces the Geospace Network with the RBSP mission, which by itself does not constitute a Geospace Network.

Subsequent priority was given to the MHM within LWS and to the GEC mission within the STP line. The decadal survey stressed that "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 the inner magnetosphere as a coupled system."[3] This intent has been undermined, however, by the development of the Solar Probe Plus and the Solar Wind Sentinels (SWS) missions in the absence of any initiative to examine the geospace response to solar activity, setting a course that diverges even more from the survey's recommendations.

## Solar Probe

**Program Grade: A**

***Finding:*** NASA is to be commended for reconstituting the Solar Probe science definition team and producing a Solar Probe Plus mission implementation plan that could be conducted with a restricted cost profile. Although its mission design is promising, Solar Probe Plus sequencing is in conflict with the decadal survey, which conditioned Solar Probe implementation on the implementation of all the moderate missions recommended in the survey or on a budget augmentation to accelerate Solar Probe implementation. Neither condition has been met. Solar Probe received the highest possible grade due to efforts to control cost via intelligent mission redefinition. However, NASA has compromised the decadal survey's mission sequence by advancing Solar Probe ahead of the fourth (Multi-Heliospheric Probes), fifth (GEC), and seventh (MagCon) moderate-mission priorities identified in the survey, an approach that has reduced the overall grade given to the Integrated Research Strategy.

***Background:*** The Solar Probe mission was defined by a science definition team report (1999), an engineering study (2002), and a more extensive science and technology definition team (STDT) study (2005). In the last mentioned report, the mission would pass twice over the solar poles within 3 solar radii of the solar surface, where both in situ and remote sensing instrumentation would probe the origin of the fast and slow solar wind very close to where it is accelerated. Because it was expected to be so expensive, Solar Probe was the only large mission to be recommended and authors of the survey recommended that it be undertaken only with a designated funding augmentation that would not disrupt the survey's moderate and small missions.

In 2008, a new STDT study yielded a revised mission concept called Solar Probe Plus, which would deliver Solar Probe science at lower cost. The close-in, two-pass polar orbit was replaced by a longer series of equatorial orbits reaching 8.5 solar radii from the surface. Solar Probe Plus would carry the same in situ instrumentation as the original Solar Probe mission. Both versions also require remote-sensing observations of the corona and photosphere to provide context for the in situ measurements. Solar Probe Plus's ecliptic-plane measurements will permit context observations from the ground or from Earth orbit rather than from the more costly sunward remote sensing instruments on Solar Probe. This

[3] 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, p. 5.

responds directly to the decadal survey's recommendation for remote-sensing instrumentation only over the poles and may deliver even more science content than the earlier Solar Probe mission designs.

The Solar Probe Plus orbit would be achieved in steps through successive flybys of Venus rather than the Jupiter-assist needed for the close polar orbit. This revised profile provides more than a hundredfold increase in sampling of the solar wind inside 20 solar radii. This significantly larger data set will enable most of the same objectives as the original mission, at a more reasonable cost.

The cost of Solar Probe Plus is estimated at $750 million provided it launches by 2015, compared to $1.1 billion for Solar Probe. This estimate follows from four closely coupled mission studies within the last 10 years, an unprecedented investment in planning and cost estimation. The report also recommends that costs be kept down by having only a single principal investigator to manage the mission.

## Magnetospheric Multiscale

**Program Grade: B**

***Finding:*** Magnetospheric Multiscale is the number-one-priority moderate mission, with a *science focus on reconnection as a fundamental plasma physical process.* MMS is scheduled for launch in 2014 and has an estimated cost of $990 million. The launch date places it outside the timeframe addressed by the decadal survey (2004-2013), and the cost places it well outside the moderate mission category of the decadal survey. Changes in payload capability, launch vehicles, and project requirements have all contributed to the increases in time and cost. Although it is encouraging to see MMS moving forward, its problems have necessitated the re-programming of subsequent moderate missions.

***Background:*** In 1999, an STDT report baselined MMS as a five-spacecraft, multiphase mission to investigate magnetic reconnection, particle acceleration, and turbulence in several regions of Earth's magnetosphere. The mission's first phase begins with an investigation of magnetic reconnection at Earth's dayside magnetopause. An apogee change is then used to investigate reconnection and particle acceleration in the near magnetotail (~25 Earth radii from Earth). Later phases utilized a lunar swing-by to investigate reconnection, acceleration, and turbulence in the distant tail and finally a high-latitude, dayside magnetopause skimming orbit for high- and low-latitude reconnection.

Several factors have caused the mission costs to grow dramatically. First, new theoretical and observational evidence indicated that the STDT instrument suite would not accomplish the reconnection science that was central to the MMS mission. As a result, the number of in situ instruments grew. Second, the increased payload increased the size, complexity, and cost. The number of spacecraft was reduced to four and the mission phases were reduced to lower total mission mass, but costs grew nonetheless when the MMS independent review panel recommended further redundancy in the instrumentation and the spacecraft. Third, the launch vehicle changed from the Delta II to the more expensive Evolved Expendable Launch Vehicle (EELV). Fourth, reductions in the STP mission line (see Figure 1.5) forced the MMS program to stretch out its development schedule, increasing total costs. Finally, although the significant cost increases are difficult to fully account for, the switch from a competitive, principle-investigator managed mission to an in-house spacecraft at NASA's Goddard Space Flight Center, and associated increases in civil servant staffing and changes in full-cost accounting, may also have resulted in significant cost increases.

In summary, all of these factors contribute to MMS's cost growth. The total mission cost is currently $990 million ($878 million for phases B through D in real-year dollars) versus the decadal survey's estimate (phases B through D in 2002 dollars) of $350 million. This cost increase, coupled with the decrease in the STP budget (see Figure 1.5), virtually guarantees that no additional STP mission will be started in the remainder of the time covered by the decadal survey. If the decadal survey had judged MMS to be a mission in the billion dollar category, with the consequences for the Integrated Research

Strategy noted above, it is unclear whether the community would have continued to give it the highest priority for moderate missions.

### Geospace Network

**Program Grade: D**

***Finding:*** As originally conceived, the Geospace Network mission *aimed at exploring the synergy and coupling between the radiation environment in the inner magnetosphere and the underlying ionosphere and thermosphere, key regions for space weather effects.* It has not been implemented, and the present plan essentially eliminates it from consideration.

***Background:*** In 2002, the LWS Geospace mission definition team published a report highlighting the RBSP and ITSP missions, and a year later the decadal survey recommended that the synergistically linked objectives of these missions be combined in a Geospace Network mission. The Heliophysics Division has not adopted this recommendation, instead deferring ITSP indefinitely and moving forward with RBSP, a mission that appears in the decadal survey only as part of a broader network.

The RBSP mission will be a valuable step toward understanding the energetic particle properties in the inner magnetosphere. However, the Geospace Network would more broadly elucidate the connections between the magnetosphere and the atmosphere in an attempt to understand the temporal and spatial evolution of the coupled system.

Joint operation of the Radiation Belt and Ionosphere-Thermosphere Storm Probes would allow measurement of the interaction between the magnetosphere, ionosphere, and thermosphere, including how magnetospheric particle populations and ring current changes affect the lower-altitude plasmasphere and how particles from the ionosphere couple to the magnetospheric population. This important goal is a requirement for the future specification and prediction of the space environment; no plan to recover or synthesize this capability from an adjusted mission sequence is evident.

The RBSP payload grew significantly in cost, mass, and complexity from 2005, when the Announcement of Opportunity (AO) was released, until the phase A selections. The plasma instrumentation was significantly more complex and massive, the electric field instrument added a third axis, and an additional instrument from the National Reconnaissance Office (NRO) for inner radiation belt studies was included (at no cost to NASA), leading to a 50 percent increase in the payload budget. The spacecraft mass and complexity grew as well, and NASA ultimately chose a more expensive EELV.

The RBSP total mission cost is now over $600 million for two radiation belt spacecraft. The decadal survey estimated the cost of the Geospace Network (two radiation belt spacecraft and two ionosphere-thermosphere spacecraft) at $400 million (phases B through D in 2002 dollars). Thus, the RBSP mission, while accomplishing much of the radiation belt science objectives in the decadal survey, now costs approximately two times more than estimated by the decadal survey. The cost increases in RBSP and SDO have delayed future LWS missions and made joint operation of RBSP and any future ITSP mission highly unlikely. The decadal survey did not put forward a stand-alone radiation belt mission, and as with MMS, it is not obvious that RBSP would still enjoy community consensus ranking as the second priority for moderate missions, especially given the mission’s cost growth and the resulting consequences for the Integrated Research Strategy.

### Jupiter Polar Mission

**Program Grade: B**

***Finding:*** Although there are some limitations due to mission design, instrumentation on the recently selected New Horizons Juno mission will allow the main objectives of the decadal survey Jupiter Polar Mission to be accomplished.

***Background:*** The decadal survey's third priority moderate mission is the Jupiter Polar Mission (JPM), which will investigate the electrodynamic coupling of the Jovian magnetosphere with the high-latitude atmosphere and the formation of aurorae at high latitudes in the Jovian atmosphere.

In 2005, the Juno mission was selected as the next New Horizons mission by the Planetary Sciences Division. Its suite of seven scientific instruments will determine the ratio of oxygen to hydrogen in the Jupiter atmosphere; precisely map Jupiter's gravitational and magnetic fields; map the variation in atmospheric composition, temperature structure, and cloud opacity; and characterize and explore the three-dimensional structure of Jupiter's polar magnetosphere and its auroras.

Development of this joint planetary exploration-heliophysics mission is ongoing, and all funding of the mission's heliophysics objectives is provided through the New Horizons program. Instruments that are directly applicable to heliophysics science objectives include the polar magnetosphere suite of particle instruments, the magnetometer, and the infrared auroral mapper. While some limitations on the heliophysics science objectives are produced by the fixed local time and inclination of the orbit, the opportunity to leverage the large launch costs associated with a planetary mission make this collaboration a notable success.

## Suborbital Program

**Program Grade: B**

***Finding:*** NASA significantly increased its funding request for the Suborbital Program in FY 2009 in response to multiple findings over the years from the community. If passed, this increase appears to be sufficient to bring the support level back above the critical threshold for a viable program. This increased support for operational engineering, infrastructure, and inventory is in line with the relevant recommendation from the decadal survey. Meeting the decadal survey recommendation for a revitalized Suborbital Program will also require an increase in science investigations to take advantage of the increased flight rate.

