The Space Studies Board is a unit of the National Research Council, which serves as an independent advisor to the federal government on scientific and technical questions of national importance. The National Research Council, jointly administered by the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, brings the resources of the entire scientific and technical community to bear through its volunteer advisory committees.

Support for the work of the Space Studies Board and its committees and task groups was provided by National Aeronautics and Space Administration Contract NASW-01001, National Oceanic and Atmospheric Administration Contract DG133R04CQ0009, and National Science Foundation Grants ATM-0109283 and AST-0075757.
From the Chair

In the foreword for the 2003 Annual Report of the Space Studies Board, we predicted that 2004 would be yet another pivotal year for the space program. Indeed, 2004 saw the release of a new presidential policy for NASA, and for human spaceflight in particular, and the beginning of the implementation of that policy. All the advice given, decisions made, and priorities established as a consequence will determine the direction of the space program for decades to come.

The Space Studies Board and its committees and special task groups have been very active during the year, as is documented in this annual report, attempting to ensure that the perspective of the science community is heard as the new space vision is implemented. The principal issue was identified early in the year. There was a certain excitement that the human spaceflight program would at last be revitalized, but the response was tempered by the view that to make this a true exploration program it would need to be founded on and pursued for science, with attention to optimum choices for the use of humans and robots. Enthusiasm for the vision was tempered also by the recognition that space science and Earth science from space have flourished in recent years, and that this success should not be allowed to diminish. We have, through our reports and our guidance, attempted to encourage NASA to recognize the opportunity that exists to alter forever our understanding of the universe in which we live through a broadly defined exploration program and to continue the inevitable march of this civilization into space.

The same vigilance will be required in 2005, to encourage the nation to develop a space program worthy of the vast opportunities for discovery and for increased knowledge that lie before us.

L.A. Fisk
Chair
Space Studies Board
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Space Studies Board Chairs

Lloyd V. Berkner, Graduate Research Center, Dallas, Texas, 1958–1962


Charles H. Townes, University of California at Berkeley, 1970–1973

Richard M. Goody, Harvard University, 1974–1976


Thomas M. Donahue, University of Michigan, 1982–1988


Claude R. Canizares, Massachusetts Institute of Technology, 1994–2000

John H. McElroy, University of Texas at Arlington (retired), 2000–2003

Lennard A. Fisk, University of Michigan, 2003–
Charter and Organization of the Board

THE ORIGINS OF THE SPACE SCIENCE BOARD

The National Academy of Sciences (NAS) was chartered by Congress, under the leadership of President Abraham Lincoln, to provide scientific and technical advice to the government of the United States. Over the years, the advisory program of the institution has expanded, leading in the course of time to the establishment of the National Academy of Engineering (NAE) and the Institute of Medicine, and of the National Research Council (NRC), the operational arm of the National Academies.

The original charter of the Space Science Board was established in June 1958, three months before final legislation creating NASA was enacted. The Space Science Board and its successor, the Space Studies Board (SSB), have provided expert external and independent scientific and programmatic advice to NASA on a continuous basis from NASA’s inception until the present.

The fundamental charter of the Board today remains that defined by National Academy of Sciences President Detlev W. Bronk in a letter to Lloyd V. Berkner, first chair of the Board, on June 26, 1958:

We have talked of the main task of the Board in three parts—the immediate program, the long-range program, and the international aspects of both. In all three we shall look to the Board to be the focus of the interests and responsibilities of the Academy-Research Council in space science; to establish necessary relationships with civilian science and with governmental science activities, particularly the proposed new space agency, the National Science Foundation, and the Advanced Research Projects Agency; to represent the Academy-Research Council complex in our international relations in this field on behalf of American science and scientists; to seek ways to stimulate needed research; to promote necessary coordination of scientific effort; and to provide such advice and recommendations to appropriate individuals and agencies with regard to space science as may in the Board’s judgment be desirable.

As we have already agreed, the Board is intended to be an advisory, consultative, correlating, evaluating body and not an operating agency in the field of space science. It should avoid responsibility as a Board for the conduct of any programs of space research and for the formulation of budgets relative thereto. Advice to agencies properly responsible for these matters, on the other hand, would be within its purview to provide.

Thus, the Space Studies Board exists to provide an independent, authoritative forum for information and advice on all aspects of space science and applications, and it serves as the focal point within the National Academies for activities on space research. It conducts advisory studies and program assessments, facilitates international research coordination, and promotes communications on space science and science policy between the research community, the federal government, and the interested public. The SSB also serves as the U.S. National Committee for the Committee on Space Research (COSPAR) of the International Council for Science (ICSU).
THE SPACE STUDIES BOARD TODAY

The Space Studies Board is a unit of the NRC’s Division on Engineering and Physical Sciences (DEPS), and it reports to the Division for oversight. DEPS is one of six major program units of the NRC through which the institution conducts its operations on behalf of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. Within DEPS there are a total of 14 boards that cover a broad range of physical science and engineering disciplines and mission areas.

Members of the DEPS Committee on Engineering and Physical Sciences provide advice on Board membership and advise on proposed new projects to be undertaken by the Board or its committees. Every 3 years the DEPS Committee also reviews the overall operations of each of its boards, with the most recent review having been conducted in September 2004.

The Board meets three times per year to review the activities of its committees and task groups and to be briefed on and discuss major space policy issues. An internal executive committee composed of seven at-large members of the Board meets at least once a year and may convene via conference call at other times to plan for SSB activities and to advise the chair between meetings. All projects proposed to be conducted by standing committees or ad hoc task groups must first be reviewed and approved by the Board or its executive committee, and the Board monitors the progress of the projects throughout the course of the studies.

MAJOR FUNCTIONS

The Board’s overall advisory charter is implemented through three key functions: discipline oversight, interdisciplinary studies, and international activities.

Oversight of Space Research Disciplines

The Board has responsibility for scientific planning and oversight in the basic subdisciplines of space research. This responsibility is discharged through a structure of discipline-oriented committees. The standard vehicle for providing long-term research guidance is the research strategy report. In addition, committees periodically prepare formal assessment reports that examine progress in their disciplines in comparison with published NRC advice. From time to time, in response to a sponsor or Board request or to circumstances requiring prompt and focused comment, a committee may prepare a short, or “letter,” report. Individual discipline committees may be called upon by the Board to prepare specialized material for use by either the Board or its interdisciplinary committees or task groups.

Interdisciplinary Studies

Although the emphasis traditionally has been on discipline planning and evaluation, the Board also recognizes a need for crosscutting technical and policy studies. To accomplish these objectives, the Board creates ad hoc task groups or internal committees. Task groups resemble standing committees in structure and operation, except that they have predefined lifetimes, typically 1 to 3 years, and more narrowly bounded charters. Internal committees, constituted entirely of appointed Board members, are formed to conduct short-duration studies or to lay the planning groundwork for subsequent formation of a regular committee or task group. The Board also organizes topical workshops and exercises the NRC’s convening function in other special activities.

International Representation and Cooperation

The Board serves as the U.S. National Committee for ICSU’s Committee on Space Research (COSPAR), an international, multidisciplinary forum for exchanging space science research. The current Board-appointed U.S. representative to COSPAR is also COSPAR vice president and thereby participates in the oversight of COSPAR’s business, finances, and operations as a member of the COSPAR Bureau. A member of the Board’s staff serves as executive secretary for the U.S. National Committee. Both the U.S. representative and executive secretary participated in activities organized in 2004 to consider future directions for COSPAR as an organization.
members may individually participate in COSPAR scientific sessions to present their research or, occasionally, to present the results of an SSB report to the international community.

The Board has a regular practice of exchanging observers with the European Space Science Committee (ESSC), an entity of the European Science Foundation, and, on occasion, conducts informal information exchange sessions with national entities such as Japan and China within COSPAR scientific assemblies. At the 2004 COSPAR scientific assembly, the Board chair and executive secretary to COSPAR participated in an informal gathering of representatives from China, Japan, and the ESSC to discuss current issues in national and regional space programs relevant to international cooperation. In addition, the Board has closely monitored developments, for example U.S. implementation of export controls and NASA’s vision for space exploration, that have implications for international scientific cooperation.

**ORGANIZATION**

The organization of the SSB in 2004 is illustrated in Figure 1.1. Taken together the Board and its committees and task groups held a total of 48 meetings during the year.

**The Space Studies Board**

The Board itself is composed of 27 prominent scientists, engineers, industrialists, scholars, and policy experts in space research, appointed for staggered 3-year terms. The Board is constituted in such a way as to include its...
standing committee chairs as members; other Board members serve on internal committees or perform other special functions as designated by the Board chair. The Board seats the chair of the Aeronautics and Space Engineering Board (ASEB) and the U.S. representative to COSPAR as ex officio members. A standing liaison arrangement also has been established with the chair of the ESSC.

**Internal Committees of the Board**

Internal committees, composed entirely of Board members, facilitate the conduct of the Board’s business, carry out the Board’s own advisory projects, and permit the Board to move rapidly to lay the groundwork for new study activities. One such internal committee is the Board’s Executive Committee, composed of one member from each major discipline area. The Executive Committee met on August 24-26, 2004, in Woods Hole, Massachusetts, for its annual session on assessment of SSB operations and future planning.

**Standing Committees**

Standing discipline committees are the means by which the Board conducts its oversight of space research disciplines. Each discipline committee is composed of about a dozen specialists, appointed to represent the broad sweep of research areas within the discipline. In addition to assisting in developing long-range research strategies and formal program and progress assessments in terms of these strategies, the standing committees sometimes organize ad hoc studies and provide oversight of the task groups created to conduct such studies. They also perform analysis tasks in support of interdisciplinary task groups and committees or in response to other requirements assigned by the Board. The standing committees in 2004 were as follows:

- Committee on Astronomy and Astrophysics (CAA)
- Committee on Planetary and Lunar Exploration (COMPLEX)
- Committee on Solar and Space Physics (CSSP)
- Committee on the Origins and Evolution of Life (COEL)
- Committee on Earth Studies (CES)
- Committee on Space Biology and Medicine (CSBM)
- Committee on Microgravity Research (CMGR)

**Task Groups**

Ad hoc task groups are created by NRC action at the Board’s request. Three task groups or ad hoc committees completed their work during 2004, and three existing groups continued their projects during the year. In addition, eight new task groups were established during 2004.

**WORKSHOPS, SYMPOSIA, AND SPECIAL PROJECTS**

Topical workshops or symposia occasionally provide the most effective vehicle for addressing certain needs of the government or the research community. In 2004, the Board published the report on the 2003 Space Policy Workshop (organized jointly with the ASEB), and the SSB Committee on Solar and Space Physics organized a workshop on the role of space physics in space exploration and a workshop on distributed arrays of small instruments.

**DISSEMINATION**

Formal reports delivered to government sponsors constitute one of the primary products of the work of the SSB, but the dissemination process has a number of other important elements. The Board is always seeking ways to ensure that its work reaches the broadest possible appropriate audience and that it has the largest beneficial impact. Copies of reports are routinely provided to key executive branch officials, members and staffs of relevant congressional committees, and members of other interested NRC and federal advisory bodies. Members of the press are notified about the release of each new report, and the Board maintains a substantial mailing list for distribution.
of reports to members of the space research community. The SSB publishes the executive summaries of all new reports in its quarterly newsletter, which is made widely available, both by mail and by e-mail. The Board also offers briefings by committee chairs and members or SSB staff to agency officials and scientific societies. Reports are posted on the SSB Web home page at www.nationalacademies.org/ssb/ssb.html and linked to the institution’s site for reports at www.nap.edu. The SSB teamed with other NRC units to exhibit and distribute copies of recent reports at the January 2004 meeting of the American Astronomical Society and the December meeting of the American Geophysical Union. In 2004, the SSB also secured NRC funds to support a special dissemination project—a publication for lay audiences on the decadal solar and space physics survey report.

COLLABORATION WITH OTHER NATIONAL RESEARCH COUNCIL UNITS

Much of the work of the Board involves topics that fall entirely within its principal areas of responsibility and can be addressed readily by its members and committees. However, there are other situations in which the need for breadth of expertise, alternative points of view, or synergy with other NRC projects leads to compelling arguments for collaboration with other units of the NRC. The Space Studies Board has been engaged in many such multiunit collaborations, and the increasingly interdisciplinary, multidimensional character of contemporary science and technology is likely to lead to more cross-NRC activities. This approach to projects has the potential to bring more of the full capability of the National Academies to bear in preparing advice for the government. Multiunit collaborative projects also present new challenges—namely, to manage the projects in a way that achieves economies of scale and true synergy rather than just adding cost or complexity. Collaborative relationships between the SSB and other NRC units during 2004 are illustrated in Figure 1.1.

INTERNERNSHIP PROGRAM

The SSB has operated a very successful summer internship program since 1992. The general goal of the internship is to provide a promising undergraduate student an opportunity to work in the area of civil space research policy in the nation’s capital, under the aegis of the National Academies. The intern works with the Board, its committees, and staff on one or more of the advisory projects currently underway. In 2004 the program was expanded to include two interns.
Activities and Membership

FIRST QUARTER HIGHLIGHTS

The Space Studies Board (SSB) held its 142nd meeting on March 16-18, 2004, at the National Academies’ Keck Center in Washington, D.C. One major topic for discussion was the administration’s fiscal year 2005 budget proposal and its implications for space research and applications. Guest speakers included David Radzanowski, Office of Management and Budget (OMB); William Jeffrey, Office of Science and Technology Policy (OSTP); David Goldston, Bill Adkins, and Richard Obermann, House Science Committee staff; and Michelle Burkett, House Appropriations Committee staff.

A NASA overview of the budget and the new Vision for Space Exploration were presented by John Schumacher, Gary Martin, and Doug Comstock. Edward Weiler, NASA Office of Space Science, spoke on the implications for the space science program and on the Hubble Space Telescope (HST). He reported that the National Academies will be asked to do a study on how to keep the HST going as long as possible. Ghassem Asrar, NASA Office of Earth Science; Mary Kicza, NASA Office of Biological and Physical Research; Douglas Cook, NASA Office of Exploration Systems; and Colleen Hartman, National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service, also spoke on programs of their offices as well as on the 2005 budget. Other special guests during the meeting included Mike Moore, NASA HST program executive, and Steven Beckwith, director of the Space Telescope Science Institute, who discussed HST lifetime and servicing issues. A luncheon splinter group meeting addressed international issues of interest to the SSB. Graham Gibbs, Canadian Space Agency; Masato Koyama, Japanese Aerospace Exploration Agency; Frederic Nordlund, European Space Agency; and Ian Pryke, George Mason University, discussed international views on NASA’s new space exploration goals.