***Background:*** Sounding rockets are the most important part of the heliophysics Suborbital Program. This program has been a mainstay for the investigation of fundamental physical processes in the ionosphere-thermosphere, for a wide range of magnetospheric studies, and for the development of new instruments for space physics. While the flight time of these rockets is small, their velocity through specific regions of space and their ability to sustain very high telemetry rates from multiple payloads launched from a single vehicle make them extremely useful for studying the fine structure of dynamic phenomena such as the aurora. Moreover, sounding rockets provide direct in situ measurements in some important regions of space that are too low in altitude to be sampled by satellites (i.e., the mesosphere below 120 km). Rockets are used to fly stand-alone individual payloads for targeted space plasma research, often in close collaboration with orbital and ground-based measurements. Besides addressing frontier space plasma problems, such as the mechanisms that govern small-scale particle acceleration regions, sounding rocket investigations have served as exemplary tools for the development of scientific ideas and measurement technologies, and they have had a significant level of student participation, often far out of proportion to the program costs. The often fast turnaround from scientific concept through engineering of the instrumentation, flight, and data return and analysis is entirely consistent with the educational objectives of universities.

The decadal survey recommendation (see Section 2.7.3) to revitalize funding for the Suborbital Program was made at a time with the launch rate for sounding rockets was declining rapidly. As recommended by the survey, an independent senior review team was convened in 2004 to examine the programmatic elements and cost structures of the Wallops Flight Facility Sounding Rocket Program Office. That review team found that the program was well run and as productive as possible within available resources. It found no way to increase the number of high-performance missions without also increasing the budget, reducing requirements, or moving funds from workforce to other costs. A recovery effort for the program was initiated, but in 2006 the redistribution of priorities associated with the exploration initiative resulted in dramatic funding cuts, putting the viability of the program in question. A rescue effort stabilized the program at an annual budget of $45 million to $50 million, with a projected increase to between $60 million and $70 million per year in the outyears.

While sounding rockets are its dominant element, the heliophysics Suborbital Program also involves balloons and aircraft; ballooning has recently focused on astrophysics but can provide platforms for space physics as well. A balloon roadmap presently under development outlines priorities, particularly the development of ultra-long-duration balloon (ULDB) capabilities, and support for long-duration balloon (LDB) campaigns in Antarctica, Sweden, and Australia, all of which will require sufficient funding for the science payloads. The balloon program was to be included in the "suborbital revitalization," but so far the increased funding has gone to the rocket program. Given the recent success of the Antarctic ULDB campaign, balloon-based research should also be a beneficiary of any suborbital program funding increases.

## Explorer Program

**Program Grade: C**

***Finding:*** The Explorer Program is characterized by high science return and a minimum of cost overruns and mission expansion. However, reductions in Explorer Program funding have reduced the mission flight rate from one or more missions per year at the time of the decadal survey to one mission every 4 years, with serious implications for the vitality and balance of programs within the Heliophysics Division. The reinstatement of the Small Explorer and Mission of Opportunity competition in 2007 reversed a downward trend but has not restored funding to levels assumed by the decadal survey.

***Background:*** The ability to conduct both small and medium-class missions within the Heliophysics Explorer Program (see Box 2.1) has produced cutting-edge investigations that are complementary to the larger STP and LWS missions. The IMAGE MIDEX mission enjoyed enormous success as the first mission dedicated to determining the global magnetosphere's response to variable solar wind input. The five-spacecraft THEMIS mission is a MIDEX currently answering long-standing fundamental questions concerning the nature of substorm instabilities that abruptly and explosively release energy stored within Earth's magnetotail. Neither mission could accomplish its science objectives in the constrained small explorer budget, but both were ideally suited for the strategic, short response time enabled by the MIDEX Program. Both have profoundly transformed the Heliophysics Division's science program. The recently launched AIM mission is already revealing new properties of ice clouds, while the IBEX mission (launched October 2008) will use state-of-the-art particle imaging techniques to examine the boundary between the interstellar medium and the heliosphere.

The long and successful history of the Explorer Program has evidenced attributes of missions typically led by principal investigators. These missions are conducted very close to the initial schedule and are completed with little deviation from the initially specified (capped) costs. The return excellent science value and excitement and usually operate successfully well beyond minimum performance periods, managing to achieve strategic objectives for the field as they fill emerging science gaps.

Despite this compelling history, in 2005 NASA a cut to the Explorer budget more than 50 percent (see Figure 1.8), delaying Explorer AOs for 2005-2006 and leaving a gap in heliophysics Explorer launches between 2010 and 2012. These cuts, coupled with the loss of the Delta-II medium-lift launch vehicle, will reduce the launch rate to one heliophysics SMEX every 4 years and eliminate the MIDEX line.

It is clear from the recent SMEX competition, which netted 14 heliophysics proposals (of which three are currently in Phase A), that there is no shortage of viable explorer mission concepts in the heliophysics community. However, only one selection will be made for a launch between 2011 and 2015. This selection will result in a gap of at least 3 years between the IBEX launch and the next SMEX launch.

**BOX 2.1**
**The Heliophysics Explorer Program, the Decadal Survey, and Other NRC Advice**

The decadal survey recognizes that "the Explorer Program has long provided the opportunity for targeted investigations, which can complement the larger initiatives recommended by the committee."[1] Because the program consists of competitively selected investigations, there are no recommendations for Explorer missions in the decadal survey. However, the decadal survey's recommended budget clearly assumes a heliophysics Explorer Program capable of producing a steady stream of medium explorers (MIDEX) and small explorers (SMEX) over the decade.

The importance of the Explorer Program was further emphasized in the report *Solar and Space Physics and Its Role in Space Exploration,*[2] which says "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. . . . Explorer missions . . . have the ability to adapt to the ever-changing, immediate needs of the space science community."

[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, p. 62.

[2] National Research Council, *Solar and Space Physics and Its Role in Space Exploration*, The National Academies Press, Washington, D.C., 2003, p. 36.

## Missions Under Development Before the Survey

The decadal survey endorsed completion of three moderate-sized NASA missions that were under development at the time of the decadal survey in 2003: Solar B, STEREO, and SDO. The budget totals for completing Solar B and STEREO are close to the original budgets in the decadal survey. SDO, however, has experienced significant cost growth and schedule delays. The decadal survey assumed that SDO could be completed in 2008 for an additional \$315 million, but SDO will require at least an additional \$700 million before its launch in late 2009 or in 2010. SDO's cost growth appears to have been driven by changes in international partner contributions, availability of launch vehicles, and technical challenges in instrument development. Although Solar B, STEREO, and SDO were not explicitly prioritized in the decadal survey, SDO cost growth—like MMS and RBSP cost growth—is a major contributor to the deferment of priority programs recommended in the decadal survey and is placing the future Heliophysics Great Observatory in jeopardy.

## Missions Deferred Beyond the Decade

The decadal survey recommended nine prioritized moderate-size initiatives to be started between 2002 and 2012. Initiatives that ranked fourth, fifth, seventh, eighth, and ninth—including the MHM, GEC, MagCon, SWS, and Stereo Magnetospheric Imager missions—will not begin development before 2012. Priority six was the Suborbital Program discussed earlier in this chapter.

## Small Programs

### Program Grade: A

***Finding:*** Significant enhancements to scientific productivity in heliophysics are being achieved with relatively small resource commitments, including NASA cooperation on the European Space Agency's Solar Orbiter mission.

***Background:*** The decadal survey identified two initiatives where a limited investment of resources could pay high dividends in science return for NASA.

Among NASA small programs in the decadal survey, collaborating with the European Space Agency's (ESA's) Solar Orbiter mission to study the magnetic structure of the Sun was given the highest priority. The ESA-led Solar Orbiter will carry imaging and in situ instrumentation to the inner heliosphere at a moderately high latitude, and its periodic co-rotation with the solar surface will permit unique observational opportunities. The mission is aimed at revealing the properties and dynamics of the inner heliosphere, the fine-scale structure of the corona, and the link between these two. NASA is successfully implementing the recommendation of the decadal survey by soliciting and reviewing proposals for the participation of U.S. hardware teams. However, due to cost growth in other missions, the European Space Agency is seeking to reduce Solar Orbiter costs and may cancel the mission. But if successful, the launch of Solar Orbiter, coincident with the launch proposed for Solar Probe Plus, offers an opportunity for complementary observations of the entire inner heliosphere for the first time.

University-class Explorer missions are a highly leveraged opportunity to engage the next generation of space scientists at universities and to push forward key frontiers in the subdisciplines that comprise heliophysics. However, the limited launch capabilities discussed in Chapter 1 restrict the ability of NASA to procure affordable launch opportunities for small payloads. The Explorer Program will continue to solicit Missions of Opportunity, allowing investigators to pursue launch opportunities beyond those offered by NASA. In addition NASA has recently considered stand-alone Missions of Opportunity that will take advantage of future NASA launches and other launches whose timing may not be synchronizeable with the Explorer opportunity.

A smaller CubeSat program is being developed by the National Science Foundation (NSF) to secure secondary payload launch capabilities using a standardized payload envelope. Such a program could allow a university group to enter a space hardware project with a limited budget and to serve as a pipeline through which both instruments and experienced personnel for the larger NASA programs could be delivered.

## Vitality Programs

### Program Grade: B

***Finding:*** Although some of the specific initiatives recommended by the decadal survey were not undertaken, NASA's Research and Analysis budget has effectively addressed the needs of present and future flight programs while continuing to foster new ideas and innovation.

***Background:*** Vitality programs should ensure that theoretical understanding and the development of numerical models stay in step with the mission data that can be used to verify and constrain them. The needs of physics-based assimilative models must be consistent with the capabilities of mission instrumentation to deliver the required data. Conversely, the most significant barriers to advancing our understanding must be identified to produce the most effective future missions. Various components of the vitality program that contribute to these goals are discussed below.

## NASA SR&T

**Program Grade: C**

***Finding:*** The decadal survey recommended that funding for the Supporting Research and Technology (SR&T) program be increased to maximize the productivity of existing resources and ensure a sound foundation for the development of future programs. However, funding for this key activity was severely cut in FY 2006. In FY 2008, funding amounts have only recovered to their levels at the time of the decadal survey.

***Background:*** In many ways the SR&T program is the foundation on which future missions and initiatives are based. The utility of mission data is demonstrated by their use in studies supported by the SR&T program. Extensions to originally proposed ideas are tested and developed, and the limitations of existing data sets are exposed. Through exhaustive investigations utilizing existing resources, the barriers to understanding are identified and the rationale for new programs can be constructed in the most robust way. As mission launch rates decrease, increases in SR&T funding will maintain scientific productivity and enable the continuous refinement of the most productive scientific targets for future programs.

## National Space Weather Program

The National Space Weather Program (NSWP) is a very successful multiagency collaboration aimed at utilizing the cumulative scientific understanding of the Sun and the space environment for the generation and validation of specification and prediction models. So important is this effort that the decadal survey devotes specific recommendations in this area in a chapter entitled "The Effects of the Space Environment on Technology and Society." These recommendations are assessed in Section 2.5 of the current report.

## Coupling Complexity Initiative

**Program Grade: C**

***Finding:*** No federal agency has led the way in creating new, interagency theory and modeling programs, such as the Coupling Complexity Initiative recommended by the decadal survey. However, within constrained budgets, NASA has supported the development of some portion of these activities through existing programs, such as its Targeted Research and Technology (TR&T) and its Community Coordinated Modeling Center (CCMC).

***Background:*** The main challenges facing space physics require a theoretical understanding of the entire Earth-Sun system across regional boundaries and involving physical processes at widely disparate scales. Accordingly, the decadal survey recommended as its number 3 vitality program priority that NASA take the lead in creating a Coupling Complexity Initiative to address multiprocess coupling, nonlinearity, and multiscale and multiregional feedback in space physics. The multiagency program would provide long-term grants ($500,000 to $1,000,000 annually for 5 years) to support critical-mass theoretical and computational groups. In the absence of specific funding increases, NASA has effectively utilized the LWS Targeted Research and Technology (TR&T) and Theory programs to support some research activities related to complex coupling. NASA's Community Coordinated Modeling Center (CCMC) can also play a role in spawning new initiatives by providing computational resources and developing the Sun-to-Earth modeling center, but has so far not done so.

Unfortunately in this area, cooperation between federal agencies operating under different mandates is an exception rather than the rule. Those notable exceptions, such as the Collaborative Space Weather Modeling program, suggest that narrowly defined objectives rather than broad themes are probably the best candidates for cooperatively funded programs.

## Solar and Space Physics Information System

**Program Grade: A**

***Finding:*** The capabilities of a Solar and Space Physics Information System are being realized through the CCMC and the emerging capabilities of virtual observatories. However, these projects are in their infancy, and continuous, careful examination should be undertaken to identify needed capabilities and specific weaknesses that could hamper their productivity.

***Background:*** Continuing growth in the number of solar and space physics data sets and the need to use them to characterize and predict the geospace environment require data and modeling tools to be ensured. The Solar and Space Physics Information System recommended by the decadal survey was designed to address this need. The system should include data validation and data delivery to experienced scientists as well as access to the latest interpretive models for all interested scientists. A central facility delivering these capabilities is not yet a reality, but NASA's open data policy and the ongoing development of virtual observatories provide access to discipline-specific data sets. The CCMC also provides a platform for running well-tested geospace numerical models. These facilities are the main components of the Solar and Space Physics Information System. Challenges lie ahead in identifying and implementing capabilities that enable integrating multidisciplinary data sets into a global characterization of the Sun-to-Earth interaction and in providing a seamless interaction between data and models. This integrated view is central in optimizing the scientific returns from the investment in the Heliophysics Great Observatory, both by enabling interdisciplinary investigations and by providing capabilities needed for more accurate space weather predictions. The present version of the Solar and Space Physics Information System is already being used by the Space Environment Center at NOAA to identify and characterize those models so they will be ready for transition to operational forecasting tools. A memorandum of understanding is being drafted to recognize interagency cooperation on these scientific challenges, as envisioned in the decadal survey.

## Guest Investigator Program

**Program Grade: A**

***Finding:*** The importance of the Guest Investigator Program *in maximizing scientific returns from mission data sets and from the Heliophysics Great Observatory by broadening the types and range of scientific investigations* is well recognized by NASA, and funding has been increased to maximize the program's effectiveness.

***Background:*** The Guest Investigator (GI) Program significantly increases the productivity of space missions by encouraging broad community involvement that extends to disciplines other than those specifically addressed by the mission itself. The GI program enables heliophysics researchers to use Heliophysics Great Observatory data in innovative scientific investigations. The focus of competitively selected research funded by the program continuously evolves to ensure that the most important current questions are addressed. Now, when the launch rate for new missions is so low and the Heliophysics Great Observatory concept is in jeopardy, it is particularly important to capitalize on the effectiveness of the program. NASA has been responsive to this need by continuing to support this program, and it recently announced increases in funding for FY 2009.

## Theory and Data Analysis Program

**Program Grade: B**

***Finding:*** The Heliophysics Theory and Data Analysis Program has labored under an inflationary funding profile. To fulfill its mission of supporting groups of critical mass without increasing resources, the number of awards made every 3 years has been decreased. While such funding at least stems deterioration of capabilities in theory and modeling, it cannot foster the bold advances envisioned by the decadal survey.

***Background:*** The Heliophysics Roadmap fully recognizes the central role that theory and modeling play in exploring and interpreting observations, in defining future missions, and in supporting the Heliophysics Great Observatory.

Theory and modeling research has traditionally been supported through small to medium-size competitive grants, which provide flexibility and quick response to new ideas from community members. The Heliophysics Theory Program (HTP, formerly the SEC-TP) supports large theoretical groups working in all areas of heliophysics. About 10 groups are funded based on triennial solicitations. Since entire research groups respond to these solicitations, the proposals are typically rather broad, though generally confined to a single heliophysics subdiscipline. The SR&T program is one way for smaller grants to support more focused investigations.

## Virtual Sun

**Program Grade: B**

***Finding:*** While no new program element has been created in response to the Virtual Sun recommendation, which proposes an interagency program to develop the theoretical and modeling framework to represent the major elements of the Sun-Earth system, some of the recommendation's objectives have been achieved through existing programs. Living With a Star (LWS) TR&T, for example, supports elements of Virtual Sun that will eventually lead to improvements in space weather applications.

***Background:*** The decadal survey recommended the creation of two new strategic funding initiatives for theory and modeling, focused on spanning boundaries of funding agencies and traditional disciplines. The first of these, Coupling Complexity, was discussed earlier. The second, the Virtual Sun, would couple our understanding of the Sun, the heliosphere, and Earth as a single system. The effort would be built up in a modular fashion, supporting focused investigations of specific components of the system.

The TR&T program of LWS is the program best suited to achieving the objectives of the Virtual Sun. Since the decadal survey, LWS has solicited proposals and awarded one large grant to deliver an operational three-dimensional model of coronal active regions as a strategic capability. It has also contributed, with NSF and the Air Force Office of Scientific Research, to interagency collaborative space weather modeling efforts aimed at delivering models coupling the ionosphere and magnetosphere and the corona and heliosphere. Finally, the TR&T program has awarded numerous grants to designated focus research teams aimed at modeling topics fitting those of the Virtual Sun.

## 2.3 TECHNOLOGY DEVELOPMENT

Chapter 3 of the decadal survey emphasized that new technology developments are vital to maintaining future leadership in solar and space physics. The decadal survey contained four recommendations to identify and develop key technologies—including advanced power and propulsion, spacecraft systems, science instrumentation, and command-and-control and data acquisition—that are important to undertaking, scientifically compelling missions on a timely basis.

**Grade: C**

***Finding:*** NASA is planning to add new small and medium launch capabilities and has made some progress in developing advanced spacecraft systems and command-and-control and data acquisition technologies for spacecraft constellations. But NASA's progress in developing solar sails is limited, and NASA has only recently begun studying the feasibility of advanced space nuclear power systems and the availability of the necessary radioactive isotopes. These technologies have been identified as strategic needs for upcoming missions. It is also unclear if the rate of technological progress in spacecraft systems can be sustained in the absence of a replacement for NASA's canceled New Millennium Program, which provided a testbed for new technologies. NASA has also not followed up on decadal survey recommendations regarding advanced scientific instrumentation.

***Background:*** The decadal survey made four specific technology recommendations to enable future solar and space physics missions.

> 2.3.1 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.

The present fleet of launch vehicles provides limited and shrinking options for the small and medium spacecraft that support most space-based solar and space physics missions and imposes a high penalty on these missions as well. NASA has recently invested almost $500 million in three contracts for its Commercial Orbital Transportation Systems (COTS) program. While COTS is an effort to support manned ground-to-space station activities, launch vehicles like the Falcon 1 and Minotaur II developed under COTS could lower costs and diversify options for future small and moderate-sized space and Earth science missions.

Solar sails have long been regarded as an inexpensive way to provide access to unstable orbits and maintain them. NASA recently attempted to launch a Nano Sail D mission, but the launch vehicle failed. The Planetary Society has also developed a solar sail package, but it suffered launch failures in 2001 and 2005. The Society is currently seeking funds for another attempt, possibly on a Russian rocket.

NASA studied the possibility of using nuclear power for the Solar Probe mission, an interstellar probe mission, and other missions but has stopped all work in this area. It has, however, contracted with the National Research Council to study radioisotope power supplies in light of future space science mission needs.

> 2.3.2 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.

NASA's New Millennium Program (NMP) Deep Space 1 (DS-1) mission tested the ion propulsion units now used on the Dawn mission. The 2006 NMP Space Technology 5 (ST-5) mission deployed three 20 kg spacecraft for studying the use of future satellite swarms in the magnetosphere. ST-5 also showed the usefulness of off-the-shelf computers in space, deployed lightweight masts that could be used to support solar sails, demonstrated the utility of very lightweight, unfolding solar power arrays, and tested a lightweight heating and cooling unit for small spacecraft. There are no plans for future NMP missions.

In addition to NMP technology demonstration missions, much development work on new spacecraft technologies is done during the early planning phases of individual missions. An example is the Solar Probe Plus mission, which has identified two main technology challenges—its thermal protection system and its power system inside 0.25 AU. The thermal protection system will use a 2.7-m-diameter carbon-carbon, low-conductivity, low-density shield that protects the spacecraft bus and instruments within its umbra during the solar encounter. The two primary solar power arrays will be retracted inside 0.25 AU, and two smaller, high-temperature-tolerant photovoltaic arrays will provide power. These liquid-cooled arrays will be gradually retracted behind the heat shield as the spacecraft approaches the Sun, keeping the incident solar power approximately constant.

2.3.3 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.