Chair Lennard Fisk reported on his testimony to the Aldridge Moon-Mars Commission and to the House Science Committee and on his attendance at the NASA Advisory Council and the Aeronautics and Space Engineering Board meetings during the week prior to the Board meeting.

The Board discussed task statements for a number of new studies and also reviewed the status of ongoing studies and committee activities.

SECOND QUARTER HIGHLIGHTS

The Space Studies Board held its 143rd meeting on June 15-17 at the NOAA Space Environment Center in Boulder, Colorado. A major agenda item for this meeting was a series of progress reports by committee chairs and National Research Council (NRC) staff members and SSB review of the status of all projects that are being conducted under SSB auspices.
Activities and Membership

NOAA staff presented a series of briefings and tours at the NOAA SEC. Ernest Hildner and Barbara Poppe’s presentations were on NOAA’s Space Weather Program; Joseph Kunches’ presentation was “Predicting Extreme Events: The Halloween Storms of 2003”; and Howard Singer’s presentation was “Research and Development at SEC.” Marc Allen from NASA Headquarters provided an update on lunar mission and exploration planning. A special highlight was the Web telecast of the press conference on the Report of the President’s Commission on Implementation of United States Space Exploration Policy. Board member Meg Urry gave a science presentation on her work on supermassive black holes, and member Hap McSween briefed the Board on new results from the Mars Exploration Rovers.

Planning for the Executive Committee meeting on August 24-26 and the next Board meeting on November 17-19 also took place. Farewells were said to several retiring members: J. Roger Angel; James L. Burch, chair of the Committee on Solar and Space Physics; Howard M. Einspahr; Steven H. Flajser; Michael H. Freilich, chair of the Committee on Earth Studies; Don P. Giddens; Bruce D. Marcus; Robert Serafin; Mitchell Sogin; and C. Megan Urry.

Board staff members continue to work with the Board and other NRC staff to broaden our pool of qualified candidates from underrepresented minority populations who can be nominated to serve on study committees formed under the aegis of the Board. In keeping with this commitment, an SSB staff member attended the NASA 2004 Chicago Diversity Workshop in June. From this workshop we successfully identified candidates who could be considered for membership on forthcoming study committees.

THIRD QUARTER HIGHLIGHTS

The Space Studies Board did not meet during the third quarter; however, the SSB Executive Committee did meet on August 24-26 at the National Academies’ J. Erik Jonsson Woods Hole Center in Woods Hole, Massachusetts, for its annual strategic planning session. In addition to a general discussion with Al Diaz, the new NASA associate administrator for science, topics during the meeting included a review of roles and operations of the Board and its committees, several studies in progress, international topics, future SSB membership, potential new study projects, as well as planning for the November Board meeting.

FOURTH QUARTER HIGHLIGHTS

SSB held its 144th meeting on November 17-19, at the National Academies’ Beckman Center in Irvine, California. The meeting provided a venue for wide-ranging discussions of guiding principles and major roles for science in the context of NASA’s new vision for space exploration. The meeting included presentations by and discussions with Al Diaz, NASA associate administrator for science, and Charles Elachi, director of the Jet Propulsion Laboratory and NASA director of advanced planning. Gerhard Haerandel, chair of the European Space Science Committee, Laurie Leshin, who served on the President’s Commission on Implementation of United States Space Exploration Policy, and SSB member Radford Byerly, who was rapporteur for the report on the 2003 NRC space policy workshop, all gave background presentations to provide perspectives for the discussions. Various SSB members also provided summary overviews of recent relevant NRC science strategy reports for consideration at the meeting. Following open plenary sessions on November 17-18, the Ad Hoc Committee on the Scientific Context for Space Exploration, consisting of the SSB members present plus Laurie Leshin and U.S. COSPAR representative Edward Stone, met in closed session to outline a draft report. The report was sent to NRC external review in mid-December, and was released in the first quarter of 2005.

Other items covered at the meeting included the SSB’s annual bias and conflict of interest discussion, reviews of ongoing and potential new SSB studies, and plans for the spring meeting.

PERFORMANCE MEASURES

A summary of all reports published by the Space Studies Board during 2004 is presented in Table 2.1. Included in that collection were reports of interest to the NASA science offices and to the National Science Foundation (NSF) and NOAA. The reports included four full-length studies, two workshop reports, two letter reports, and a special publication for lay audiences.
TABLE 2.1  Space Studies Board Reports Published in 2004

<table>
<thead>
<tr>
<th>Report Title</th>
<th>Authoring Committee or Board</th>
<th>Principal Agency Audience a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report</td>
<td>CSSP</td>
<td>X</td>
</tr>
<tr>
<td>Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy</td>
<td>SSB</td>
<td>X X</td>
</tr>
<tr>
<td>Plasma Physics of the Local Cosmos</td>
<td>CSSP</td>
<td>X</td>
</tr>
<tr>
<td>“Review of Science Requirements for the Terrestrial Planet Finder: Letter Report” (September 23)</td>
<td>TG</td>
<td>X</td>
</tr>
<tr>
<td>Solar and Space Physics and Its Role in Space Exploration</td>
<td>TG</td>
<td>X X</td>
</tr>
<tr>
<td>Space Studies Board Annual Report—2003</td>
<td>SSB</td>
<td>All</td>
</tr>
<tr>
<td>Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics [booklet]</td>
<td>CSSP</td>
<td>X X X X X X X</td>
</tr>
<tr>
<td>Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond</td>
<td>TG</td>
<td>X X</td>
</tr>
</tbody>
</table>

aAuthoring committee or board

CES Committee on Earth Studies
CSSP Committee on Solar and Space Physics
SSB Space Studies Board
TG Ad Hoc Task Group

Principal agency audience

SMD NASA Science Mission Directorate
ExSMD NASA Exploration Systems Mission Directorate
NOAA National Oceanic and Atmospheric Administration
NSF National Science Foundation

Except for the Space Studies Board Annual Report—2003 and the illustrated booklet Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics, all reports were subjected to full peer review overseen by the NRC Report Review Committee (RRC). Typically from 4 to 7 reviewers (occasionally as many as 12) are selected, on the basis of recommendations by NAS and NAE section liaisons and SSB members and staff and subject to approval by the NRC. The identities of external reviewers are not known to the report’s authors until after the review has been completed and the report has been approved by the RRC. The report authors, with the assistance of SSB staff, must provide some response to every specific comment from every external reviewer. The response-to-review process is overseen and refereed by an independent coordinator, to ensure that appropriate technical revisions are made to the report, and by a monitor appointed by the RRC, to ensure that the revised report complies with NRC policy and standards. All of the reviews place an emphasis on scientific and technical clarity and accuracy and on proper substantiation of the findings and recommendations presented in the report. Names of
Another important measure of the capacity of the Board to produce high-quality work derives from the size, breadth, and depth of the cadre of experts who serve on SSB committees and task groups or who participate in other ways in the activities of the Board. Some highlights of the demographics of the SSB in 2004 are presented in Tables 2.2 and 2.3. During the year, a total of 276 individuals from 67 colleges and universities and 59 other public or private organizations served as formally appointed members of the Board and its committees and task groups. Over 200 individuals participated in SSB activities either as presenters or as invited workshop participants. The report review process is as important as the writing of reports, and during the period 60 different external reviewers contributed to critiques of draft reports. Overall, approximately 575 individuals from 75 academic institutions, 69 industry or nonprofit organizations, and 21 government agencies or offices participated in SSB activities. That number included 45 elected members of the NAS, NAE, and/or the Institute of Medicine (IOM). Being able to draw on such a broad base of expertise is a unique strength of the NRC advisory process.

### TABLE 2.2 Experts Involved in the SSB and Its Subunits, January 1, 2004, to December 31, 2004

<table>
<thead>
<tr>
<th>Category</th>
<th>Number of Board and Committee Members</th>
<th>Number of Institutions or Agencies Represented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academia</td>
<td>174</td>
<td>67</td>
</tr>
<tr>
<td>Government and national facilities</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>Private industry</td>
<td>53</td>
<td>30</td>
</tr>
<tr>
<td>Nonprofit and other</td>
<td>27</td>
<td>16</td>
</tr>
<tr>
<td>Total</td>
<td>276</td>
<td>126</td>
</tr>
</tbody>
</table>

*a* Includes NASA and other U.S. agencies and national facilities (e.g., Los Alamos National Laboratory (LANL), National Institute of Standards and Technology (NIST), U.S. Geological Survey (USGS), NOAA).

*b* Other includes foreign institutions and entities not classified elsewhere.

*c* Includes 33 NAS, NAE, IOM members.

*d* Thirty-seven SSB members, 239 committee and task group members.

### TABLE 2.3 Summary of Participation in Space Studies Board Activities, January 1, 2004, to December 31, 2004

<table>
<thead>
<tr>
<th>Category</th>
<th>Academia</th>
<th>Government and National Facilities</th>
<th>Private Industry</th>
<th>Nonprofit and Others</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board/committee members</td>
<td>174</td>
<td>22</td>
<td>53</td>
<td>27</td>
<td>276</td>
</tr>
<tr>
<td>Guest experts</td>
<td>42</td>
<td>87</td>
<td>18</td>
<td>31</td>
<td>178</td>
</tr>
<tr>
<td>Reviewers</td>
<td>40</td>
<td>10</td>
<td>6</td>
<td>5</td>
<td>61</td>
</tr>
<tr>
<td>Workshop participants</td>
<td>25</td>
<td>20</td>
<td>4</td>
<td>11</td>
<td>60</td>
</tr>
<tr>
<td>Total</td>
<td>281</td>
<td>139</td>
<td>81</td>
<td>74</td>
<td>575</td>
</tr>
</tbody>
</table>

NOTE: Counts of individuals are subject to an uncertainty of ±3 due to possible miscategorization.

*a* Includes government agencies and national facilities (e.g., National Optical Astronomy Observatory (NOAO), LANL, National Radio Astronomy Observatory, Space Telescope Science Institute).

- Total number of NAS, NAE, and/or IOM members: 45
- Total number of non-U.S. participants: 10
- Total number of countries represented, incl. United States: 6
- Total number of participants by gender: 346(M); 74(F)
- Total number of different institutions represented:
  - Academia: 75
  - Government and national facilities: 21
  - Industry: 40
  - Nonprofit and other: 29

U.S. government agencies represented: NASA, NOAA, NSF, NIST, USGS, Environmental Protection Agency (EPA), OSTP, OMB, Smithsonian Institution, U.S. Congress.

the external reviewers, including the coordinator and monitor, are published in the final report, but their individual comments are not released.
FIGURE 2.1 Number and type of peer-reviewed Space Studies Board reports published from 1988 through 2004.

FIGURE 2.2 Principal federal agency audiences for Space Studies Board reports published from 1998 through 2004. NOTE: Totals are inclusive of more than one agency audience per report.
A different way to assess the performance of the SSB is to examine its productivity with respect to study reports. The chart in Figure 2.1 shows the total number of peer-reviewed reports published by the SSB from 1988 to 2004. “Broad” reports include classical scientific strategies (long-range goals and priorities in a particular discipline or set of disciplines) and programmatic strategies or analyses that cross all of an agency office or even several agencies. “Focused” reports include more narrowly directed topical studies, assessments, and letter reports.

Finally, one can also examine the extent to which the Board’s efforts have been relevant to the full range of government interests in civilian space research. Figure 2.2 summarizes the principal federal agency audiences to which SSB reports were directed from 1998 through 2004. Reports on NASA-wide issues were addressed to multiple NASA offices or the whole agency; reports on SMD issues to the Science Mission Directorate (created in 2004 from the consolidation of the former Office of Space Science and Office of Earth Science); reports on ExSMD issues to the Exploration Systems Mission Directorate (formerly the Office of Biological and Physical Research). The “multiple government agencies” category covers reports that were directed to one or more agencies besides NASA—for example, NOAA, NSF, the Department of Energy (DOE), and/or the Department of Defense (DOD). One also sees a few reports prepared specifically for NSF. Within NASA, SMD has been the leading sponsor of reports.

SSB OUTREACH AND DISSEMINATION

Enhancing outreach to a variety of interested communities and improving dissemination of Board reports was a special priority for the SSB during the year. The quarterly newsletter’s print distribution list was expanded and supplemented with an electronic version that continued to attract over 300 subscribers at year’s end. Several kinds of report announcements, fliers, and mailing list sign-up cards were designed and used at SSB committee meetings and national and international scientific society meetings. The Board teamed with other NRC units (including the Division on Earth and Life Studies, the Board on Physics and Astronomy, the National Academies Press, the Office of News and Public Information, the Proceedings of the National Academy of Sciences, and the Office of Scientific and Engineering Personnel) to take exhibits to national meetings of the American Geophysical Union (AGU) and the American Astronomical Society. Popular versions of two recent decadal surveys (the Solar System Exploration Survey and the Solar and Space Physics Survey) were shipped to Native American schools in Wisconsin. In addition to these schools, NASA Explorer Schools and Science Outreach Centers affiliated with several universities continue to request the popular versions. As a consequence of these activities, roughly 6,000 additional SSB reports were distributed.