The decadal survey panel reports on the Sun and heliospheric physics, on solar wind and magnetospheric interactions, and on atmosphere-ionosphere-magnetosphere interactions contained a number of specific recommendations for the development of new instrumentation. NASA has not taken any specific actions on these recommendations, although it is possible to submit instrument development proposals through the regular supporting research and technology channels.

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

The MMS project is developing the Interspacecraft Ranging and Alarm System (IRAS). It will provide the absolute and relative position of four satellites and will use data from any of the spacecraft to alert the others to periods of scientific interest when data should be recorded at high bit rate for transmission back to Earth.

## 2.4 CONNECTIONS BETWEEN SOLAR AND SPACE PHYSICS AND OTHER DISCIPLINES

Chapter 4 of the decadal survey emphasized that solar and space physics is a remarkably broad and interdisciplinary field of investigation, encompassing virtually all physical and chemical processes acting in the solar system and beyond. Thus, research in this area could be leveraged by collaborations, with scientists studying the same physical processes in different environments. The decadal survey made two recommendations to NASA and NSF to foster such collaborations by establishing new initiatives in laboratory plasma science and interdisciplinary research programs.[4]

**Grade: F**

[4] Similar recommendations were also made in the recent plasma physics decadal survey. See National Research Council, *Plasma Science: Advancing Knowledge in the National Interest*, The National Academies Press, Washington, D.C., 2003.

***Finding:*** NASA has taken no specific action on the connections recommendations, which remain valid. However, community interest in interdisciplinary interactions remains strong, and supporting research and technology programs continue to elicit interdisciplinary interest.

***Background****:* The decadal survey panel divided this topic into four major elements: Laboratory Plasma Physics, Astrophysical Plasmas, Atmospheric Science and Climatology, and Atomic and Molecular Physics and Chemistry. Two recommendations were offered:

> 2.4.1 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.

> 2.4.2 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.

NASA has traditionally supported many of these areas through its supporting research and technology program. The solar and heliophysics program, for example, includes one matrix element (of five) expressly devoted to supporting ancillary laboratory research—for example, derivation of atomic constants, photometric calibrations, or simulation of solar and heliospheric phenomena. Still, NSF has devoted more explicit resources to fostering such interdisciplinary collaborations—for example, through its NSF/Department of Energy partnership in basic plasma science and engineering.

The four elements listed in the survey all have clear links to the space plasma physics of the heliophysics division. Laboratory plasma experiments can help isolate and study the underlying plasma physics phenomena observed in both solar system plasmas and remote astrophysical systems, including magnetic reconnection, magnetic dynamos, plasma-neutral interactions, and waves unique to magnetized plasmas (e.g., whistler and shear Alfvén waves). Sounding rockets are used to probe the nearby plasma physics laboratory of the ionosphere and mesosphere by isolating particular wave-particle interactions or other partially ionized plasma processes for study.

Astrophysics and planetary plasma physics processes are well-represented in the heliosphere. Virtually all astrophysical plasmas comprise ionized hydrogen, with varying levels of collisional neutral particles, embedded in magnetic fields. Earth's geocorona, which extends between 500 and 1,000 km, offers processes both common to and contrasting with plasmas in a host of cosmic settings, for instance, interstellar clouds. Hydrogen ions (atomic and molecular) and electrons are also the components of the ionospheres of all of the giant planets, including all of the "hot Jupiters" found around other stars.

In areas of climate-scale processes, the decadal survey pointed out that "the influence of global climate change on the geospace environment—at least on its lower reaches—must also be considered" (p. 109). Advances in this area have been slow in coming. More observational and modeling work is needed to understand both the signatures and consequences of anthropogenic gases on the upper atmosphere and the transmission of any such effects to the exosphere and magnetosphere.

Space plasma physicists and their instruments typically participate in NASA's Planetary Science Division missions, including the upcoming Juno mission to Jupiter and the MAVEN mission to Mars.

Finally, atomic and molecular physics and chemistry provide the fundamental linkage between the Sun and atmospheres throughout the solar system. Modern physics originated in the need to understand the interaction between radiation and matter, and quantum chemistry became a partner in probing how photons, neutral gases, ions, and electrons interact. NASA has supported approximately one new research award per year in this area, although recent awards have tended to be given to theoretical rather than laboratory investigations.

The 2003 decadal survey's recommendations listed above were amplified in the 2007 NRC decadal survey on plasma physics, *Plasma 2010*.[5] Clearly, the plasma physics community feels it would benefit from increased collaboration with the NASA community.

## 2.5 EFFECTS OF THE SOLAR AND SPACE ENVIRONMENT ON TECHNOLOGY AND SOCIETY

Chapter 5 of the decadal survey focuses on the mechanics of combining the efforts of several government agencies to meet the challenges posed to numerous technologies by solar activity and Earth's space environment. It makes recommendations to NASA to improve its role in theory and modeling to understand space weather, to transition from science-based studies to environmental monitoring, and to formulate policy decisions that affect public and private efforts to acquire and use space weather–related resources.

**Grade: C**

***Finding:*** NASA/NOAA/NSF joint efforts on modeling and simulations are excellent examples of successful and close interagency coordination. However, the use of scientific spacecraft like NASA's Advanced Composition Explorer for operational purposes by other agencies at L1 is ill-advised and is a potential obstacle to an independent space weather monitoring program.

***Background:*** While the Sun's energy output in the visible part of the spectrum is nearly constant, its output at other wavelengths that affect the upper atmosphere and its output in the form of the solar wind are quite variable. This variability and the complex coupling to the upper atmosphere and magnetosphere create space weather, which is driven by the physics of a coupled system that starts in the Sun's interior and extends throughout the heliosphere, including Earth's atmosphere all the way down to and beneath Earth's surface.

Space weather has deleterious effects on numerous technologies, as demonstrated during the 2003 Halloween storms, when a series of CMEs produced effects in Earth's environment that lasted for weeks—a blackout in southern Sweden, surge currents in Swedish pipelines, degraded or occluded GPS signals, numerous interferences in high-frequency radio communications, rerouted aircraft, electronic upsets, data noise, significant proton degradation of solar arrays, orbit degradation, and high levels of accumulated radiation on spacecraft. Although no spacecraft were lost, one instrument on the Mars Odyssey spacecraft was disabled by radiation at Mars's orbit. While these events occurred during extreme space weather, the list is by no means uncommon or exhaustive.

Many of the recommendations in this chapter are directed at agencies other than NASA, but NASA's Heliophysics Division plays two critical roles in meeting the challenges of space weather.

First, NASA is the lead agency for producing the scientific understanding that underlies space weather. This mission is clearly distinct from monitoring the space environment. The distinction is best illustrated by the difference between meteorology (the science of weather) and obtaining and using weather information for forecasting. NASA does the meteorology while other agencies obtain and use space weather information, ultimately for long-term and short-term forecasting.

Second, NASA is important to transitioning data acquisition programs and platforms into operational use. Often the data taken for science and for monitoring the environment are the same but are put to different uses. For example, at the Earth-Sun L1 Lagrange point (the Lagrange point upstream of Earth) solar wind data must be real-time for now-casting and forecasting but not necessarily for scientific studies. This contrast in scientific and operational use of data led to the following recommendation:

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[5] National Research Council, *Plasma Science: Advancing Knowledge in the National Interest,* The National Academies Press, Washington, D.C., 2007.

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

The decadal survey recognized several measurements (e.g., monitoring of L1 solar wind and solar and geospace imaging) that should be transitioned from science to operations. Monitoring the solar wind is most straightforward because the requirements are well known. The importance of L1 measurements for space weather resulted in the recommendation that NOAA assume responsibility for obtaining L1 solar wind measurements. In contrast, the 2005 Roadmap recommends three *partnership* missions (Heliostorm, L1-Heliostorm, and L1 Earth-Sun) to satisfy future L1 monitoring. These recommendations clearly mix science goals (NASA's mandate) with monitoring requirements (NOAA's mandate) and do not adhere to the decadal survey recommendation.

The continued success in acquiring real-time solar wind data at L1 from the ACE spacecraft has led to a dangerous complacency at both NASA and NOAA, by causing NOAA to rely on ACE for operational purposes. ACE is a scientific mission, not an operational mission. The spacecraft is well beyond its 2-year mission design, and while it may continue to operate for many years, there are several spacecraft systems and solar wind instruments on ACE that could fail at any time. ACE has neither the on-orbit redundancy nor the backup spacecraft that are standard of operational missions like NOAA's weather satellites. By not recognizing these deficiencies, NASA and NOAA have created a barrier to transitioning L1 and other measurements to real-time operations.

Interagency coordination for theory and modeling is much better than for the transition of measurements from science to operations. The decadal survey recommended as follows:

2.5.2 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.

NASA's CCMC, a multiagency R&D partnership for the next generation of space science and space weather models, is evidence of this coordination. CCMC functions are (1) to serve the research community by providing model runs on request and (2) to support the transition of research models to operations through systematic metrics-based evaluations as well as science-based validations. CCMC also has a strong educational component; it routinely hosts summer students and provides model outputs for K-12 and college space science education. While CCMC is a NASA-funded research program, its steering committee is interagency. It is also highly cross-disciplinary, combining numerical analysis, high-performance computational science, and integrated solar, interplanetary, magnetospheric, ionospheric, and atmospheric physics. NASA clearly recognizes CCMC as both a research asset and as a LWS tool for enabling transition to operations.

The NASA/NOAA agreement to share modeling and verification for potential operational space weather models is another important step in improving interagency coordination. This effort is relevant to the recommendation that NOAA and the Department of Defense (DOD) should prioritize operational needs and determine which of the competing models is best suited for particular operational environments.

## 2.6 EDUCATION AND PUBLIC OUTREACH

Chapter 6 of the decadal survey addresses NASA's important role in education and public outreach (E/PO). It contains recommendations to expand and improve the program beyond the capabilities that are presently in place.

**Grade: C**

***Finding:*** NASA's E/PO programs are regarded as generally successful, with several notable successes among the mission-associated programs. However, NASA programs have emphasized elementary school and public education despite the decadal survey recommendation that educational efforts should focus on college and university-level training, a goal that remains poorly addressed.

***Background:*** Mission-associated E/PO programs continue to draw praise from many segments of the community. The number of Web sites is growing, informing the public about the accomplishments of various missions and the relevance of their science to society as a whole. Scientific movies of auroral displays or solar eruptions remain among the most compelling examples of how space can directly affect Earth and translate directly into public appreciation of the overall NASA mission of space exploration.