Membership of the Space Studies Board

Lennard A. Fisk,§ University of Michigan (chair)
George A. Paulikas,§ The Aerospace Corporation (retired) (vice chair)
J. Roger P. Angel,§ University of Arizona
Daniel N. Baker, University of Colorado, Boulder
Ana P. Barros,§ Duke University
Reta F. Beebe, New Mexico State University
Roger D. Blandford, Stanford University
James L. Burch,§ Southwest Research Institute
Radford Byerly, Jr.,§ University of Colorado, Boulder
Judith A. Curry, Georgia Institute of Technology
Howard M. Einspahr,* Bristol-Myers Squibb Pharmaceutical Research Institute (retired)
Jack D. Farmer, Arizona State University
Steven H. Flajser,* Loral Space and Communications Ltd.
Michael Freilich,* Oregon State University
Don P. Giddens,* Georgia Institute of Technology/Emory University
Jacqueline N. Hewitt, Massachusetts Institute of Technology
Donald E. Ingber, Harvard Medical School
Ralph H. Jacobson,§ Charles Stark Draper Laboratory (retired)
Tamara E. Jernigan, Lawrence Livermore National Laboratory
Margaret G. Kivelson,§ University of California, Los Angeles
Calvin W. Lowe, Bowie State University
Bruce D. Marcus,* TRW (retired)
Harry Y. McSween, Jr., University of Tennessee
Berrien Moore III, University of New Hampshire
Norman P. Neureiter, Texas Instruments (retired)
Suzanne Oparil, University of Alabama, Birmingham
Ronald F. Probstein, Massachusetts Institute of Technology
Dennis W. Readey, Colorado School of Mines
Anna-Louise Reysenbach, Portland State University
Roald Z. Sagdeev, University of Maryland, College Park
Carolus J. Schrijver, Lockheed Martin Solar and Astrophysics Laboratory
Robert J. Serafin,* National Center for Atmospheric Research
Mitchell Sogin,* Marine Biological Laboratory
Harvey D. Tananbaum, Smithsonian Astrophysical Observatory
C. Megan Urry,* Yale University
J. Craig Wheeler, University of Texas, Austin
A. Thomas Young, Lockheed Martin Corporation (retired)
Edward C. Stone, California Institute of Technology (ex officio, U.S. representative to COSPAR)
William W. Hoover, U.S. Air Force (retired) (ex officio, chair of the Aeronautics and Space Engineering Board)
Gerhard Haerendel, International University Bremen (liaison, chair of the European Space Science Committee)

Joseph K. Alexander, Director
Betty C. Guyot, Administrative Officer
Barbara S. Akinwole, Information Management Associate
Vern Menkir, Financial Associate
Christina O. Shipman, Financial Associate
Richard Leshner, Research Associate (through July 9, 2004)
Claudette K. Baylor-Fleming, Senior Program Assistant
Catherine A. Gruber, Assistant Editor

*Term ended during 2004.
§Member of the Executive Committee.

Membership of the Ad Hoc Committee on the Scientific Context for Space Exploration

Lennard A. Fisk, University of Michigan (chair)
Daniel N. Baker, University of Colorado
Ana P. Barros, Duke University
Reta F. Beebe, New Mexico State University
Roger D. Blandford, Stanford University
Radford Byerly, Jr., University of Colorado
Donald E. Ingber, Harvard Medical School
Tamara E. Jernigan, Lawrence Livermore National Laboratory
Margaret G. Kivelson, University of California, Los Angeles
Laurie Leshin, Arizona State University
Suzanne Oparil, University of Alabama, Birmingham
George A. Paulikas, The Aerospace Corporation (retired)
Ronald F. Probststein, Massachusetts Institute of Technology
Dennis W. Readey, Colorado School of Mines
Edward C. Stone, California Institute of Technology
Harvey D. Tananbaum, Smithsonian Astrophysical Observatory
The Committee on Astronomy and Astrophysics (CAA) did not meet during the first quarter but instead prepared for upcoming meetings and a NASA-requested review of the scientific goals for the Terrestrial Planet Finder (TPF) mission. The TPF mission was recommended by the 2000 astronomy and astrophysics decadal survey, *Astronomy and Astrophysics in the New Millennium*. As a result, the Panel to Review the Science Requirements for the Terrestrial Planet Finder was tasked with producing a brief letter report that reviews NASA’s current scientific objectives for the TPF mission by conducting an independent scientific assessment as to whether these objectives remain consistent with the priority given to the mission by the Astronomy and Astrophysics Survey Committee. Other topics studied were the implementation of the decadal survey report’s theory recommendations, interagency cooperation on a Joint Dark Energy Mission (JDEM), and effects of the new NASA exploration vision on the astronomy program.

The CAA panel to review the science goals of the TPF mission met on May 18 in Washington, D.C. Mike Brown of the California Institute of Technology, Jim Kasting of Pennsylvania State University, and Ben Oppenheimer of the American Museum of Natural History provided the committee with extended knowledge in certain key areas. The committee heard presentations on recent decisions on TPF science, technology for finding and characterizing Earth-like planets, and the status of the TPF project.

CAA did not meet during the third quarter, but several projects that were organized under its auspices passed key milestones. The letter report on the TPF mission was delivered to NASA on September 23, 2004. The committee also began work on organizing a group to prepare a document that will help interested lay audiences appreciate research to understand the origins of galaxies, stars, and planets.

CAA met on November 30-December 1, in Irvine, California. The committee examined plans for the Advanced Technology Solar Telescope as presented by Thomas Rimmele and Steve Keil of the National Solar Observatory. A science talk from Alan Title helped the committee place the instrument in its scientific context. Other topics were the Laser Interferometer Space Antenna (LISA) and the Laser Interferometer Gravitational-Wave Observatory (LIGO) Scientific Collaboration, presented by Tom Prince and Albert Lazzarini, respectively (both from Caltech). In addition, the committee heard program updates from the astronomy divisions at the NSF and NASA.

A new ad hoc committee, the Committee on Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision, was established to begin review of the scientific discoveries and technical advances in astronomy and astrophysics over the 5 years since the publication of the 2000 decadal survey. The committee will address the implications of recent scientific and technical developments as well as changes in the federal program and assess progress toward realizing the vision for the field articulated in the decadal survey and the report *Connecting Quarks with the Cosmos*. Chaired by Meg Urry, the committee’s first meeting was October 23-24 in Washington, D.C. The report is planned for early in 2005.

A historical summary of reports from CAA and related committees is presented in Figure 2.3.
FIGURE 2.3  SSB-NRC advice on astronomy and astrophysics (1979-2004).
Activities and Membership

Richard S. Ellis,* California Institute of Technology
Alexei Filippenko, University of California, Berkeley
Andrea Ghez,* University of California, Los Angeles
Timothy M. Heckman, Johns Hopkins University
David J. Hollenbach, NASA Ames Research Center
Chryssa Kouveliotou, NASA Marshall Space Flight Center
Stephan Meyer, University of Chicago
Eve Ostriker, University of Maryland
Frazer N. Owen,* National Radio Astronomy Observatory
Mark J. Reid, Harvard-Smithsonian Center for Astrophysics
Scott Tremaine, Princeton University
Jean L. Turner, University of California, Los Angeles
Charles E. Woodward, University of Minnesota

Brian Dewhurst, Study Director
Celeste Naylor, Senior Program Assistant

*Term ended during 2004.

Membership of the Committee on Review of Progress in Astronomy and Astrophysics
Toward the Decadal Vision

C. Megan Urry, Yale University (chair)
Lars Bildsten, University of California, Santa Barbara
Roger D. Blandford, Stanford University
John E. Carlstrom, University of Chicago
Neal J. Evans, University of Texas at Austin
Jacqueline N. Hewitt, Massachusetts Institute of Technology
Craig James Hogan, University of Washington
John P. Huchra, Harvard-Smithsonian Center for Astrophysics
Christopher F. McKee, University of California, Berkeley
Anneila I. Sargent, California Institute of Technology
Sara Seager, Carnegie Institution of Washington
Charles E. Woodward, University of Minnesota, Minneapolis

COMMITTEE ON PLANETARY AND LUNAR EXPLORATION

The Committee on Planetary and Lunar Exploration (COMPLEX) met on March 3-5 at the National Academies’ Keck Center in Washington, D.C., devoting the meeting to advanced planning and preparation for the forthcoming study on priorities for space science enabled by nuclear power and propulsion. In addition, the committee heard presentations on the current status of NASA’s Solar System Exploration and Mars Exploration programs and on the formation of NASA’s new Exploration Systems Office.

COMPLEX’s planned June meeting was cancelled so that committee members could assist with the activities of the Committee on Space Science Priorities Enabled by Nuclear Power and Propulsion.

COMPLEX’s final meeting of 2004 was held on October 20-22 at New Mexico State University in Las Cruces, New Mexico. The meeting was devoted to preparing material, requested by the Space Studies Board, on the impact of NASA’s new exploration vision on solar system decadal science priorities. In addition, the committee heard presentations on the current status of NASA’s Solar System, Lunar, and Mars Exploration programs. NASA representatives Marc Allen and Doug McCuistion briefed the members on the proposed roadmap for the coming year. Members continue to offer assistance with PI-led missions and the panels of the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion as requested.

A historical summary of reports from COMPLEX and related committees is presented in Figure 2.4.
FIGURE 2.4 SSB-NRC advice on solar system exploration (1969-2002).
COMPLEX Membership

Reta F. Beebe, New Mexico State University (chair)
Stephen W. Bougher, University of Michigan
Michael E. Brown, California Institute of Technology
William D. Cochran, University of Texas, Austin
Robert Farquhar, Johns Hopkins University
Martha S. Gilmore, Wesleyan University
William B. Hubbard, University of Arizona
Krishan Khurana, University of California, Los Angeles
Thomas R. Spilker, Jet Propulsion Laboratory

David H. Smith, Study Director
Rodney N. Howard, Senior Program Assistant

*Term ended during 2004.

TASK GROUP ON EXPLORING ORGANIC ENVIRONMENTS IN THE SOLAR SYSTEM

The Task Group on Exploring Organic Environments in the Solar System (TGOESS), a joint committee under the auspices of COMPLEX, COEL, and the Board on Chemical Sciences and Technology, continued work on finalizing its report *Exploring Organic Environments in the Solar System*, which looks at the sources, location, and history of organic carbon in the solar system. TGOESS did not meet during 2004; however, the report will be released in 2005.

TGOESS Membership

James P. Ferris, Rensselaer Polytechnic Institute (chair)
Luann Becker, University of California, Santa Barbara
Kristie A. Boering, University of California, Berkeley
George D. Cody, Carnegie Institution of Washington
G. Barney Ellison, University of Colorado
John M. Hayes, Woods Hole Oceanographic Institution
Robert E. Johnson, University of Virginia
William Klemperer, Harvard University
Karen J. Meech, University of Hawaii, Honolulu
Keith S. Noll, Space Telescope Science Institute
Martin Saunders, Yale University

David H. Smith, Study Director, Space Studies Board
Sandra J. Graham, Study Director, Space Studies Board
Christopher K. Murphy, Senior Program Officer, Board on Chemical Sciences and Technology
Rodney N. Howard, Senior Program Assistant

COMMITTEE ON THE ORIGINS AND EVOLUTION OF LIFE

The Committee on the Origins and Evolution of Life (COEL), a joint activity between the Space Studies Board and the Board on Life Sciences, met on January 26-28 in Tucson, Arizona. The majority of the meeting was devoted to work on *The Astrophysical Context of Life*. In addition, the committee heard presentations on planetary protection issues, NASA’s Phoenix mission to Mars in 2007, the activities of the NASA Astrobiology Institute (NAI) Titan Focus Group, and the research being performed by the University of Arizona node of NAI. Committee members also toured the University of Arizona’s Mirror Laboratory and other research facilities.
During the second quarter, COEL and the Task Group on the Limits of Organic Life in Planetary Systems (LIMITS) jointly hosted a workshop in Washington, D.C., on May 10-12. The meeting served as a forum for experts in the fields of terrestrial and martian evolution, along with research scientists specializing in the icy moons Europa (Jupiter) and Titan (Saturn). Both satellites are thought to be the best locations, along with Mars, to discover evidence of water, which might hold the key to forms of life. Following the workshop, both committees convened separately to discuss matters pertaining to their respective statements of task.

During the third quarter, COEL did not meet, but work on The Astrophysical Context of Life continued. A complete draft of the report was assembled in late April and sent to nine external reviewers in early May. Revisions to the draft report responding to reviewers’ comments were completed in mid-August, and the report was approved for release in October.

COEL’s final meeting of 2004 was held October 11-13 at the National Academies’ Beckman Center in Irvine, California. The meeting was devoted to a variety of presentations on the current status of NASA’s Mars exploration activities. In addition, the committee received an update on NASA’s Astrobiology program and on the activities of the University of Hawaii lead NAI center.

A historical summary of reports from COEL and related committees is presented in Figure 2.5.

**COEL Membership**

Jack W. Szostak, Massachusetts General Hospital (co-chair)
J. Craig Wheeler, University of Texas, Austin (co-chair)
Steven A. Benner,* University of Florida
Joseph A. Berry,* Carnegie Institution of Washington
Ruth Blake, Yale University
Wendy M. Calvin,* University of Nevada, Reno
Michael Daly, Uniformed Services University of the Health Sciences
Katherine H. Freeman,* Pennsylvania State University
Johann P. Gogarten,* University of Connecticut
James F. Kasting,* Pennsylvania State University
Anthony Keefe, Archemix Corporation
Martin Keller, Diversa Corporation
Sandra Pizzarello,* Arizona State University
Janet Siefert, Rice University
Roger Summons, Massachusetts Institute of Technology
Neville J. Woolf, University of Arizona
Lucy M. Ziurys,* University of Arizona

Pascale Ehrenfreund, European Space Science Committee Liaison

David H. Smith, Study Director
Robert L. Riemer, Senior Program Officer
Rodney N. Howard, Senior Program Assistant

*Term ended during 2004.

**TASK GROUP ON THE LIMITS OF ORGANIC LIFE IN PLANETARY SYSTEMS**

During the second quarter, COEL and the Task Group on the Limits of Organic Life in Planetary Systems (LIMITS) jointly hosted a workshop in Washington, D.C., on May 10-12. LIMITS met September 28-30 at the University of Colorado’s Laboratory for Atmospheric and Space Physics in Boulder, Colorado. The meeting was devoted to drafting an outline of the task group’s report and initial discussion of conclusions and recommendations. LIMITS did not meet during the fourth quarter.
FIGURE 2.5  SSB-NRC advice on astrobiology and planetary protection (1965-2003).
COMMITTEE ON SOLAR AND SPACE PHYSICS

The Committee on Solar and Space Physics (CSSP) met on January 13-15 at the National Academies’ Beckman Center in Irvine, California. Most of the meeting was devoted to response to external review of *Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report*. The committee also completed a first draft of a popularization of the decadal survey in solar and space physics (*The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics, 2002*) to be distributed to a broad audience that includes federal policy makers, students, and the public. Also during the meeting, the committee was briefed on Project Prometheus by Krishan Khurana, University of California, Los Angeles, and later developed its contribution to a new SSB-led study on priorities for space science enabled by nuclear power and propulsion. The committee finalized its contribution to another SSB-led study, “PI-led Missions in the Space Sciences: Lessons Learned.” In addition, the committee developed plans for a workshop on distributed arrays of small instruments.

On February 6, a prepublication version of *Plasma Physics of the Local Cosmos* was delivered to NASA.

On March 18, CSSP chair Jim Burch and Solar and Space Physics Survey Committee chair Lou Lanzerotti briefed the staff of the House Space and Aeronautics Subcommittee, focusing on implementation of the priorities outlined in the 2002 decadal survey in solar and space physics. As a result of this briefing and discussions with NASA, the committee made plans to examine the role of Office of Space Science’s Sun-Earth Connections (SEC) program in supporting NASA’s space exploration initiative and analyze how to best align SEC activities in the near future with those recommended in the decadal survey.

During the second quarter, CSSP met April 26-29 at Southwest Research Institute in Boulder, Colorado, May 26-27 at the National Academies’ Keck Center in Washington, D.C., and June 8-10 at the National Academies’ Woods Hole, Massachusetts, conference facility. These meetings examined the role of NASA’s Office of Space Sciences SEC program in supporting NASA’s new vision for space exploration and analyzed how to best align SEC activities in the near future with those recommended in the recently completed decadal survey. At the June meeting, the committee met in conjunction with the June 8-9 DASI workshop, which was chaired by CSSP member John Foster.

During the third quarter, CSSP completed and delivered prepublication versions of two reports: *Solar and Space Physics and Its Role in Space Exploration and Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report*. In addition, the committee also began work on its draft report from the DASI workshop, scheduled to be released in 2005. Finally, the committee completed work on a richly illustrated booklet, *Understanding the Sun and Solar System Plasma: Future Directions in Solar and Space Physics*, that is intended to make the results of the solar and space physics decadal survey accessible to the general public.

CSSP welcomed its new chair Daniel Baker, director and researcher at the Laboratory for Atmospheric and Space Physics at the University of Colorado, Boulder. Baker replaces James Burch from the Southwest Research Institute, whose highly successful tenure included a central role in the organization and execution of the 2002 decadal survey, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*. 
During the fourth quarter, CSSP met on October 28-29 at the National Academies’ Keck Center in Washington, D.C. Richard Fisher, deputy director of NASA’s Sun-Earth System Division, and Richard Behnke, head of NSF’s Upper Atmosphere Research Section, provided updates for the committee on their respective agency programs. Much of the meeting was devoted to reviewing the progress of ongoing studies being conducted under CSSP auspices, planning for future studies, and support that the committee will provide for NRC reviews of NASA’s strategic roadmaps in 2005. The final edited version of the report *Solar and Space Physics and Its Role in Space Exploration* was published during this quarter. Work continued of the draft report of the DASI workshop, to be completed in early 2005. CSSP’s new publication for lay audiences, *Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics*, was completed in early December. The 40-page, richly illustrated document was distributed for the first time at the fall AGU meeting in San Francisco, California, along with copies of a new CD-ROM collection of recent CSSP reports.

A historical summary of reports from CSSP and related committees is presented in Figure 2.6.

**CSSP Membership**

Daniel N. Baker, University of Colorado, Boulder (chair)
James L. Burch,* Southwest Research Institute (chair)
Claudia J. Alexander, Jet Propulsion Laboratory
Vassilis Angelopoulos, University of California, Berkeley
Anthony Chan, Rice University
Andrew F. Cheng, Johns Hopkins University
James F. Drake, Jr.,* University of Maryland, College Park
John C. Foster, Massachusetts Institute of Technology
Stephen A. Fuselier,* Lockheed Martin Advanced Technology Center
Sarah Gibson, National Center for Atmospheric Research
Jack R. Jokipii, University of Arizona
Paul M. Kintner, Cornell University
Craig Kletzing,* University of Iowa
William S. Lewis, Southwest Research Institute
Dana W. Longcope, Montana State University
Gang Lu, National Center for Atmospheric Research
Barry H. Mauk, Johns Hopkins University
Frank B. McDonald,* University of Maryland, College Park
Eugene N. Parker,* University of Chicago (retired)
Robert W. Schunk,* Utah State University
Howard J. Singer, National Oceanic and Atmospheric Administration
Leonard Strachan, Jr., Harvard-Smithsonian Center for Astrophysics
Niescja Turner, Florida Institute of Technology
Gary P. Zank,* University of California, Riverside
Thomas H. Zurbuchen University of Michigan

Arthur A. Charo, Study Director
Theresa M. Fisher, Senior Program Assistant

*Term ended during 2004.

**Membership of the Ad Hoc Committee on Distributed Arrays of Small Instruments for Research and Monitoring in Solar-Terrestrial Physics: A Workshop**

James L. Burch, Southwest Research Institute (chair)
Claudia J. Alexander, Jet Propulsion Laboratory
Vassilis Angelopoulos, University of California, Berkeley
Anthony Chan, Rice University
FIGURE 2.6 SSB-NRC advice on solar and space physics (1980-2004).
Activities and Membership

James F. Drake, Jr., University of Maryland, College Park
John C. Foster, Massachusetts Institute of Technology
Stephen Fuselier, Lockheed Martin Advanced Technology Center
Sarah Gibson, National Center for Atmospheric Research
Craig Kletzing, University of Iowa
Gang Lu, High Altitude Observatory at National Center for Atmospheric Research
Barry H. Mauk, Johns Hopkins University, Applied Physics Laboratory
Eugene N. Parker, University of Chicago (retired)
Robert W. Schunk, Utah State University
Gary P. Zank, University of California, Riverside

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

Fran Bagenal, University of Colorado, Chair
Claudia J. Alexander, Jet Propulsion Laboratory
James L. Burch, Southwest Research Institute
Anthony Chan, Rice University
James F. Drake, University of Maryland
John C. Foster, Massachusetts Institute of Technology
Stephen A. Fuselier, Lockheed Martin Advanced Technology Center
Sarah Gibson, National Center for Atmospheric Research
Roderick A. Heelis, University of Texas at Dallas
Craig Kletzing, University of Iowa
Louis J. Lanzerotti, New Jersey Institute of Technology
Gang Lu, National Center for Atmospheric Research
Barry H. Mauk, Johns Hopkins University
Terrance G. Onsager, National Oceanic and Atmospheric Administration
Eugene N. Parker, University of Chicago, Professor Emeritus

Membership of the Ad Hoc Committee on the Exploration of the Outer Heliosphere: A Workshop*

James L. Burch, Southwest Research Institute (chair)
Claudia J. Alexander, Jet Propulsion Laboratory
Vassilis Angelopoulos, University of California, Berkeley
Anthony Chan, Rice University
Andrew F. Cheng, Johns Hopkins University
James F. Drake, Jr., University of Maryland, College Park
John C. Foster, Massachusetts Institute of Technology
Stephen A. Fuselier, Lockheed Martin Advanced Technology Center
Sarah Gibson, National Center for Atmospheric Research
Craig Kletzing, University of Iowa
Gang Lu, National Center for Atmospheric Research
Barry H. Mauk, Johns Hopkins University
Frank B. McDonald, University of Maryland, College Park
Eugene N. Parker, University of Chicago (retired)
Robert W. Schunk, Utah State University
Gary P. Zank, University of California, Riverside

*All terms expired during 2004.
COMMITTEE ON EARTH STUDIES

The Committee on Earth Studies (CES) did not meet during the year; however, members were working on a number of activities. During the first quarter CES assisted in planning a major new study on Earth science and applications from space (ESAS). The final version of the report *Steps to Facilitate Principal-Investigator-Led Earth Science Missions* was delivered to NASA and published in the second quarter. Several members also responded to congressional queries regarding the future of the Tropical Rainfall Measuring Mission (TRMM). The committee continued to revise its report *Extending the Effective Lifetimes of Earth Observing Research Missions*. The report release is planned for early 2005.

The Committee on Earth Science and Applications from Space was established to conduct a major new study to address the following tasks:

1. Review the status of the Earth sciences to assess recent progress in resolving major scientific questions.
2. Develop a consensus of the top-level scientific questions that should provide the focus for Earth and environmental observations in the period 2005-2015.
3. Survey the principal federal- and state-level users of these observations and identify opportunities and challenges to the exploitation of the data generated by Earth observations from space.
4. Recommend a prioritized list of flight missions and supporting activities within NASA and NOAA to support national needs for research and monitoring of the dynamic Earth system during the decade 2005-2015. In addition to elucidating the fundamental physical processes that underlie the interconnected issues of climate and global change, these needs include weather forecasting, seasonal climate prediction, aviation safety, natural resources management, agricultural assessment, homeland security, and infrastructure planning.
5. Identify important directions that should influence planning for the decade beyond 2015.

The study will address critical technology development requirements and opportunities; needs and opportunities for establishing and capitalizing on partnerships between NASA and NOAA and other public and private entities; and the human resource aspects of the field involving education, career opportunities, and public outreach. A minor but important part of the study is the review of complementary initiatives of other nations in order to identify potential cooperative programs. The 2-year study will generate consensus recommendations regarding a systems approach to space-based and ancillary observations that encompasses the research programs of NASA, the related operational programs of NOAA, and associated programs such as Landsat, a joint initiative of USGS and NASA. Planning meetings were held in April and May.

An initial step in the study was a planning workshop held on August 23-25, 2004 in Woods Hole, Massachusetts. In preparation for a workshop, a letter from co-chairs Berrien Moore and Richard Anthes was sent to nearly 100 scientific community leaders, requesting input on how to set directions for the study. The responses to the committee’s request for input from the scientific community were discussed at the August 23-25 meeting. This meeting was attended by some 50 researchers and representatives from NASA, NOAA, and the USGS. Agency representatives at the meeting included NASA science associate administrator Al Diaz and science deputy administrator Ghassem Asrar. NOAA representatives included the administrator, Conrad C. Lautenbacher, Jr., and David L. Johnson, director of the National Weather Service.

The study will be carried out by the committee and seven thematically organized panels: (1) Earth science applications and societal objectives; (2) land use change, ecosystem dynamics, and biodiversity; (3) weather; (4) climate variability and change; (5) water resources and the global hydrologic cycle; (6) human health and security; and (7) solid-earth dynamics, natural hazards, and resources.

The committee held its first meeting November 8-9 at the National Academies’ Keck Center in Washington, D.C. During the meeting, the committee heard from representatives of NASA, NOAA, USGS, and the House Science Committee about their needs and expectations with respect to the study. Committee co-chairs Richard Anthes and Berrien Moore hosted a well-attended town-meeting discussion about the survey at the fall AGU meeting in San Francisco. The committee has established a Web site at http://qp.nas.edu/decadalsurvey, where interested members of the community can stay up to date with the study and provide views to the committee. The study is being led by the SSB, but it is benefiting from collaboration and assistance from other units in the NRC, especially the Board on Atmospheric Sciences and Climate, the Board on Earth Studies and Resources, the Ocean Studies Board, and the Coordinating Committee on Global Change.


Activities and Membership

CES Membership

Michael Freilich, Oregon State University (chair)
Antonio J. Busalacchi, Jr., University of Maryland, College Park
Carol Anne Clayson, Florida State University
William B. Gail, Ball Aerospace and Technologies Corporation
William C. Gibson, Southwest Research Institute
Sarah T. Gille, Scripps Institution of Oceanography
Ross N. Hoffman, Atmospheric and Environmental Research, Inc.
Bruce D. Marcus, TRW, Inc. (retired)
Steve W. Running, University of Montana, Missoula
Robert A. Shuchman, Altarum, Inc.
Roy W. Spencer, University of Alabama, Huntsville
William Stoney, Mitretek Corporation
Jan Svejkovsky, Ocean Imaging, Inc.
Kurt Thome, University of Arizona
John Townshend, University of Maryland, College Park

Arthur A. Charo, Study Director
Theresa M. Fisher, Senior Program Assistant

Membership of the Committee on Earth Science and Applications from Space

Richard A. Anthes, University Corporation for Atmospheric Research (co-chair)
Berrien Moore III, University of New Hampshire (co-chair)
James G. Anderson, Harvard University
Susan K. Avery, University of Colorado, Boulder
Eric J. Barron, Pennsylvania State University
Otis B. Brown, Jr., University of Miami
Susan L. Cutter, University of South Carolina
William B. Gail, Vexcel Corporation
Bradford H. Hager, Massachusetts Institute of Technology
Anthony Hollingsworth, European Centre for Medium-Range Weather Forecasts (retired)
Kathryn A. Kelly, University of Washington
Neal F. Lane, Rice University
Dennis P. Lettenmaier, University of Washington
Aram M. Mika, Lockheed Martin Space Systems Company
Warren M. Washington, National Center for Atmospheric Research
Mark L. Wilson, University of Michigan
Mary Lou Zoback, U.S. Geological Survey

Arthur A. Charo, Study Director, Space Studies Board
Anne Linn, Senior Program Officer, Board on Earth Sciences and Resources
Theresa M. Fisher, Senior Program Assistant, Space Studies Board

COMMITTEE ON SPACE BIOLOGY AND MEDICINE

The Committee on Space Biology and Medicine (CSBM) was not active in 2004 except for various tracking and dissemination activities, providing requested materials and information on prior reports, and developing a journal article for publication. NRC staff provided assistance in organizing a study with the Institute of Medicine and the Aeronautics and Space Engineering Board to conduct an independent assessment of NASA’s Bioastronautics Critical Path Roadmap.

A historical summary of reports from CSBM and related committees is presented in Figure 2.7.
FIGURE 2.7 SSB-NRC advice on space biology and medicine (1960-2002).
Activities and Membership

**CSBM Membership**

Donald E. Ingber, Harvard Medical School (chair)

Sandra J. Graham, Study Director
Celeste Naylor, Senior Program Assistant

**COMMITTEE ON REVIEW OF NASA’S BIOASTRONAUTICS CRITICAL PATH ROADMAP**

The Committee on Review of NASA’s Bioastronautics Critical Path Roadmap is a joint committee organized under the auspices of the Institute of Medicine (IOM) Board on Health Sciences Policy with assistance from the Space Studies Board and the Aeronautics and Space Engineering Board.