However, the decadal survey was clear in defining two main concerns for education and public outreach:

- College and university-level undergraduate and graduate training aimed at providing "a sufficient number of scientists trained in solar and space physics . . ."
- Lower level education and public outreach aimed at contributing to the "national effort to enhance education in science and technology."

NASA's E/PO efforts have been focused solely on the second concern—elementary and high school level general-interest educational materials. This disconnect is serious and requires an examination of whether NASA is capable of meeting higher-level educational needs. It becomes apparent when specific recommendations from the survey are recalled:

> 2.6.1 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.

The survey concluded that educational activity in solar and space physics is most influential at the undergraduate level and above. The challenges in this area arise from too few faculty positions at universities and too few institutions having comprehensive programs. The NSF has established and funded a program of faculty positions that addresses very well the spirit of this recommendation, but NASA has taken no action and made no progress in establishing bridged faculty positions.

> 2.6.2 The NSF and NASA should jointly support an initiative that provides increased opportunities for distance education in solar and space physics.

NASA has expressed interest in coordinating E/PO activities that are presently distributed across many different programs, a prerequisite for engaging in serious distance education. There have been notable mission-specific successes in distance education, including the solar irradiance monitoring program in Africa established under the SDO program at Stanford University. However, there has been no effort to develop a coordinated distribution of materials to schools or remote sites.

> 2.6.3 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.

Undergraduate students involved in research activity go on to pursue careers in science in far greater numbers than those not involved in research. Despite the well-documented success of NSF's Research Experiences for Undergraduates program, no specific avenue for support of undergraduate education can be identified in the Heliophysics Division. The recent elevation of support for education-related activities to fully fledged proposals for evaluation within the SR&T program is a significant step.

But successful SR&T E/PO proposals will require closer coordination and monitoring, either from NASA or from experts at external institutions, to develop meaningful college-level participation in research. The restoration of a regional broker/facilitator network could also contribute substantially to more competitive college and university participation in NASA's heliophysics programs.

> 2.6.4 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.

NASA has been successful in primary and secondary education primarily owing to the mission-specific E/PO efforts of external groups. Some recent notable examples include the development of teacher training seminars and materials on solar physics through Solar-B funding to the Chabot Space and Science Museum in Oakland, California. The Chabot team has also created a prominent Hinode (Solar-B) display of Sun-Earth connection science that is seen by thousands of museum visitors every year.

Education apart from mission-based programs has until recently been accomplished through supplemental funding attached to NASA SR&T grants. This methodology has met with only limited success, largely because there has not been enough funding to support the teachers and develop the materials themselves. Recently, the Heliophysics Division changed this approach and expects to evaluate a limited number of proposals for E/PO activities as part of the annual competition supported through the R&A funding line. This will improve the effectiveness of the heliophysics education program, but only if the emphasis is on funding the best ideas from established experts in the field of E/PO *and* experts in student learning and curriculum development.

## 2.7 STRENGTHENING THE SOLAR AND SPACE PHYSICS RESEARCH ENTERPRISE

Chapter 7 of the decadal survey described the variety of ways in which solar and space physics research is conducted in the nation and cited four ways to strengthen the enterprise by improving the vitality of the research community, using resources efficiently, applying appropriate policy and management to the programs, and fostering interagency and international coordination and partnership.

**Grade: C**

***Finding:*** Some initiatives to strengthen the solar and space physics enterprise have made progress. NASA has processes in place to capitalize on existing research assets, has allocated funding to revitalize the Suborbital Program, includes space physics instruments in Planetary Division missions, and continues to have an open door data policy. However, there has been limited or no progress on other initiatives. Launch capabilities continue to be inadequate, NASA has not undertaken an independent review of its relationship with academia, and some Announcements of Opportunity could better tailor mission rules to mission scope. Moreover, International Traffic in Arms Regulations (ITAR) continue to hamper international cooperation on missions.

***Background:*** Having identified the four main areas in which the solar and space physics enterprise could be improved, the decadal survey makes several recommendations concerning each.

> 2.7.1 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.

Unfortunately, there is no mention of this recommendation in the NASA Heliophysics Roadmap and no steps appear to be in place to set up the recommended review. The lack of continuity in spaceflight programs is a serious impediment to university participation in the development of new space instrumentation and associated analysis of space data. Only very large institutions and NASA field centers have the diversity to sustain the engineering and management expertise required for spaceflight missions. It is nevertheless important that the university community maintain the nation's ability to produce the scientists and technicians that are needed and for this NASA field centers and universities must collaborate.

2.7.2 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.

The power of the linking space and ground assets was demonstrated during the 2003 Halloween solar super-storm, when the effects of the storms were observed at the Sun, at Earth, in the solar system, and out to the edge of the heliosphere. Existing assets are effectively used in the Heliophysics Great Observatory, which will continue to evolve as new assets become available. At NASA there is a framework within the senior review process to support prioritized space assets that contribute to the Heliophysics Great Observatory.

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

The Suborbital Program earned a grade of *B* in Section 2.2, which provides additional information on the status of the program and support for it.

2.7.4 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 strength of the Heliophysics Division's research program stems from its balanced distribution of missions, which have historically utilized the Suborbital Program, the SMEX Pegasus launcher, and the MIDEX Taurus and Delta II launch vehicles. Nevertheless, the survey listed specific issues that needed attention:

- Launch vehicle costs were growing, by as much as 25 percent for a SMEX and 33 percent for larger missions.
- Pegasus was the only qualified launch vehicle for SMEX missions.
- There were no launch vehicles for spacecraft that fit between the suborbital and SMEX missions.

The recommendations above were crafted to address these issues. Unfortunately, since the decadal survey, the launch vehicle market has worsened dramatically.

- Pegasus costs have increased to 30 percent of the total SMEX mission cost.

- There are still no low-cost launch vehicles between the suborbital and Pegasus-launched SMEX missions.
- There have been no secondary payload opportunities.
- There have been no heliophysics missions manifested on foreign launch vehicles.
- There are no viable and reasonably priced medium-size launch vehicles.
- There is a limited selection of relatively expensive heavy-lift launchers.

Currently, there are no MIDEX missions and no plans for them in the future because there are no viable launch options between the Pegasus and the Atlas V and Delta IV class launchers. Attempts to obtain a new, qualified medium-size launch vehicle to replace the Delta II, such as the Minotaur II, have yet to bear fruit. Similarly, a lack of low-cost launch options for the smallest payloads has resulted in the effective termination of the University Explorer Program. This situation contributes significantly to increased mission costs and threatens the future of a balanced program of missions of different sizes.

2.7.5 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.

NASA's Planetary Science Division has incorporated space plasma physics instruments in its missions, including the New Frontiers Program's Juno mission to Jupiter and the Mars Exploration Program's MAVEN mission to Mars. The Juno mission will satisfy the main objectives of the JPM, the third-ranked moderate mission recommendation from the decadal survey, without using Heliophysics Division funds.

2.7.6 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.

2.7.7 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.

The decadal survey recognized the power of principal investigator–led, cost-capped missions in establishing and maintaining cost discipline during mission development and cited several successful Explorer-class missions that were completed within their budgets. Based on these successes, the decadal survey made a three-part recommendation to NASA.

Mission rules and responsibilities of the various contracting parties are defined in mission AOs, and recently released AOs clearly intend to meet the spirit of these recommendations. However, more attention to tailoring mission rules to mission scope will improve the present path. Since the decadal survey, there have been one SMEX AO and one mission AO (the 2007 SMEX AO and the RBSP AO). In the SMEX AO, there is specific intent to define mission rules clearly in the proposal stage and to tailor mission rules to mission scope and complexity.[6] The AO also clearly states the responsibilities of the principal investigator in mission implementation and execution.

[6] The 2007 SMEX AO states as follows: "In this AO the reason for changing the risk classification of SMEX missions from Class C to tailored Class D is to return to the original intent of the Explorer Program's SMEX missions."

The RBSP AO is considerably vaguer in defining mission rules.[7] No mission classification is given for the instruments and there are only the vague references to the rules themselves. The RBSP mission science, though more complex than that of a SMEX mission, was divided into several instrument and instrument suite proposals that are of the same level and complexity as a SMEX mission. The RBSP AO does not recognize the complexity or the tailoring of the mission rules to the mission scope.

> 2.7.8 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.

NASA's open data policy ensures the timely distribution of science products to the community. The introduction of virtual observatories to unify the interfaces required to make use of the available data sets is also commendable, as is NASA's collaboration with other agencies to provide research opportunities of common interest. No unified data distribution system is available for spaceflight missions conducted under the auspices of other agencies, which means the full potential of the nation's resources in this area cannot be achieved.

> 2.7.9 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

For interagency modeling efforts, the CCMC program earned a grade of *A* in Section 2.5, which provides additional information on the status of the program and support for it.

For instruments, the present pace of development does not present any barriers to incorporating state of the art sensors into operational programs.

> 2.7.10 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.

The 1999 DOD Authorization Act placed all space satellites, as well as related ground equipment, technical data, and services, on the U.S. Munitions List. Although the State Department loosened the ITAR restrictions on some interactions involving accredited U.S. institutions of higher learning in 2002, a year later the decadal survey observed as follows: "Much of the ease with which international cooperation in space-based research was achieved in the past has been lost in the last several years as regulatory changes intended to apply to arms and related matters have been applied to scientific activities" (p. 160).

Little has changed in the implementation of ITAR since the decadal survey. The ITAR regulations continue to have major deleterious effects on international scientific activities that depend on satellites and have caused serious problems in the teaching of university space science and engineering

[7] "NASA intends to give the Principal Investigator and his/her team the ability to use their own management processes, procedures, and methods to the fullest extent possible," from Section 3.5.1 of *Small Explorers (SMEX) and Missions of Opportunity 2003,* Solicitation AO_03_OSS_02, released February 3, 2003, p. 14, available at http://nspires.nasaprs.com.

classes. An NRC workshop[8] highlighted a number of ongoing issues that are making international collaborations much more problematical: (1) uncertainty about the definition of fundamental research, (2) confusion of rules applying to publication of results, (3) confusion over how ITAR regulations apply differently to universities, national laboratories, government, and industry, (4) confusion over license requirements related to the transmittal of information to non-U.S. project participants, and (5) added costs and time delays involved in obtaining licenses and technical-assistance agreements from the Department of State.