**Membership of the Committee on Review of NASA’S Bioastronautics Critical Path Roadmap**

David E. Longnecker, University of Pennsylvania Health System (chair)
James P. Bagian, Veterans Health Administration
Elizabeth R. Cantwell, Lawrence Livermore National Laboratory
Valerie J. Gawron, Veridian Corporation
Christopher Hart, Federal Aviation Administration
Charles E. Land, National Cancer Institute
Daniel R. Masys, University of California, San Diego
Bruce McCandless, Lockheed Martin Space Systems Company
Tom S. Neuman, University of California, San Diego
Thomas F. Oltmanns, Washington University
Lawrence A. Palinkas, University of California, San Diego
James Pawelczyk, Pennsylvania State University
Bruce Rabin, University of Pittsburgh Medical Center
Karlene H. Roberts, University of California, Berkeley
Carol Scott-Conner, University of Iowa Hospitals and Clinics
Margaret Rhea Seddon, Vanderbilt University Medical Center
Jay R. Shapiro, Kennedy Krieger Institute
Thomas R. Ten Have, University of Pennsylvania School of Medicine

Lisa M. Vandemark, Staff Officer, Institute of Medicine
Sandra J. Graham, Senior Staff Officer, Space Studies Board

**COMMITTEE ON MICROGRAVITY RESEARCH**

The Committee on Microgravity Research (CMGR) was not active during 2004, except for various tracking and dissemination activities such as providing requested materials and information on prior reports. CMGR is awaiting NASA feedback regarding a proposed task to develop a physical sciences research strategy that would enable advanced exploration technology development. The committee chair, Dennis Readey, proposed some restructuring of the committee to reflect recent changes in the content of NASA’s microgravity program.

A historical summary of reports from CMGR and related committees is presented in Figure 2.8.

**CMGR Membership**

Dennis W. Readey, Colorado School of Mines (chair)
Cristina H. Amon,* Carnegie Institute of Technology
Howard R. Baum,* National Institute of Standards and Technology
Jayavant P. Gore,* Purdue University
John L. Hall,* University of Colorado

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FIGURE 2.8  SSB-NRC advice on microgravity research (1978-2002).
COMMITTEE ON ENVIRONMENTAL SATELLITE DATA UTILIZATION

The Committee on Environmental Satellite Data Utilization (CESDU) held its final writing meeting on February 17 at the National Academies’ Keck Center in Washington, D.C. Its report, *Utilization of Operation Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond*, concerns such topics as the likely multiplicity of uses of environmental data collected by operational environmental satellites, the likely interfaces between the data provider (principally the National Oceanic and Atmospheric Administration as the satellite system operator) and the range of data users, the implications of these interfaces in terms of data management activities, and approaches to secure the engagement of the science and applications community in successfully dealing with the challenges identified in the topics above.

Preparation of *Utilization of Operation Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond* continued during the second quarter. Prepublication copies were delivered to NASA and NOAA on September 2. Committee chair Allen Huang briefed NASA and NOAA on September 7. Dissemination of the printed report began on December 9.

CESDU Membership

Hung-Lung Allen Huang, University of Wisconsin-Madison (chair)
Philip E. Ardanuy, Raytheon Information Technology and Scientific Services
John R. Christy, University of Alabama
James Frew, University of California, Santa Barbara
Susan B. Fruchter, Smithsonian Institution
Aris P. Georgakakos, Georgia Institute of Technology
Ying-Hwa (Bill) Kuo, University Corporation for Atmospheric Research
David S. Linden, DSL Consulting, Inc.
Kevin P. Price, University of Kansas
Steven W. Running, University of Montana
Marijane T. Seelbach, QuakeFinder
Thomas H. Vonder Haar, Colorado State University
Robert A. Weller, Woods Hole Oceanographic Institution

Robert L. Riemer, Study Director
Richard Leshner, Research Associate
Rosalyn A. Pertzborn, Assistant to Chair, University of Wisconsin-Madison
Claudette K. Baylor-Fleming, Senior Program Assistant

*All terms ended during 2004.

COMMITTEE ON PREVENTING THE FORWARD CONTAMINATION OF MARS

The Committee on Preventing the Forward Contamination of Mars (PREVCOM) held its first meeting on February 26-27 at the National Academies’ Keck Center in Washington, D.C. The meeting focused on obtaining an overview of planetary protection and on understanding the statement of task for the study. John Rummel, NASA’s
planetary protection officer, provided an overview of NASA’s Planetary Protection Program and the COSPAR Planetary Protection Program. Other briefings to the committee covered the 1992 National Research Council (NRC) study *Biological Contamination of Mars: Issues and Recommendations*; planetary protection for the Mars Spirit and Opportunity rovers; methods for detecting bioload on spacecraft; and an overview of the NASA Mars program and recent science results. The committee also heard about issues relevant to preventing forward contamination of Mars; lessons learned from planetary protection on the Beagle 2 rover of the Mars Express mission; and lessons learned from planetary protection for the Viking landers.

During the second quarter, PREVCOM held its second meeting on May 5-7 at Diversa Corporation in San Diego, California, to obtain data and information for the report, develop a preliminary outline for the report, identify preliminary conclusions and recommendations, and discuss assignments for drafting the report. The committee held a miniworkshop that included speakers on microbial contamination on Viking missions and recent Mars rovers; measurement techniques and molecular methods for detecting life; new methods and instrumentation for detecting life; organic contamination and the Astrobiology Field Laboratory; the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) on the European Space Agency’s Mars Express spacecraft; the SHAllow RADar (SHARAD) that will fly on the Mars Reconnaissance Orbiter (MRO); life detection experiments for Mars and sensitive techniques in the search for life; and work on radioisotope thermoelectric generators and melting ice. Eric Mathur, vice president of scientific affairs at Diversa and a member of the PREVCOM, led the committee and visitors on a tour of Diversa.

On the second day, the committee heard presentations on planetary protection and human missions to Mars and theory and evidence for the distribution of water on Mars: the Mars Odyssey mission’s Gamma Ray Spectrometer (GRS) observations of hydrogen and water on the near surface; ground-penetrating radar as applied to the search for ground-water and ground ice; nucleic-acid-based techniques for microbial discovery; high-throughput cultivation; and microbial diversity research at the Jet Propulsion Laboratory (JPL). The committee devoted the remainder of its meeting to preparing a preliminary outline for the report, deliberating on key issues, identifying gaps, and discussing the schedule.

PREVCOM held its third meeting on August 3-5 at the Search for the Extraterrestrial Intelligence (SETI) Institute in Mountain View, California, to conduct final data-gathering efforts, deliberate on its findings, and to work on a first draft of the committee’s report. Topics included a geographic information system (GIS) to aid decision making on Mars planetary protection; the search for life on Mars and the implications of planetary protection on life detection; sterilization techniques and their potential application for spacecraft; and research projects and plans to explore methods for bioburden reduction at JPL. The committee also toured the SETI Institute.

During the fourth quarter, PREVCOM held a splinter group meeting with five members on November 8-10 at the National Academies’ Beckman Center in Irvine, California, to revise the draft report. External review, approval, and release of the report are planned for the first quarter of 2005.

**PREVCOM Membership**

Christopher F. Chyba, Stanford University (chair)
Stephen Clifford, Lunar and Planetary Institute
Alan Delamere, Ball Aerospace and Technologies Corporation
Martin S. Favero, Johnson & Johnson
Eric J. Mathur, Diversa Corporation
John C. Niehoff, Science Applications International Corporation
Gian Gabriele Ori, Università d’Annunzio
David A. Paige, University of California, Los Angeles
Ann Pearson, Harvard University
John C. Priscu, Montana State University
Margaret S. Race, SETI Institute
Mitchell Sogin, Marine Biological Laboratory
Cristina Takacs-Vesbach, University of New Mexico

Pamela L. Whitney, Study Director
Carmela J. Chamberlain, Senior Program Assistant
The Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope held its first meeting on June 1-3 in Washington, D.C., and met again on June 22-24. This joint SSB and Aeronautics and Space Engineering Board study was tasked to consider issues of safety of use of the space shuttle for servicing with an astronaut crew, feasibility of robotic servicing approaches, the impacts of servicing options on the scientific capability of the HST, and risk/benefit relationships between servicing options that are deemed acceptable.

During the third quarter, the committee’s third meeting, on July 12-14, at the National Academies’ Keck Center in Washington, D.C., was devoted to development of the final committee report and briefings related to that effort. The committee heard presentations from NASA on planning for a robotic servicing option and on recent analyses of lifetime expectancies for Hubble components such as batteries and fine guidance sensors. Representatives of the Defense Advanced Research Projects Agency gave a presentation on the Orbital Express program. The interim report was transmitted to NASA and congressional staff on July 13.

On August 23-25, the committee met at the National Academies’ Beckman Center in Irvine, California. The committee received briefings from Al Diaz, NASA associate administrator for science, and Jennifer Wiseman, Hubble program scientist, regarding the status of NASA studies and plans. Former astronaut Bruce McCandless shared his perspectives with the committee, and the committee spent considerable time in discussions with representatives of the Aerospace Corporation regarding the Aerospace Corporation’s analysis of servicing alternatives. The remainder of the meeting was devoted to the committee’s own analysis efforts and preparation of its report. The committee’s final meeting, held on September 27-29 at the National Academies’ Keck Center in Washington, D.C., was devoted entirely to work on the final report.

During the fourth quarter, prepublication copies of Assessment of Options for Extending the Life of the Hubble Space Telescope were delivered to NASA and the public on December 8. Committee chair Louis Lanzerotti briefed the agency on December 7. On December 8 a press briefing was held with commentary from a panel of four committee members, and several briefings were also given to congressional staff. The release of the final printed report was scheduled for the first quarter of 2005. The terms of the committee members were extended through April 2005 in order to support congressional briefings on Hubble planned for February 2005 and potential follow-up requests from Congress.

Membership of the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope*

Louis J. Lanzerotti, Bell Laboratories; Lucent Technologies; and New Jersey Institute of Technology (chair)
Steven J. Battel, Battel Engineering
Charles F. Bolden, Jr., U.S. Marine Corps (retired); TechTrans International, Inc.
Rodney A. Brooks, Massachusetts Institute of Technology
Jon H. Bryson, The Aerospace Corporation (retired)
Benjamin Buchbinder, National Aeronautics and Space Administration (retired)
Bert Bulkin, Lockheed Missiles and Space (retired)
Robert F. Dunn, U.S. Navy (retired); National Consortium for Aviation Mobility
Sandra M. Faber, University of California Observatories/Lick Observatory; University of California, Santa Cruz
John G. Garrick, Independent Consultant
Riccardo Giaconi, Johns Hopkins University; Associated Universities, Inc.
Gregory J. Harbaugh, Sun ’n Fun Fly-In, Inc.; Florida Air Museum
Tommy W. Holloway, National Aeronautics and Space Administration (retired)
John M. Klineberg, Space Systems/Loral (retired)
Vijay Kumar, University of Pennsylvania
Forrest S. McCartney, U.S. Air Force (retired); Lockheed Martin Astronautics (retired)
Stephen M. Rock, Stanford University
Joseph H. Rothenberg, Universal Space Network
Joseph H. Taylor, Jr., Princeton University
Roger E. Tetrault, McDermott International, Inc. (retired)
Richard H. Truly, U.S. Navy (retired); National Renewable Energy Laboratory
Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion

The Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion was organized jointly with the Aeronautics and Space Engineering Board to identify meritorious space science missions that could be enabled in the time frame beyond 2015 by development of advanced spacecraft nuclear power and propulsion systems. The committee’s study also considers the engineering requirements for such missions and makes recommendations for an evolutionary technology development program for future space science mission nuclear power and propulsion capabilities.

The steering committee, supported by three science panels and an engineering panel, met for the first time in Washington, D.C., on April 7-9. The steering group held its second meeting on August 31-September 2 at the National Academies’ Keck Center in Washington, D.C.

The panels met during the second, third, and fourth quarters: Solar System Exploration Panel (May 5-7 and June 21-23), Solar and Space Physics Panel (September 9-11 and October 4-6), and Astronomy and Astrophysics Panel (August 16-18 and September 22-24). Each panel forwarded draft material to the steering group prior to the November meeting. Prior to its first meeting, the steering committee had received extensive input from the SSB’s standing committees, in particular, the Committee on Planetary and Lunar Exploration (COMPLEX) and the Committee on Solar and Space Physics. In addition, COMPLEX members made up a significant fraction of the membership of the Solar System Exploration Panel and, to a lesser extent, the steering committee.

The steering committee held its final meeting at the Beckman Center in Irvine, California, on November 15-16. Input to the report has been received from the Astronomy and Astrophysics Panel, the Solar System Exploration Panel, and the Solar and Space Physics Panel. The committee is on track to release its phase one report in the second quarter of 2005.