One result of the 2007 workshop was a renewed commitment by both the State Department and members of the university community to communicate more effectively on issues involving ITAR and to facilitate improvements in the efficiency and clarity with which the regulations are implemented. However, the only significant change in ITAR implementation that has occurred over the past year has been the appointment of a representative of the scientific community to the Defense Trade Advisory Group, which advises the Department of State on issues involving munitions exports.

[8] The workshop was held on September 12 and 13, 2007, and *Space Science and the International Traffic in Arms Regulations: Summary of a Workshop* was published in 2008 (The National Academies Press, Washington, D.C.). The meeting had broad participation from the scientific community, university and laboratory administration, industry, the federal government, congressional staff, international space agencies, the policy community, and NRC staff.

# 3

# Recommendations

The third and last item in the committee's charge is to deliver recommendations that could improve the next decadal survey and optimize the value of NASA's heliophysics programs without altering the priorities and recommendations of the 2003 solar and space physics decadal survey,[1] (the "decadal survey"). Based on the background information and grades provided in Chapters 1 and 2, the committee makes 17 recommendations in the following three areas:

- *Recommendations to fulfill the Integrated Research Strategy*. The central recommendation of the decadal survey was for a coordinated set of spacecraft missions and other research activities that could provide concurrent observations of the same solar and space phenomena as well as other research synergies. Although it would be extremely difficult now to restore all of the science content anticipated in the Integrated Research Strategy, this committee makes five recommendations that could help restore key features of the decadal survey's Integrated Research Strategy before the end of the decade.
- *Other recommendations to fulfill the decadal survey*. The decadal survey also made recommendations on research priorities, technology development, societal effects, education and public outreach, and supporting activities. This committee makes four recommendations to improve NASA's execution of the decadal survey recommendations in these areas.
- *Guidance to improve the next decadal survey*. The committee also provides eight guidelines intended to improve the quality of the next decadal survey in solar and space physics.

The committee recognizes that the decadal survey is the primary process for establishing science and mission priorities for solar and space physics research. Wherever possible, the committee's recommendations seek to reinforce the recommendations of the 2003 decadal survey.

## RECOMMENDATIONS TO FULFILL THE INTEGRATED RESEARCH STRATEGY

With the Magnetospheric Multiscale (MMS) mission, NASA has begun to implement the Integrated Research Strategy of the decadal survey. But the budget issues described in Chapters 1 and 2, including cost growth in the MMS and Radiation Belt Storm Probes (RBSP) missions and funding limitations in the Solar-Terrestrial Probes (STP) program, have forced the deferment of the other missions that the decadal survey anticipated would be under development by 2009. Subsequent NASA decisions, also described in Chapter 1, including the reallocation of funding to the Solar Probe Plus mission and the inadequate implementation of the Geospace Network mission, threaten to upset the recommended mission queue and further adversely affect the decadal survey's Integrated Research Strategy.

The committee makes five recommendations to buttress the survey's Integrated Research Strategy, to restore as many of the planned concurrent observations as possible, and to mitigate the underlying budget issues.

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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.

**Recommendation 1: (a) If no budget augmentation is forthcoming that is large enough to support the planned Solar Probe launch date of 2017 without impacting other Heliophysics Division missions, NASA should consult with the community through a formal review mechanism (such as committees of the NASA Advisory Council or other independent, external, community priority-setting bodies) to determine Solar Probe's priority relative to that of other decadal survey recommendations and its launch date. (b) An implementation plan for the science objectives of the Geospace Network that includes both ionosphere-thermosphere and magnetosphere components should be developed as soon as possible in advance of lower-ranked moderate missions in the 2003 decadal survey's recommended mission queue.**

The queue of missions and their timing recommended in the decadal survey provides the concurrent observations that underpin the survey's Integrated Research Strategy and NASA's Heliophysics Great Observatory.

The decadal survey recommended that NASA should pursue Solar Probe concurrently with its moderate mission recommendations only if the heliophysics budget was augmented to support Solar Probe development. The decadal survey recommended that if that was not possible NASA should pursue Solar Probe only after the survey's moderate mission recommendations had been developed.

NASA recently completed a promising study to redesign the Solar Probe mission, and NASA's FY 2009 budget reallocates $238 million in the outyears to begin development of the new Solar Probe Plus mission. However, the current FY 2009 budget runout is not large enough to allow Solar Probe Plus to meet its originally planned launch date. Moreover, contrary to the decadal survey, Solar Probe Plus would begin development before most of the survey's recommended moderate missions, including the Multispacecraft Heliospheric, Geospace Electrodynamic Connections, Magnetospheric Constellation, Solar Wind Sentinels, and Stereo Magnetospheric Imager missions.

Consistent with the mission queue recommended in the decadal survey, NASA should not begin development of the Solar Probe Plus mission unless the Heliophysics Division's budget is adequate to support the original launch date or unless NASA formally consults with the community and it recommends beginning development of the Solar Probe Plus mission before the remaining moderate mission recommendations in the 2003 decadal survey.

The Geospace Network mission was the second-ranked moderate mission recommendation in the decadal survey's Integrated Research Strategy and would consist of "two radiation-belt mapping spacecraft and two ionosphere-mapping spacecraft to determine the global response of geospace to solar storms.

As described in Chapter 2, NASA has begun implementing the radiation-belt mapping component of the Geospace Network mission but not its ionosphere mapping component. Because solar storms are transient events, both components of the Geospace Network must operate simultaneously to obtain data that allow understanding of how energy is exchanged between the Earth's radiation belts and its ionosphere during solar storms. Without full implementation of the Geospace Network mission, a state-of-the-art ionosphere-thermosphere mission is the most critical gap in the decadal survey's Integrated Research Strategy. Thus, NASA should immediately identify and pursue means to reestablishing an ionosphere-thermosphere mission to achieve the science goals of the Geospace Network mission.

Consistent with the mission queue recommended in the decadal survey, NASA should begin implementation of the full Geospace Network before pursuing the survey's other moderate mission recommendations.

**Recommendation 2: Funding for the Heliophysics Explorer Program should be restored to recommended levels as rapidly as possible. The ramp-up in the current 5-year-projection budget is encouraging and should be accelerated as soon as possible.**

In addition to providing frequent flight opportunities for world-class investigations, the Heliophysics Explorer Program offers the most likely path forward for restoring as much of the 2003 decadal survey's Integrated Research Strategy as possible before the next decadal survey. Although the decadal survey could not explicitly rank the Explorer Program missions, which are competitively selected, it incorporated a steady funding level for the Explorer Program in its budget recommendations.

Since the decadal survey, the annual budget for the Heliophysics Explorer Program has decreased, from almost $120 million in FY 2005 to just over $45 million in FY 2008. NASA's FY 2009 budget run out proposes to reverse this trend, increasing the Explorer Program's budget to $90 million by FY 2013. (These figures assume that the future Explorers budget line is evenly allocated between heliophysics and astrophysics missions.) The committee endorses the budget projections and recommends that NASA seek to accelerate Heliophysics Explorer budget growth.

Heliophysics Explorer funding should be restored irrespective of launch availability for the medium-sized (MIDEX) payloads. The number of awards in the 2008 Small Explorer (SMEX) downselect demonstrates the depth of viable mission proposals available to NASA.

**Recommendation 3: Funding for the Solar-Terrestrial Probes flight program should be restored to enable the recommended coordination of investigations.**

Most of the decadal survey's moderate mission recommendations fall under NASA's STP program. Stable STP funding was therefore necessary to carry out the decadal survey. However, STP funding instead fell from its peak of approximately $140 million in FY 2004 to approximately $70 million in FY 2008.

Although the planned restoration of funding for the Heliophysics Explorer Program may restore some of the science content anticipated for the decadal survey's Integrated Research Strategy, NASA does not know in advance what missions will be proposed to the Heliophysics Explorer Program and therefore cannot rely on the program to fulfill the decadal survey. To carry out the Integrated Research Strategy, NASA needs to fund the Solar-Terrestrial Probes program at the originally planned levels.

**Recommendation 4: Future Solar-Terrestrial Probes and Living With a Star missions should reduce mission requirements that exceed those assumed in the decadal survey to match resource constraints.**

As described in Chapter 2, the content in the Announcements of Opportunity (AOs) for the MMS and RBSP missions substantially exceeded the assumptions underlying the budget estimates in the decadal survey, leading to larger and more complex spacecraft, larger launch vehicles, and other cost increases that grew development budgets by a factor of two or more. In turn, larger MMS and RBSP budgets forced the deferment of other missions in the decadal survey's Integrated Research Strategy and NASA's Heliophysics Great Observatory.

For the remainder of the decade, NASA should take steps to ensure that the science content and mission requirements for future missions in the STP and Living With a Star (LWS) programs do not imply cost estimates that exceed these missions' budgets and require additional resources. In particular, before releasing a future science payload AO, NASA should revisit the relevant mission science content and budget estimates from the decadal survey, and ensure that departures from those assumptions are well understood, justified, and necessary. If mission growth still exceeds the budget estimates from the decadal survey, NASA should take additional actions, including de-scoping mission requirements, to be consistent with the science content assumed in the decadal survey.

**Recommendation 5: The mission management mode (principal-investigator-led versus center-led) on future Solar-Terrestrial Probe and Living With a Star missions should match resource constraints. Changes in management mode and in associated overhead costs that depart from the original decadal survey should be matched by changes in mission budgets.**

A key assumption for many of the moderate mission recommendations in the decadal survey was that the entire mission, not just the science payload, would be competitively selected from proposals by principal investigator–led teams and managed by those teams. The decadal survey also recommended that NASA "place as much responsibility as possible in the hands of the principal investigator." NASA has instead chosen to have a NASA field center manage the development of the survey's first moderate mission recommendation, the MMS mission. It is possible that the change in management mode was one reason for MMS cost growth.

NASA should ensure that a switch in management mode for missions after MMS in the STP program does not increase cost beyond the mission's budget and requires additional resources. In particular, before deciding on a management mode for future STP and LWS missions, NASA should revisit the assumptions of the decadal survey and ensure that departures from them are not only well understood, justified, and necessary but also accompanied by appropriate budgetary resources.

## OTHER RECOMMENDATIONS TO FULFILL THE DECADAL SURVEY

To better support NASA's implementation of the decadal survey's recommendations in the areas of research priorities, technology development, societal effects, education and public outreach, and supporting activities, the committee makes the following four recommendations.

**Recommendation 6: NASA's mission roadmapping activities should seek to retain the balance and synergy of the decadal survey's Integrated Research Strategy.**

Several key science questions in the decadal survey receive little or no attention in the Heliophysics Roadmap, including coronal heating, the heliosphere's interaction with the interstellar medium, and the magnetospheres and ionospheres of other planets. NASA should ensure that future roadmaps incorporate these elements and reflect the balance and synergy of the decadal survey's Integrated Research Strategy in detail.

**Recommendation 7: NASA should continue to aggressively pursue the recovery of a range of launch capabilities, including replacement or restoration of the Delta II medium-lift launch vehicle, secondary payload capabilities, and access to foreign launch capabilities.**

Solar and space physics research relies heavily on access to the lighter end of the space access spectrum, and the dominance of moderate, small, and vitality recommendations in the decadal survey reflects this fact. However, options for launching lighter payloads are shrinking, and moves to larger launch vehicles in the MMS and RBSP missions increased costs for both missions. NASA is pursuing new medium-lift launch capabilities, such as the Minotaur II, through the Commercial Orbital Transportation Systems (COTS) program. Although limited by national policy, NASA's Heliophysics Division has also attempted to expand the community's launch options by the conversion of excess ballistic missiles. The committee applauds these efforts and recommends that NASA press hard on all possible options for space access for solar and space physics payloads, including use of secondary payload and foreign launch assets.

**Recommendation 8: The future of key measurements at L1 needs to be resolved between NASA and NOAA at the earliest possible time.**

Solar wind measurements at L1 are critical for both research analysis and space weather prediction, and the decadal survey recommended that NOAA assume responsibility for operationalizing these measurements. However, NASA's Heliophysics Division Roadmap includes three NASA missions

(Heliostorm, L1-Heliostorm, and L1 Earth-Sun) to be undertaken in partnership with NOAA that mix research and operational L1 requirements.

Given the age of the current L1 monitoring spacecraft (Advanced Composition Explorer) and the and lack of redundant systems to support operational measurements, it is critical that L1 measurements be operationalized at NOAA quickly. Consistent with the decadal survey, NASA should work with NOAA to handoff cleanly and clearly L1 measurement responsibilities as soon as possible.

**Recommendation 9: NASA should emphasize the involvement of undergraduate and graduate students in educational outreach grants. NASA should also consider restoring facilitator positions for coordinating educational outreach efforts between researchers, and NASA and should improve the coordination of education efforts between NASA's Heliophysics Division and its Office of Education.**

The decadal survey recommended that NASA establish education activities to better support college and university faculty in solar and space physics and to encourage college students to enter the field. Much of NASA's education and outreach effort has instead focused on primary and secondary school students.

Even in the absence of such higher education initiatives, investigators can make stand-alone higher education proposals to NASA's supporting research and technology grants program. This fact is little known in the solar and space physics community, and NASA should advertise it more widely.

NASA could also improve university involvement by restoring the network of regional brokers/facilitators who created and nurtured partnerships between space scientists and educators to carry out highly leveraged education activities prior to 2007. NASA's Heliophysics Division could also explore ways to leverage resources in NASA's Office of Education to increase university participation in the Division's programs.

## GUIDANCE TO IMPROVE THE NEXT DECADAL SURVEY

Although carried out over a span of years, National Research Council's (NRC's) decadal planning is an iterative process where the lessons learned in the formulation and execution of one decadal survey can inform and improve the next decadal survey. To improve the next decadal survey in solar and space physics, the committee offers eight guidelines. These guidelines are not formal recommendations to NASA, but they do provide important advice to the next decadal survey committee on, among other things, negotiating the statement of task for the next decadal survey.

**Guideline 1: Schedules for future NASA roadmapping exercises should be phased to follow future NRC decadal surveys and midterm assessments.**

Every 2 years, NASA's Heliophysics Division undertakes a roadmapping exercise to formalize the science, technology, and mission details that underpin the Division's activities. Ideally, NASA's roadmaps provide planning depth that builds on the research priorities identified through the NRC's broad decadal planning process.

The Heliophysics Division roadmapping exercise is out of sync with the NRC decadal planning process. For example, NASA undertook its 2008 roadmapping exercise in parallel with the development of this report, and both documents were planned for release in February 2009. This makes it difficult, if not impossible, for NASA's 2008 heliophysics roadmap to consider and incorporate the findings and recommendations of this NRC mid-decade assessment.

NASA should ensure that the schedule for the development of future heliophysics roadmaps follow and can build upon the release of the next decadal survey in solar and space physics.

**Guideline 2: The next decadal survey should reconsider any missions from the 2003 decadal survey that have not begun development at the time of the next decadal survey.**

Even if this report's recommendations on fulfilling the Integrated Research Strategy will have been executed, most of the recommended spacecraft missions from the 2003 decadal survey will not have begun development at the time of the next decadal survey. Advances in the field, changes in research priorities, and other factors may make some or all of those unimplemented recommendations obsolete. The next decadal survey should therefore revisit the science goals attached to the spacecraft mission recommendations from the 2003 decadal survey that will not have entered development and prioritize them against newly proposed missions and activities.

**Guideline 3: The next decadal survey should incorporate cost thresholds beyond which NASA must consult with the community through a formal mechanism (such as committees of the NASA Advisory Council or other independent, external, community priority-setting bodies) to review a mission's continued priority.**

Given the considerable cost growth on the MMS and RBSP missions and its negative impact on the 2003 decadal survey's Integrated Research Strategy and NASA's Heliophysics Great Observatory, the next decadal survey should include cost thresholds for spacecraft missions. Cost thresholds could be based on broad categories of mission size (a mission may, for instance, have graduated to a more expensive category since the survey), a percentage of mission cost, amounts specific to each mission, or another mechanism. When a mission's projected cost exceeds the threshold, NASA should consult with the solar and space physics community through a formal review mechanism (such as a committee of the NRC or the NASA Advisory Council) before deciding to continue the mission's development, reduce the mission's scope, or terminate it in favor of another mission or other research activities.

**Guideline 4: The next decadal survey should develop a methodology to preserve mission coordination when the importance of mission coordination is equal to or greater than the importance of the missions themselves.**

Coordinated observations by multiple spacecraft of the same solar and space events are central to the 2003 decadal survey's Integrated Research Strategy and to NASA's Heliophysics Great Observatory. However, the decadal survey did not explicitly weigh the priority of coordinated observations against the priority of individual missions. Budget issues have forced the deferral of several missions recommended by the decadal survey, reducing or eliminating opportunities for coordinated observations and putting the decadal survey's Integrated Research Strategy at risk.

The next decadal survey should provide explicit recommendations about the relative priority of science from coordinated observations versus science from individual spacecraft missions. If coordinated observations are deemed a high priority, the next decadal survey should provide clear guidance on how to preserve coordinated observations, such as descoping a mission, setting science floors for individual missions, or rescheduling mission timelines.

**Guideline 5: In addition to refining cost estimates for mission development, the next decadal survey should improve cost estimates for mission operations and data analysis.**

The next survey committee should include cost and technical readiness experts to help it arrive at realistic budgets. Also, actual costs for mission operations and data analysis in NASA's Heliophysics Division have been 50 to 100 percent greater than assumed in the 2003 decadal survey. The next decadal survey should incorporate more realistic cost estimates for mission operations and data analysis.

**Guideline 6: The next decadal survey should explicitly budget for all recommendations, not just those associated with missions, MO&DA, and research.**

The 2003 decadal survey included a number of recommendations for technology development, interdisciplinary research, education and public outreach, and supporting activities that were not called out in the budget estimates. Although the individual budget impact of each initiative is small, together the impacts can be significant. The next decadal survey should incorporate cost estimates for all recommendations with a budget impact. It should emphasize the explicit role of the Explorer Program rather than simply including a proposed Explorer wedge as part of a decadal budgetary figure.

**Guideline 7: The next decadal survey should maintain the practice of providing a prioritized consensus list of program recommendations.**

One suggestion to the committee from NASA was that the next decadal survey should spell out only the highest-level science objectives for NASA and other agencies, leaving program and mission definition to the agencies. In the area of flight programs, for example, this would allow NASA to make its own decisions on when and how to configure and implement specific missions. The committee realizes, and indeed stresses throughout this report, that there should be mechanisms in place to deal with changing fiscal conditions. However, the suggestion to abandon defining and ranking actual programs and missions, set by thoughtful analysis from the community, is not the appropriate solution.

**Guideline 8: The next decadal survey should include a sufficient number of scientists with spaceflight investigation experience from each of the relevant subdisciplines.**

Having the full breadth of observational methods, theory, and modeling all represented in a decadal survey is central to a community consensus report. For the specific case of recommendations for NASA that deal overwhelmingly with spaceflight missions, it is crucial that each of the subdisciplines (solar, heliosphere, magnetosphere, and aeronomy) have a comparable number of experienced spaceflight investigators on the final survey panel.

# Appendixes

# A

# Letter of Request from NASA

National Aeronautics and Space Administration
**Headquarters**
Washington, DC 20546-0001

NOV 15 2007

Science Mission Directorate

Dr. Lennard A. Fisk
Chair, Space Studies Board
National Research Council
500 5th Street, NW
Washington, DC 20001

Len—
Dear ~~Dr. Fisk~~:

The NASA Authorization Act of 2005 established a requirement for rolling annual assessments of NASA's science programs. The two principal components of this new oversight requirement are National Academy of Sciences (NAS) reviews and reports by the NASA Administrator to the House Committee on Science and the Senate Committee on Commerce, Science, and Transportation on findings of these and any other timely reviews of the programs in question and planned actions to be taken in response to these reviews. It has been NASA's plan to phase these reports and the underlying NAS assessments in the order in which the most recent Academy science program decadal surveys have been delivered to NASA.

The first two reviews in this series address NASA's astrophysics and planetary science programs, with the latter now nearing completion. According to our plan, the third of these congressionally required reports would cover the field of heliophysics. We anticipate that the primary recommendations against which NASA's performance should be evaluated would be those provided in the relevant NAS decadal survey, The Sun to the Earth-and Beyond, (2002). In order to support development of NASA's report to the Committees, I would like to request that the National Research Council (NRC) conduct a review that will assess the following:

- How well NASA's current program addresses the strategies, goals, and priorities outlined in the heliophysics decadal survey and other relevant Academy reports;
- Progress toward realizing these strategies, goals and priorities; and
- Any actions that could be taken to optimize the science value of the program in the context of current and forecasted resources available to it.

The review should not revisit or alter the scientific priorities or mission recommendations provided in the 2002 decadal survey, but may provide guidance about implementing the recommended mission portfolio in preparation for the next decadal survey.