Steering Committee Membership

William A. Anders, General Dynamics Corporation (retired) (co-chair)
Ellen R. Stofan, Proxemy Research (co-chair)
Reta F. Beebe, New Mexico State University
William D. Cochran, University of Texas
Robert Farquhar, Johns Hopkins University
Sergio B. Guarro, The Aerospace Corporation
William W. Hoover, U.S. Air Force (retired)
Steven D. Howe, Los Alamos National Laboratory
William Madia, Battelle Memorial Institute
William B. McKinnon, Washington University
Nathan A. Schwadron, Southwest Research Institute

David H. Smith, Senior Program Officer, Space Studies Board
Maureen Mellody, Program Officer, Aeronautics and Space Engineering Board, until August 2004
Alan C. Angleman, Program Officer, Aeronautics and Space Engineering Board
Rodney N. Howard, Senior Program Assistant, Space Studies Board

Astronomy and Astrophysics Panel Membership

E. Sterl Phinney, California Institute of Technology (chair)
Activities and Membership

William D. Cochran, University of Texas (vice chair)
Gary Bernstein, University of Pennsylvania
Webster C. Cash, University of Colorado, Boulder
Michael S. Kaplan, The Boeing Company
Victoria M. Kaspi, McGill University
Daniel F. Lester, University of Texas, Austin
Ho Jung Paik, University of Maryland
Edward L. Wright, University of California, Los Angeles

Solar and Space Physics Panel Membership

William C. Feldman, Los Alamos National Laboratory (chair)
Nathan A. Schwadron, Southwest Research Institute (vice chair)
Stephen W. Bougher, University of Michigan
Herbert Funsten, Los Alamos National Laboratory
Umran S. Inan, Stanford University
William S. Kurth, University of Iowa
Paulett C. Liewer, Jet Propulsion Laboratory
Robert P. Lin, University of California, Berkeley
Ralph McNutt, Johns Hopkins University
Mark E. Wiedenbeck, California Institute of Technology

Solar System Exploration Panel Membership

Richard P. Binzel, Massachusetts Institute of Technology (chair)
Reta F. Beebe, New Mexico State University (vice chair)
Anita L. Cochran, University of Texas, Austin
Michael Duke, Colorado School of Mines
Martha S. Gilmore, Wesleyan University
Heidi B. Hammel, Space Science Institute
James W. Head III, Brown University
Krishan Khurana, University of California, Los Angeles
Ralph Lorenz, University of Arizona
Louise M. Prockter, Johns Hopkins University
Thomas R. Spilker, Jet Propulsion Laboratory
David J. Stevenson, California Institute of Technology

Engineering Panel Membership

William W. Hoover, U.S. Air Force (retired) (chair)
Samim Anghaie, University of Florida
Douglas M. Chapin, MPR Associates, Inc.
Alec D. Gallimore, University of Michigan
Sergio B. Guarro, The Aerospace Corporation
Yacov Y. Haimes, University of Virginia
Robert Hanrahan, Jr., U.S. Department of Energy
Steven D. Howe, Los Alamos National Laboratory
Ivana Hrbud, Purdue University
Anthony K. Hyder, University of Notre Dame
Andrew Klein, Oregon State University
William Madia, Battelle Memorial Institute
Dennis Readey, Colorado School of Mines
David A. Waite, CH2M Hill, Inc.
COMMITTEE ON PI-LED MISSIONS IN THE SPACE SCIENCES: LESSONS LEARNED

The Committee on Principal Investigator (PI)-Led Missions in the Space Sciences (COMPILED) is exploring factors that have contributed to the successes and challenges of PI-led missions, mainly in the Discovery and Explorer lines. The committee also is considering the Mars Scout and New Frontiers PI mission lines. The committee held its first meeting on September 1-2 at the National Academies’ Keck Center in Washington, D.C. During the meeting Al Diaz, associate administrator for NASA’s Science Mission Directorate, spoke to the committee on perspectives on PI-led space science missions. The committee also heard presentations from NASA project managers, project scientists, and PIs on the Explorer, Discovery, Mars Scout, and New Frontiers projects, including Deep Impact, SPIDR, TERRIERS, WMAP, Messenger, SWIFT, SAMPEX, CINDI Mission of Opportunity, and PI-Led Missions in the Earth Sciences. On the last day of the meeting, the committee discussed the next steps, study process, communications, and meeting and report schedule.

COMPILED held its second meeting on November 17-19 at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado, Boulder, to continue conducting interviews of principal investigators, project managers, and industry officials as part of its data gathering efforts. The presentations included industry perspectives on PI-led missions, project management on Deep Impact, Solar Radiation and Climate Experiment (SORCE), Jupiter Magnetospheric Explorer, Stardust, Student Nitric Oxide Explorer (SNOE), Lunar Prospector, Genesis, Comet Nucleus Tour Mission (CONTOUR), Phoenix, Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), and New Horizons. The remainder of the meeting was devoted to discussing an outline and writing assignments for the report. Publication of the report is planned for mid-2005.

COMPILED Membership
Janet G. Luhmann, University of California, Berkeley (chair)
James S. Barrowman, NASA Goddard Space Flight Center (retired)
Mary Chiu, Johns Hopkins University, Applied Physics Laboratory (retired)
Hugh H. Kieffer, U.S. Geological Survey (retired)
John W. Leibacher, National Solar Observatory
Gary J. Melnick, Harvard-Smithsonian Center for Astrophysics
H. Warren Moos, Johns Hopkins University
Kathryn Schmoll, University Corporation for Atmospheric Research
Alan M. Title, Lockheed Martin Advanced Technology Center

Pamela L. Whitney, Study Director
Carmela J. Chamberlain, Senior Program Assistant

LARGE OPTICAL SYSTEMS IN SPACE

During a project scoping meeting on Large Optical Systems in Space held at and funded by the NRC in late September 2003, several federal agencies (National Reconnaissance Office, NASA, the U.S. Air Force, NOAA, and the Defense Advanced Research Projects Agency) expressed interest in a full NRC study on the topic. SSB staff members began work with several agencies to obtain sponsorship for the study. Staff members also solicited suggestions for candidates—especially individuals with active security clearances—to chair the study, which requires access to classified information.

In consultation with the ASEB, a committee will be formed to summarize existing studies and activities that identify scientific and operational goals for large spaceborne optical systems; conduct an initial, top-level assessment of technology, infrastructure, and policies relevant to goals and needs and identify key areas for in-depth
analysis in a subsequent study; and identify the issues that would need to be analyzed with respect to locating large optics on the Moon, if that alternative were to be evaluated in a future study.

The study will summarize national goals for large optics in space and identify key technologies and infrastructures needed to meet those goals. The study will include a review of the conclusions of previous studies by the NRC and by the different agencies and consideration of which goals cannot be achieved through options other than large space optics. It will also identify those specific key technology, infrastructure, and policy issues that may warrant thorough exploration in a more detailed investigation, thereby providing the basis for decision and tasking for a subsequent new study.

A subcommittee made up of committee members with appropriate security clearances will focus on specific aspects of the charge to the committee that may involve specific technologies and issues pertaining to classified national security applications of large optical systems in space. Members of the subcommittee will also serve on the full committee.

There will be a report of the full committee and there may also be a separate report of the subcommittee.

Pamela L. Whitney, Study Director
Carmela J. Chamberlain, Senior Program Assistant

U.S. NATIONAL COMMITTEE FOR COSPAR

Officers of the Publications Committee, the Program Committee, and the Bureau of the Committee on Space Research (COSPAR) met March 29-April 1 at COSPAR headquarters in Paris. The meetings focused on approaches for continuing to strengthen COSPAR publications, especially Advances in Space Research (ASR), on planning for the COSPAR scientific assembly to be held July 18-25 in Paris, and on COSPAR business and operations.

COSPAR continued to make strides in improving the quality, image, and speed of ASR. All papers must be refereed by two scientists, and editors are encouraged to insist on high standards of quality in the content of the journal. The journal has a newly designed cover, and all papers are now typeset to create a more uniform and professional appearance. In addition, COSPAR has contracted with Elsevier Sciences, publisher of ASR, for an editorial office for the journal. This measure streamlines the processing of ASR papers and improves the speed of getting papers published. Further, Elsevier is publishing ASR papers through its online Science Direct service. As soon as individual papers are ready for publication, they can be posted to Science Direct, accessed, and referenced by readers. Printed, hardcopy issues of ASR continue to be published as thematic volumes.

The president of COSPAR, Roger Bonnet, initiated an effort to reflect and brainstorm on the future of COSPAR and any necessary changes the organization should consider. To that end, the Space Studies Board, as the U.S. National Committee to COSPAR, invited input on the future of COSPAR. General questions to scientists active in the COSPAR community included these: What is the value added of COSPAR? What role should COSPAR play vis-à-vis the science community, agencies, and international scientific bodies—e.g., the International Council for Science (ICSU), the International Astronomical Union, and the International Academy of Astronautics? What will space research be like 20 years from now? Should the COSPAR commissions change, and in what ways?

COSPAR met July 18-27 in Paris for its 35th scientific assembly. Key issues on the COSPAR agenda included continuing improvements to COSPAR publications and an assessment of the future of COSPAR as a scientific organization. A brainstorming workshop, which included COSPAR officers and invited speakers, was held following the COSPAR Paris meeting. The participants considered whether and how COSPAR should change, how the organization can best meet the needs of the scientific community, and how COSPAR can attract young scientists, among other issues regarding COSPAR’s future. Several task groups were formed to explore key issues identified during the brainstorming sessions and to report their results at COSPAR’s next Bureau meeting in March 2005.

Edward C. Stone, California Institute of Technology, U.S. representative to COSPAR

Pamela L. Whitney, Executive Secretary
Carmela J. Chamberlain, Senior Program Assistant
PRESIDENT’S CIRCLE COMMUNICATION INITIATIVE

The SSB obtained internal NRC funds to expand outreach and dissemination efforts for the 2003 report of the Steering Committee on Space Applications and Commercialization, *Using Remote Sensing in State and Local Government: Information for Management and Decision Making*. The outreach effort focused on bringing the results of the report to state and local managers and elected officials and on further dissemination of the report to interested individuals. Roberta Balstad, chair of the authoring committee, presented the results of the report at a workshop held in May 2004 at Rutgers University. The workshop focused on the use of remote sensing data in New Jersey state and local government. In addition, the SSB used President’s Circle Communication Initiative (PCCI) funds to create and distribute CDs including all three of the steering committee’s remote sensing reports to the 100 workshop participants. PCCI funds also supported the wide dissemination of a lay-audience publication, *New Frontiers in Solar System Exploration*, which was prepared to summarize highlights of the decadal science strategy for solar system exploration, and the funds were used to prepare and distribute a similar document, *Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics*. Both publications have been made available via a variety of education venues.
3

Summaries of Major Reports

3.1 Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report

A Report of the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope

BACKGROUND

The Hubble Space Telescope (HST) was launched from the space shuttle in 1990 and has operated continuously in orbit for the past 14 years. HST was designed to be serviced by astronauts, and a series of four shuttle servicing missions from 1993 to 2002 replaced nearly all the key components except the original telescope mirrors and support structure. Three of the four servicing missions added major new instrument observing capabilities. A fifth planned mission, designated SM-4 (servicing mission 4), was intended to replace aging spacecraft batteries, fine-guidance sensors, and gyroscopes and install two new science instruments on the telescope.

Following the loss of the space shuttle Columbia and its crew in February 2003, NASA suspended all shuttle flights until the cause of the accident could be determined and steps taken to reduce the risks of future shuttle flights. In mid-January 2004 NASA decided, on the basis of risk to the astronaut crew, not to pursue the HST SM-4 mission. This cancellation, together with the predicted resulting demise of Hubble in the 2007-2008 time frame, prompted strong objections from scientists and the public alike. NASA continued to investigate options other than a shuttle astronaut mission for extending Hubble’s science life and is currently in the early stages of developing an unmanned mission that would attempt to service Hubble robotically. NASA also plans to de-orbit HST by approximately 2013 by means of a robotic spacecraft.

This report assesses the options for extending the life of HST. In keeping with its statement of task (Appendix A), the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope assessed the scientific value of continued HST operation, issues of safety in using the space shuttle for servicing HST with an astronaut crew, the feasibility of robotic servicing, the impacts of servicing options on HST’s science capability, and risk/benefit relationships between those servicing options deemed acceptable.

Approximately every decade the U.S. astronomical research community develops a decadal strategy for the field. A premise of the most recently developed strategy\(^1\) was that the HST SM-4 mission was an integral part of NASA’s facility planning for the future of the field and that this servicing mission would occur as planned at the time necessary to prevent the demise of the telescope. The strategy’s advisory recommendations reflect this assumption, and the committee, which was neither asked nor constituted to address any possible changes in priorities for astronomical research or research facilities, assumed that NASA would follow the decadal survey advisory recommendations. If NASA concludes that it cannot move forward with portions of the decadal survey strategy, then NASA will have to carry out an in-depth examination of priorities for the research field. The committee does not endorse such a re-examination. The committee notes, however, that if a re-examination should occur it would have to be conducted in a very timely and very expeditious fashion in order to ensure the continued operation and integrity of Hubble.

ANTICIPATED HUBBLE FAILURES

The Hubble systems with the greatest likelihood of failing and thus ending or significantly degrading Hubble science operations are the gyroscopes, the batteries, and the fine-guidance sensor (FGS) units. In addition, the HST avionics system is vulnerable to the aging of the facility.

The telescope uses three gyroscopes to provide precision attitude control. There are currently four functional gyros on HST—three in operation plus one spare. It is likely that the HST system will be reduced to two operating gyros in the latter half of 2006. The HST engineering team is currently working on approaches to sustaining useful, though potentially degraded, astronomical operations with only two gyros, and NASA expects to have that capability by the time it becomes necessary. Eventually, without servicing, the telescope will be reduced to operation with a single gyro in mid to late 2007. The spacecraft can be held in a safe configuration with one or no operating gyros, but science operations will not be possible.

Battery failures are another likely cause of loss of science operations. HST now has six batteries, of which five are necessary for full operations. If battery levels fall too low, the temperature of the structural elements in the Optical Telescope Assembly will fall below permissible levels, causing permanent damage to the facility. Recovery of scientific operations from this state is not possible.

The FGS units (in combination with their electronics subsystems) are used for precision pointing of the observatory. Two operating FGS units are required to support the HST observing program, with a third to supply redundancy. Based on recent test and performance data, one of the three currently operating FGS units is projected to fail sometime between October 2007 and October 2009, and a second is expected to fail sometime between January 2010 and January 2012.

Based on its examination of data and numerous technical reports on Hubble component operations, as well as discussions held with Hubble project personnel, the committee developed the following findings predicated on an estimated SM-4 earliest launch date of July 2006 and a most likely robotic mission launch date of February 2010.

**FINDING:** The projected termination in mid to late 2007 of HST science operations due to gyroscope failure and the projected readiness in early 2010 to execute the planned NASA robotic mission result in a projected 29-month interruption of science operations. No interruption of science operations is projected for a realistically scheduled SM-4 shuttle mission.

**FINDING:** The planned NASA robotic mission is less capable than the previously planned SM-4 shuttle astronaut mission with respect to its responding to unexpected failures and its ability to perform proactive upgrades. Combined with the projected schedule for the two options, the mission risk\(^2\) associated with achieving at least 3 years of successful post-servicing HST science operations is significantly higher for the robotic option, with the respective risk numbers at 3 years being approximately 30 percent for the SM-4 mission and 80 percent for the robotic mission.

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\(^2\)Mission risk is the risk of failing to achieve the mission objectives.
BENEFITS OF SERVICING HUBBLE

Impact of Hubble

Over its lifetime, HST has been an enormous scientific success, having earned extraordinary scientific and public recognition for its contributions to all areas of astronomy. Hubble is the most powerful space astronomical facility ever built, and it provides wavelength coverage and capabilities that are unmatched by any other optical telescope currently operating or planned.

The four key advantages that Hubble provides over most other optical astronomical facilities are unprecedented angular resolution over a large field, spectral coverage from the visible and the near infrared to the far ultraviolet, access to an extremely dark sky, and highly stable images that enable precision photometry. Hubble’s imaging fields of view are also considerable, permitting mapping of extended objects and significant regions of sky. In contrast, ground-based telescopes have a view that is blurred by the atmosphere, and they are completely blind in the ultraviolet and large portions of the near infrared. Hubble can see sharply and clearly at all wavelengths from the far ultraviolet to the near infrared. Hubble images are 5 to 20 times sharper than those obtained with standard ground-based telescopes, in effect bringing the universe that much “closer.” Image sharpness and the absence of light pollution in orbit help Hubble to see objects 10 times fainter than even the largest ground-based telescopes. Moreover, Hubble’s images are extremely stable, in contrast to those obtained with ground telescopes, whose view is continually distorted by changing atmospheric clarity and turbulence.