In order for NASA to be able to use the results of the heliophysics review in formulating its report to the House and Senate Committees on the schedule required, the NAS findings must be received by NASA no later than January 15, 2009.

I would like to request that the NRC submit a suitable proposal for execution of the review by the Space Studies Board. Once agreement on the scope, cost, and schedule of the proposed study has been achieved, the Contracting Officer will issue a task order for implementation. The technical point of contact for this study within the Science Mission Directorate will be Dr. Barbara Giles, who can be reached at
(202) 358-1762 and barbara.l.giles@nasa.gov.

Sincerely,

S. Alan Stern
Associate Administrator for
Science Mission Directorate

# B

## Committee and Staff Biographical Information

STEPHEN A. FUSELIER, *Co-Chair,* is a researcher at Lockheed Martin Advanced Technology Center. He has been involved with the development of the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) spacecraft since its inception. Dr. Fuselier served as co-investigator on two instruments on-board IMAGE: Far Ultraviolet (FUV) imagers and the Low Energy Neutral Atom (LENA) imager. He also led the U.S. investigation on the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) on the joint European Space Agency/NASA ROSETTA mission. Dr. Fuselier is the author or co-author of over 60 scientific publications, a fellow of the American Geophysical Union (AGU), and the 1995 recipient of the AGU James B. Macelwane Award. He served on the NRC Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop, Committee on the Assessment of the Role of Solar and Space Physics in NASA's Space Exploration Initiative, and Committee on Exploration of the Outer Heliosphere: A Workshop.

RODERICK A. HEELIS, *Co-Chair,* is a Cecil and Ida Green Honors Professor at the University of Texas at Dallas where he is also Director of the William B. Hanson Center for Space Sciences. He is active in observation and modeling research and education programs devoted to understanding the electrodynamic interactions between charged and neutral particles in the space environments of the Earth and other planets. He has been a principal investigator for grant and contract research sponsored by NASA, DoD and NSF, presently serving as the principal investigator on the NASA Coupled Ion Neutral Dynamics Investigation (CINDI). Dr. Heelis is a fellow of the American Geophysical Union and has served on the NASA Sun-Earth Connections Advisory subcommittee, the NASA Space Science Advisory Committee, the NRC Committee on Solar and Space Physics, and the NRC Solar and Space Physics Survey Committee.

THOMAS BERGER is solar physicist at the Lockheed Martin Solar and Astrophysics Laboratory. He specializes in the design, implementation, and use of advanced optical filters in studies of the Sun's magnetic field and outer atmosphere. Dr. Berger has been involved in the SOHO/MDI, TRACE, and SDO/HMI satellite instrument programs. He has been principal investigator on two NASA grants studying the smallest observable magnetic fields on the Sun and is currently a co-investigator on the Japanese Hinode/Solar Optical Telescope mission where he has discovered new flows in solar filaments. Dr. Berger's technical specialties include image and movie processing and analysis, optical telescope design, optical filter and polarimetric instrumentation and analysis. He has served on several NASA proposal evaluation committees as well as the Missions Operations Working Group and is currently the chair of the NSF Advanced Technology Solar Telescope Science Working Group.

JACK R. JOKIPII (NAS) is the Lunar and Planetary Laboratory Regents' Professor at the University of Arizona. Dr. Jokipii's research is in the areas of theoretical astrophysics and space physics. His research covers the transport and acceleration of cosmic rays and energetic particles in the solar wind and in the galaxy, with major emphasis on the Ulysses and ACE space missions. Dr. Jokipii and his research group conduct theoretical research to determine the transport coefficients of energetic particles in irregular plasmas and magnetic fields. Dr. Jokipii was a member of the NRC Panel on Theory, Computation, and

Data Exploration of the Committee on Solar and Space Physics: A Community Assessment and Strategy for the Future. He currently chairs the NRC Panel on Physical Sciences of the Associateship and Fellowship Programs Advisory Committee and serves on the NRC Committee on Solar and Space Physics.

KRISHAN KHURANA is a professor of space physics in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles. Dr. Khurana has worked on many theoretical and empirical investigations relating to the magnetospheres of Venus, Earth, Jupiter, and Saturn and is currently a co-investigator on the MAG investigation onboard Galileo. His recent research has covered theoretical models for flux ropes, a semi-theoretical model for the structure of the Venusian bow shock, ULF waves in outer magnetospheres, the structure and composition of the Jovian plasma sheet, and the maintenance of corotation in the Jovian magnetosphere. Dr. Khurana was a member of the NRC Committee on Planetary and Lunar Exploration. He currently serves on the NRC Committee on Solar and Space Physics.

DANA W. LONGCOPE is an associate professor of physics at Montana State University-Bozeman. Dr. Longcope conducts theoretical research on the basic physics of magnetic fields in ionized plasmas and the application of these concepts to magnetic fields on the Sun. He has studied the storage and release of magnetic energy in the Sun's corona through a process known as reconnection. Dr. Longcope's honors and awards include a 1997 Faculty Early Career Development grant from the National Science Foundation, the 2000 Presidential Early Career Award for Science and Engineering, the 2003 Karen Harvey Prize from the Solar Physics Division of the American Astronomical Society, and the 2003 Charles and Nora L. Wiley Award for Meritorious Research from Montana State University. He is a member of the NRC Committee on Solar and Space Physics and previously served on the NRC Panel on Solar Astronomy of the Astronomy and Astrophysics Survey Committee.

GANG LU is a senior scientist at the National Center for Atmospheric Research High Altitude Observatory. Dr. Lu specializes in space physics, with an emphasis on high-latitude ionospheric electrodynamics and the coupling of the solar wind with the upper layers of Earth's atmosphere. In particular, she analyzes and interprets space- and ground-based observations of ionospheric and magnetospheric electrodynamic quantities, and models and interprets disturbances in the ionosphere and thermosphere. One of her most significant accomplishments was to obtain the first quantitative assessment of interhemispheric asymmetry of high-latitude ionospheric convection configuration, which she achieved by combining and analyzing a large set of multi-instrument data. This collaborative study formed the backbone of the National Science Foundation-sponsored Global Environment Modeling Boundary Layer Campaigns. Dr. Lu is currently Secretary General of the Scientific Committee on Solar-Terrestrial Physics, which is an interdisciplinary body of the International Council for Science and is a former member of the NRC Committee on Solar and Space Physics.

KRISTINA A. LYNCH is associate professor of physics and astronomy at Dartmouth College. Her research interests cover auroral space plasma physics; ionospheric and mesospheric sounding rocket experiments, instrumentation, and data analysis; and wave-particle interactions in the auroral ionosphere. Dr. Lynch leads the Rocket Laboratory where studies are conducted on the structure and dynamics of auroral acceleration, specifically on sounding rocket missions such as Cascades; and on the use of multiple-payload probes to look at spatial and temporal variations in auroral precipitation. Other studies at the Rocket Laboratory include the FAST auroral satellite data set, which allows statistical investigations of auroral processes, and the development of a large calibration/plasma vacuum chamber to characterize the response of particle detectors to the auroral plasma. Dr. Lynch served on the NRC Committee on Plasma 2010: An Assessment of and Outlook for Plasma and Fusion Science and currently serves on the NRC Committee on Solar and Space Physics.

FRANK B. MCDONALD (NAS) is a pioneer and leader in cosmic-ray astrophysics and high-energy astronomy in general. He is also well known in the areas of solar wind and planetary magnetospheres. He is currently a senior research scientist in the Institute for Physical Science and Technology at the University of Maryland and formerly served as NASA chief scientist. Dr. McDonald has been involved in the study of energetic particles in the heliosphere for many years. His energetic particle experiments on the Pioneer and Voyager spacecraft continue to be a resource for studying the dynamics of the outer heliosphere and the properties of low-energy galactic and anomalous cosmic rays. Dr. McDonald is a former NAS section 16 liaison and was chair of the NRC Panel on Space Sciences. He also served on the NRC Committee on Solar and Space Physics and Committee on NASA Astrophysics Performance Assessment.

MICHAEL MENDILLO is a professor of astronomy and of electrical and computer engineering at Boston University. Dr. Mendillo leads a space physics research group that studies the upper atmospheres of the Earth, moons, and planets. Dr. Mendillo's research includes the use of radio science experiments to investigate the ionospheres of Earth, Mars and Saturn; low light-level imaging of sub-visual emissions from the Earth atmosphere; and active experiments where gaseous perturbations are introduced into space plasmas and the resulting effects observed. His studies have led to the discovery of large, tenuous sodium atmospheres escaping from Jupiter, the Moon, comet Hale-Bopp, and Mercury. Dr. Mendillo previously served on the NRC Committee on Planetary and Lunar Exploration, the Committee on Solar and Space Physics, and the Space Studies Board.

ROBERT E. PALMER is an expert on science policy and the U. S. Congress. He was staff director for the U.S. House of Representatives' Committee on Science for 12 years until his retirement in January 2005. As staff director, Dr. Palmer was involved in policy matters related to space, energy, environment, and the physical sciences. He also organized or supervised hundreds of Congressional hearings, and drafted or supervised the drafting of scores of bills, including agency authorization bills, which became public law. In addition, Dr. Palmer was the committee's lead staff member involved in analyzing federal R&D budgets and interacting with the House and Senate Appropriations Committees. Dr. Palmer served on the NRC Committee on NASA Astrophysics Performance Assessment, Committee on Solar and Space Physics, and Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop.

### *Staff*

BRANT SPONBERG, *Study Director,* is the associate director of SSB, the senior program officer for the Committee on Solar and Space Physics, and serves as a study director for the assessment of NASA's performance in solar and space physics and the astrophysics decadal survey. Before joining the SSB, Mr. Sponberg was a program analyst with the Department of Energy (2007-2008), managed commercial launch and innovative technology development programs at NASA Headquarters (2004-2006), staffed the development of the Vision for Space Exploration under the NASA Comptroller (2003-2004), and covered NASA programs for the White House Office of Management and Budget (1997-2003). Mr. Sponberg received his M.A. in science, technology, and public policy from George Washington University (1997) and his A.B. in astrophysics and history from Harvard University (1995).

CARMELA J. CHAMBERLAIN has worked for the National Academies since 1974. She started as a senior project assistant at he Institute for Laboratory Animals for Research, which is now a board in the Division on Earth and Life Sciences, where she worked for 2 years, then transferred to the Space Science Board, which is now the Space Studies Board (SSB). She is now a program associate with the SSB.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board. She joined SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.