Singly, each of these advantages would represent a significant advance for science. Combined, they have made Hubble the most powerful optical astronomical facility in history. Hubble is a general-purpose national observatory that enables unique contributions to and insights concerning most astronomical problems of greatest current interest. Among the most profound contributions of Hubble have been the following:

- Direct observation of the universe as it existed 12 billion years ago,
- Measurements that helped to establish the size and age of the universe,
- Discovery of massive black holes at the center of many galaxies,
- Key evidence that the expansion of the universe is accelerating, which can be explained only by the existence of a fundamentally new type of energy, and therefore new physics, and
- Observation of proto-solar systems in the process of formation.

In addition to its impact on science, Hubble discoveries and images have generated intense public interest. Examples of Hubble data and images that have fascinated the public (and scientists) include the big “black eye” left by comet Shoemaker-Levy’s direct hit on Jupiter’s atmosphere, which alerted the public to the dangers of asteroids impacting Earth; a panoply of jewel-like planetary nebulas that illustrate the ultimate death of our Sun; portraits of planets in the solar system, including auroras on Jupiter and Saturn; and such astronomical spectacles as the “pillars of dust” in the Eagle nebula that appeared on nearly every front page in America and became iconic for Hubble itself. The Hubble Space Telescope has clearly been one of NASA’s most noticed science projects, garnering sustained public attention over its entire lifetime.

Maintaining and Enhancing Hubble’s Capabilities

The four previous servicing missions to Hubble have added new observing modes and increased existing capabilities, typically by factors of between 10 and 100, since the telescope first flew in 1990. As a result, Hubble now produces more data per unit time than it did originally. The total rate of calibrated data has grown by a factor of 33 since launch. A further increase was expected with the installation of the two new science instruments, the Wide-field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS), each of which would provide a greater

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1Adaptive optics are not able to give such stable images at such short wavelengths over such a wide field of view.
than 10-fold improvement in scientific efficiency and sensitivity compared with previous instruments. Both of these instruments are already built.

With the installation of WFC3 and COS, and the continued operation enabled by a fifth servicing mission, a broad range of new discoveries would be expected from Hubble. In fact, the committee concluded that Hubble’s promise for future discoveries following a fifth servicing mission would be comparable to the telescope’s promise when first launched. For example, an important new technique that Hubble would offer for finding planets could enable detection of as many as 1000 new planets in the Milky Way Galaxy in the years after servicing. In addition, a large number of new supernovas could be found for the study of dark energy, reducing uncertainties in its properties by a factor of two. A wealth of data would also be collected to explore the nature of stars in the Milky Way Galaxy and in neighboring galaxies. Hubble is just now beginning to image objects being found by sister NASA missions such as Chandra (an x-ray observatory), Galaxy Evolution Explorer (GALEX; an ultraviolet imager), and Spitzer (an infrared imager and spectrograph), which are currently in orbit. These satellites are relatively wide-field survey telescopes whose goal in part is to detect objects for Hubble follow-up observations. These detailed follow-ups take time because of Hubble’s smaller field of view; a large fraction of the scientific benefit of these other satellites will be lost if Hubble’s mission is cut short prematurely. And finally, a servicing mission is needed to allow an orderly completion of large, homogeneous data sets such as spectral libraries and imaging surveys of large areas of the Milky Way Galaxy that Hubble is now gathering. These data sets will be archived to serve astronomers for decades to come, given that there are no foreseeable plans to replace Hubble with a telescope of comparable size, wavelength coverage, and high resolution.

The key findings of the committee related to the benefits of future servicing of Hubble are as follows:

**FINDING:** The Hubble Space Telescope is a uniquely powerful observing platform in terms of its high angular optical resolution, broad wavelength coverage from the ultraviolet to the near infrared, low sky background, stable images, exquisite precision in flux determination, and significant field of view.

**FINDING:** Astronomical discoveries with Hubble from the solar system to the edge of the universe are among the most significant intellectual achievements of the space science program.

**FINDING:** The scientific power of Hubble has grown enormously as a result of previous servicing missions.

**FINDING:** The growth in the scientific power of Hubble would continue with the installation of the two new instruments, WFC3 and COS, planned for the SM-4 shuttle astronaut mission.

**THE RISKS OF ROBOTIC SERVICING**

Because a robotic servicing mission does not involve risks to the safety of an astronaut crew, the principal concerns are the risk of failure to develop a robotic mission capability in time to service Hubble, and the risk of a mission failure that results in an inability to perform the needed servicing, or worse, critically damages Hubble during the mission. Both schedule risk and mission risk are composed of a large number of factors that were studied in considerable detail by the committee.

Some of the critical components of mission risk include lack of adequate development time to validate the hardware, level of software and system performance required to rendezvous with Hubble, failure to successfully grapple and dock with Hubble, failure to successfully execute the combination of complex autonomous and robotic activities required to actually accomplish HST revitalization and instrument replacement, and the risk of unforeseen Hubble failures prior to mission execution that the robotic mission will not have been designed to repair. One example of a mission risk that concerned the committee is the complicated docking maneuver required for a Hubble robotic servicing, which has never been performed autonomously or teleoperated with time delays. Specifically, the use of the grapple system to autonomously perform close-proximity maneuvers and the final capture of Hubble is a significant challenge and is one of the key technical aspects of a robotic servicing mission that has no precedent in the history of the space program.

The components of schedule risk examined by the committee included the readiness levels of such technologies as the sensors, software and control algorithms, and vision-based closed-loop support for autonomous docking.
operations, as well as NASA’s relevant programmatic and technical expertise, resources, and specific development plans for a robotic servicing mission. From the risk mitigation viewpoint, the committee judged that the planned use of the mature International Space Station robotic arm and robotic operational ground system helps reduce both the schedule risk and the development risk for the robotic mission. In addition, the committee assessed the development schedule for the robotic servicing mission based on its experience with programs of similar complexity and the historical spacecraft development schedule data provided by both NASA and the Aerospace Corporation. The committee’s key findings regarding the question of the risk of robotic servicing are as follows:

**FINDING:** The technology required for the proposed HST robotic servicing mission involves a level of complexity, sophistication, and maturity that requires significant development, integration, and demonstration to reach flight readiness and has inherent risks that are inconsistent with the need to service Hubble as soon as possible.

**FINDING:** The Goddard Space Flight Center HST project has a long history of HST shuttle servicing experience but has little experience with autonomous rendezvous and docking or robotic technology development, or with the operations required for the baseline HST robotic servicing mission.

**FINDING:** The proposed HST robotic servicing mission involves a level of complexity that is inconsistent with the current 39-month development schedule and would require an unprecedented improvement in development performance compared with that of space missions of similar complexity. The likelihood of successful development of the HST robotic servicing mission within the baseline 39-month schedule is remote.

Based on extensive analysis, the committee concluded that the very aggressive schedule for development of a viable robotic servicing mission, the commitment to development of individual elements with incomplete systems engineering, the complexity of the mission design, the current low level of technology maturity, the magnitude of the risk-reduction efforts required, and the inability of a robotic servicing mission to respond to unforeseen failures that may well occur on Hubble between now and the mission, together make it highly unlikely that NASA will be able to extend the science life of HST through robotic servicing.

**THE RISKS OF SHUTTLE SERVICING**

The risks that must be considered in making a decision to service Hubble with the shuttle are the risk to the safety of the crew and the shuttle, as well as the risk of failing to accomplish the servicing objectives. As part of its assessment of safety risk, the committee looked carefully at the findings and recommendations of the Columbia Accident Investigation Board (CAIB) and at NASA’s return-to-flight (RTF) requirements. Strong consideration was given to understanding differences in the safety risk factors between shuttle missions to the International Space Station (ISS)—to which NASA still plans to fly 25 to 30 missions—and a shuttle mission to Hubble. Technical considerations examined by the committee included comparisons of on-orbit inspection and repair capabilities at ISS and Hubble, various safe-haven and rescue options, and the likelihood of the shuttle being damaged by micrometeoroid orbital debris (MMOD). With regard to mission risk, the committee considered both the known on-orbit operations required for Hubble servicing and past experience with Hubble shuttle astronaut servicing, including such factors as unforeseen on-orbit contingencies.

The committee developed a large number of findings based on the various analyses cited above. Some of the key findings relevant to the question of the risk of shuttle servicing of HST are as follows:

**FINDING:** Meeting the CAIB and NASA requirements (relative to inspection and repair, safe haven, shuttle rescue, MMOD, and risk to the public) for a shuttle servicing mission to HST is viable.

**FINDING:** The shuttle crew safety risks of a single mission to ISS and a single HST mission are similar and the relative risks are extremely small.

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FINDING: Previous human servicing missions to HST have successfully carried out unforeseen repairs as well as executing both planned and proactive equipment and science upgrades. HST’s current excellent operational status is a product of these past efforts.

FINDING: Space shuttle crews, in conjunction with their ground-based mission control teams, have consistently developed innovative procedures and techniques to bring about desired mission success when encountering unplanned for or unexpected contingencies on-orbit.

FINDING: The risk in the mission phase of a shuttle HST servicing mission is low.

COMPARISON OF THE RISKS AND THE BENEFITS OF SERVICING

As noted above, the Hubble Space Telescope provides unique capabilities for astronomical research. These capabilities will not be replaced by any existing or currently planned astronomy facility in space or on Earth. Hubble’s continuing and extraordinary impact on human understanding of the physical universe has been internationally recognized by scientists and the public alike.

Upgrading Hubble to address the predictable decline in HST component performance over time and thus ensure system reliability requires a timely and successful servicing mission in order to minimize further degradation and prevent a significant gap in science data return. Although it considered other options for extending the life of Hubble, the committee focused on two approaches: robotic servicing and shuttle astronaut servicing.

The need for timely servicing of Hubble imposes difficult requirements on the development of a robotic servicing mission. The very aggressive schedule, the complexity of the mission design, the current low level of technology maturity, and the inability of a robotic servicing mission to respond to unforeseen failures that may well occur on Hubble between now and a servicing mission make it unlikely that the science life of HST will be extended through robotic servicing.

A shuttle astronaut servicing mission is the best option for extending the life of Hubble and preparing the observatory for eventual robotic de-orbit by, for example, attaching targets to Hubble. The committee believes that a shuttle HST servicing mission could occur as early as the seventh shuttle mission following return to flight, at which point critical shuttle missions required for maintaining ISS will have been accomplished. All important systems needed to keep Hubble functioning well through 2011 were included in the original SM-4 shuttle servicing plan. Replacement of batteries and gyro and one FGS is deemed essential. Any spacecraft is subject to unanticipated failures, but if the repairs planned for the SM-4 mission are carried out promptly, there is every prospect that Hubble can operate effectively for another 4 to 5 years after servicing.

The committee finds that the difference between the risk faced by the crew of a single shuttle mission to ISS—already accepted by NASA and the nation—and the risk faced by the crew of a single shuttle servicing mission to HST, is very small. Given the intrinsic value of a serviced Hubble, and the high likelihood of success for a shuttle servicing mission, the committee judges that such a mission is worth the risk.

RECOMMENDATIONS

1. The committee reiterates the recommendation from its interim report that NASA should commit to a servicing mission to the Hubble Space Telescope that accomplishes the objectives of the originally planned SM-4 mission.

2. The committee recommends that NASA pursue a shuttle servicing mission to HST that would accomplish the above stated goal. Strong consideration should be given to flying this mission as early as possible after return to flight.

3. A robotic mission approach should be pursued solely to de-orbit Hubble after the period of extended science operations enabled by a shuttle astronaut servicing mission, thus allowing time for the appropriate development of the necessary robotic technology.
3.2 Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report

A Report of the Committee on Solar and Space Physics

Summary

In May 2003 the Space Studies Board’s Committee on Solar and Space Physics held the Workshop on Exploration of the Outer Heliosphere to synthesize understanding of the physics of the outer heliosphere and the critical role played by the local interstellar medium (LISM)1 and to identify directions for the further exploration of this challenging environment. What emerged was a palpable sense of excitement about the field’s progress in the past 8 to 10 years.

It was only in the mid-1990s that the fundamental role of neutral interstellar hydrogen in determining the global structure of the heliosphere was elucidated and the hydrogen wall predicted. With the later discovery of the hydrogen wall, and then, the discovery of hydrogen walls about other stars in our galactic neighborhood and the associated discovery of stellar winds from solar-like stars, the field of solar and space physics underwent dramatic change.

Coupled to the theoretical advances were the increasingly exciting observations being returned by the Voyager Interstellar Mission, Ulysses, ACE (Advanced Composition Explorer), and Wind—ranging from observations of cosmic rays signaling the approach to the termination shock, to the large- and small-scale magnetic fields responsible for guiding and scattering energetic particles, to name only two types. At the workshop, the greatest excitement was generated by the suggestion that the low-energy cosmic rays showed evidence that Voyager may have crossed the termination shock—completely unexpected observations illustrating Voyagers’ promise for returning results with a capacity to surprise and baffle for years to come.

To further the exploration of the outer heliosphere four strategic directions became clear in workshop discussions:

- **Making use of existing assets.** ACE, SOHO (Solar and Heliospheric Observatory), Wind, Ulysses, and the Voyagers are all currently furthering understanding of the outer heliosphere. In particular, the importance of the Voyagers cannot be overstated as Voyager 1 is capable of lasting another 16 years, allowing it to reach 150 AU. The Voyager Interstellar Mission is impossible to replace at its current location in the next 20 years, making it a uniquely valuable platform. The spacecraft are reasonably well instrumented for the mission, making the Voyagers the best and only near-term hope for exploring the heliospheric boundaries and interstellar medium in situ. The other vital mission is Ulysses, since it is currently the best-situated, best-instrumented mission that directly addresses the fundamental question of how the solar wind couples to the LISM. Scientific understanding of the physics of pickup ions, their relation to interstellar atoms and anomalous cosmic rays, and their influence on the solar wind has been advanced almost entirely by Ulysses (and to a lesser extent ACE), and it is the only spacecraft to directly measure neutral interstellar material. Workshop participants agreed that continued support and a long-term vision from NASA Headquarters, and the provision of continuing data coverage of the Voyagers and Ulysses missions from the Deep Space Network, are essential.

- **Developing new outer heliosphere missions.** New missions should be developed that can use current and moderately improved in situ and remote techniques to conduct heliospheric studies from 1 to 3 AU and beyond. The possibilities include in situ studies and remote observations. For example, the ability to image the region of the termination shock and heliosheath remotely is steadily increasing, with several laboratories now working on experiments in this area. Energetic neutral atom imaging is a promising avenue, with technology outstripping theory

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1The LISM is that region of space in the local galactic arm where the Sun is located (Thomas, 1978), the local interstellar cloud is the cloud within it in which the Sun resides, and the heliosphere is the region in space filled with solar wind material (both supersonic and subsonic flow).
at present. Other possibilities for remote observations involve the use of Lyman-alpha absorption and backscatter techniques; the former is possible at 1 AU with space-based spectroscopic telescopes, and the latter offers the possibility of monitoring the temporal response of interstellar gas to the solar cycle as it flows into the heliosphere. In situ studies within 1 to 4 AU will remain critical to furthering understanding of the fundamental coupling of LISM material and solar wind plasma. Such studies will require spacecraft with instrumentation that can study the inflowing neutral gas and dust, pickup ions, cosmic rays (anomalous and galactic), energetic particles, and magnetic field directly since the measurements of these variables are essential if we are to eventually probe both the LISM and the heliospheric boundaries with new spacecraft (and even remotely). Understanding of the critical microphysics will be advanced best by in situ measurements. It is now possible to build instruments that allow orders-of-magnitude more accurate measurements than those made by the instruments that currently fly on missions. Both in situ and remote measurement could be accomplished within the MIDEX (Medium-Class Explorer) program or perhaps the SMEX (Small Explorer) program. For the interim period, this approach would complement current Voyager and Ulysses activities well.

- **Continuing support of theory and modeling.** Continuing theoretical and modeling studies are essential to ensure progress in understanding the interaction of the solar wind and the LISM. Numerous questions raised by Voyager, Ulysses, and other spacecraft missions remain unanswered, and theoretical studies continue to lag observations. Optimal planning for a mission of the magnitude of Interstellar Probe requires a sufficient understanding of the physics of the remote outer heliosphere and local interstellar medium, which in turn requires far more elaborate modeling of the outer heliosphere, and incorporation of current and future in situ and remote sensing results. In particular, remote sensing techniques, because they are by nature integrated line-of-site observations, produce results whose interpretation depends on theoretical models of the global heliosphere.

- **Preparing for Interstellar Probe.** Interstellar Probe, a mission characterized by both enormous scientific potential and technical challenge, will be one of the most exciting undertakings of NASA in the new millennium. For a mission as ambitious as Interstellar Probe, the technical requirements, the scientific payload, including instrument and communications requirements, and feasibility have to be addressed far in advance. Developing the required propulsion technology is the primary technical challenge of this mission. At least three approaches—nuclear-electric propulsion, solar sail propulsion, and powered Sun-gravity assist—are well suited for and, in principle, capable of accelerating Interstellar Probe to the speeds needed to reach the heliopause within 15 years or less from launch. However, as detailed in the text, none of these options are currently available and all present significant hurdles in their development.

Because Interstellar Probe will require only a rather straightforward trajectory with little need for precise navigation, it could be regarded as an ideal demonstration of nuclear-electric propulsion or solar sailing.

The development of a mission as scientifically and technologically far-reaching as Interstellar Probe will require considerable planning. The eventual scientific payload must be guided by current missions, Pathfinder missions, and theory. A crucial role will be played by Pathfinder missions, which may explore interstellar material such as pickup ions, neutral atoms, or anomalous cosmic rays directly, or explore the boundary regions using remote measuring techniques such as Lyman-alpha or energetic neutral atoms, or explore physical processes induced by the complex partially ionized plasma populations that make up the outer heliosphere beyond some 10 AU.

Sending a well-equipped spacecraft to the boundaries of the heliosphere to begin the exploration of our galactic neighborhood will be one of the great scientific enterprises of the new century—one that will capture the imagination of people everywhere. Significant questions about the outer heliosphere and the LISM still to be addressed include the following:

- What are the nature, structure, and temporal character of the termination shock, and is the termination shock the same in all directions?
- How do pickup ions and solar wind plasma evolve at the shock and in the heliosheath?
- What are the size and shape of the heliopause?

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1Radioisotope electric propulsion is another propulsion option that should not be ruled out yet.
• Does reconnection between the solar and interstellar magnetic fields at the heliopause affect the structure and dynamics of the heliosphere?
• What are the physical state and the degree of ionization of the LISM?
• What is the elemental and isotopic composition of the LISM? What are the direction and magnitude of interstellar magnetic field?
• Is the interstellar wind subsonic or supersonic?

These are among the most fundamental of the questions that can be addressed by space and planetary physics in the next 20+ years, and the answers will have far-reaching implications, not only revealing the nature of the heliosphere but also informing theories on the evolution of our galaxy, and, indeed, the entire universe.
3.3 Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy

A Report of the Space Studies Board

Summary

The workshop on national space policy was organized to air perspectives on the question, What should be the principal purposes, goals, and priorities of U.S. civil space? Or to simplify, What should be our national space policy? The timing of this workshop coincides with a newly directed focus on the long-term direction of the U.S. civil space program. In the wake of the space shuttle Columbia tragedy, the Columbia Accident Investigation Board (CAIB) found that a contributing factor in NASA’s organizational decline was the lack of an agreed national vision for human spaceflight. Congress has held several hearings on this topic, the press is commenting on it, and the Bush Administration is developing a new space policy (see Chapter 2).

The workshop’s six sessions are summarized in the chapters that follow. Through the course of these sessions several matters were addressed that transcended the subject of any one session in particular, emerging as more general themes relevant to the workshop’s principal questions. These seven themes become apparent when one reads the session summaries as a whole and are presented in this summary chapter.

THEME 1: SUCCESSFUL SPACE AND EARTH SCIENCE PROGRAMS

Many workshop participants (panelists and ASEB and SSB members alike; see Appendix B) accepted that U.S. space and Earth science programs are currently productive and progressing steadily, and they described them as being of continuing importance. Many commented during the workshop on the inspiration, success, and progress of the science programs, and they elaborated in their contributed abstracts on the benefits of the approach taken by the science programs. Much of the success of NASA’s science programs was attributed to having clear long-range goals and roadmaps that are framed by scientists and periodically reassessed by the science community in the light of new knowledge and capability. The comments on science were brief, largely because many participants saw the human exploration program as more problematic than the science programs, which were considered healthy and solid. For example, as discussed in Chapter 3, Logsdon challenged the participants to consider that “discussion about the future of the space program would really be discussion about the future of the human spaceflight program. The space and Earth science programs are part of the nation’s portfolio of basic research and are not controversial in principle, though budget levels of course are always a concern.”

Participants who commented that the science programs were successful noted not just the “facts” of success, but the means by which the science programs achieved their successes. They identified the following attributes of the science programs that are the primary contributing factors for their success:

1. Participation from the scientific community. An external-to-NASA constituency that has some “ownership” in the program creates “constructive tension” that pushes the programs to excel.
2. Clear goals. The science programs set out explicit goals and utilize the interest of the scientific community to establish these goals (e.g., through the decadal-scale strategy surveys conducted by the NRC).
3. Strategic planning. The science programs lay out a strategy for achieving their goals.
4. A sequence of successes. The science programs progress via a series of individual steps that can accumulate successes that help measure progress and sustain momentum for the program.


1See Chapter 4, “Rationales for the Space Program: Science, Technology, and Exploration.”
2See Appendix E, especially contributed abstracts by Fink, Giacconi, Huntress, Malow, Stone, and Wheelon.
3See Malow, “A Tale of Two NASAs,” contributed abstract, Appendix E.
4See Chapter 3, page 14.
A number of participants observed that many of these attributes from the science programs were missing in the human exploration program and saw the opportunity to apply them as lessons learned for the improvement of the human spaceflight program.

**THEME 2: A CLEAR GOAL FOR HUMAN SPACEFLIGHT**

Through the course of the day-and-a-half workshop, no participant argued either (1) that we already have a clear human spaceflight goal or (2) that we do not need one. As Chapter 2 suggests, these two points seemed to be part of the context that set the stage for a debate over national space policy.

Many participants echoed the CAIB’s conclusion that a lack of an agreed vision for the human spaceflight program has had a negative impact on the health of that program in NASA. Those participants noted that without such a long-range goal the human spaceflight program’s *reason for being* is hard to articulate. This is true for the specific elements of the human spaceflight program, the space shuttle and the space station, as well as for the program in general. It is not clear to what end the International Space Station (ISS) contributes or what would be the next logical step after the ISS has served its purpose. This stands in contrast to other programs, like military and commercial space programs, which have more easily stated justifications. Wesley Huntress made a crucial point about why such a goal is necessary in our risk-averse society: Human spaceflight is dangerous and requires risk taking, and the public may support risk taking if there is a clear, understandable purpose. Risk cannot be eliminated, but risk due to poor management or lack of rigor should be minimized. A bold goal could enable breaking out of this programmatic drift, providing a transcendent purpose for the risk of human endeavors in space.

Lennard Fisk’s closing statement (Chapter 8) synthesized comments of several others in saying that we no longer need to demonstrate U.S. technological prowess as Apollo did, because there are many such demonstrations, but there is a need to demonstrate U.S. leadership and goodwill. Human spaceflight could provide the opportunity for leadership if the United States would openly invite others to participate in setting and steadily pursuing a shared long-range goal.

**THEME 3: EXPLORATION AS THE GOAL FOR HUMAN SPACEFLIGHT**

The nation originally sent humans to space to demonstrate U.S. technical prowess and political will. Why should we do it now? Many workshop participants emphasized two fundamental reasons:

1. Exploration can and does add to the acquisition of new knowledge, that is, knowledge of space as a place for human activity, and knowledge of the solar system, including Earth, from the vantage point of space.
2. Exploration is a basic human desire: people explore. Riccardo Giacconi called it a general impulse of human nature, and others concurred, suggesting that exploration should be the primary motivation of human spaceflight in order to fulfill an innate human need to explore.

As Robert Frosch said, exploration can be the first step of science. He referred to the oceanographic community, noting that scientists want to dive on the *Alvin* and look at the deep oceans because they see things and they can get from the experience something that they don’t get from remote presentations. Fisk picked up on this point, stating that exploration is a legitimate form of science, if properly conducted. There is a need to incorporate defendable, legitimate science into the human exploration endeavor.

If science can generally be understood as the process through which we acquire new knowledge, then the search for new knowledge may in many ways be akin to humans’ innate desire to explore. As such we may think of these two reasons together as “the human desire to know, to learn.” It was former astronaut Thomas Jones who most clearly articulated the tie that binds these reasons to the tangible benefits of human spaceflight: Only a human can experience what being in space feels like, and only a human can communicate this to others. Indeed, communication of the space experience is the foundation for the entire cultural aspect of the space program. Several participants

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agreed with this statement, including Todd La Porte, who stated that the important cultural benefits from the human space program are not always well articulated for the general public to recognize and understand. Better communication of the space experience, therefore, is seen as necessary to maintain the space program’s political support among the general public. A strong human spaceflight program can help secure public ownership and involvement in the rest of the civil space program. Several participants enunciated this point and spoke of the need for “heroes” and of how people can have a sense of participation through the participation of these heroes.

This cultural aspect, the communication of the space experience, reveals the unique opportunity that space presents for international cooperation. Norman Neureiter was most eloquent in describing how human spaceflight can be a means to enable fruitful and healing international collaboration. Saying that there is a perception that some in the world may fear our power, Neureiter argued that space exploration can be a compelling instrument for building a global fabric of relationships that dispel that fear—relationships that will endure whatever other bad things may happen. In other words we can increase national security by increasing understanding and trust through cooperation.

Participants described a need for human space exploration because it speaks across cultures to some of our greatest natural characteristics and intellectual curiosity: our desire to learn, to extend our grasp with technology, to modernize, to enhance that which makes us human. They also discussed the need for the nation to set a target for our exploration—a goal or a destination for humans to arrive at (that is, beyond low Earth orbit) as a way to help focus the exploration effort. Whatever the goal, participants argued that it will be decided through the course of a national and international dialogue that should begin now.

Participants expressed the importance of making the goal or destination one that excites the imagination and speaks best to our curiosities. Many of the participants suggested that the goal that best meets these criteria is the eventual human exploration of Mars. Others suggested that a mission to the Moon as a precursor to a human visit to Mars could be valuable, while some even suggested that the eventual human exploration of planetary bodies farther out in the solar system should be considered. Whatever the nation may decide through the course of an open dialogue, what emerged as important considerations for achieving that goal is the subject of the next several themes.

THEME 4: EXPLORATION AS A LONG-TERM ENDEAVOR TO BE ACCOMPLISHED VIA A SERIES OF SMALL STEPS

Many participants argued that having a clear, agreed upon, long-term goal, such as the human exploration of Mars, is essential for the future success of the human spaceflight program. It was seen as premature, however, to set a firm date for or cost of that goal. What is possible is a first assessment of what has to be accomplished to reach that long-term goal, and the identification of intermediate, subsidiary goals that can be met as a means to enable the achievement of that long-term goal. In this context the human spaceflight program would be conducted as a series of smaller steps and would evolve at a pace that reflects a meaningful rate of learning. Speakers suggested that this approach requires a coherent architecture or roadmap, which would elucidate how each intermediate step could be accomplished through a sequence of smaller projects that are both technically feasible and acceptable in the political environment.

Several participants observed that a national decision to pursue an ambitious long-term goal would be a political decision, not a scientific one. Therefore such a decision would require political support, which in turn requires realistic costs and broad support. Regarding costs, several participants suggested that the response to a statement by Congressman Sherwood Boehlert that “any vision that assumes massive spending increases for NASA is doomed to fail” should be one in which the nation agrees to pursue a long-term goal with a “buy it by the yard” approach. The big challenge of attaining the goal would be broken into many small achievable challenges. Instead of a fixed deadline, the budget would fund only as many of the “small steps” as could be afforded. Participants talked about an exit strategy for the shuttle and the space station, and, if adopted, that strategy could free up funds.

On the issue of coalitions of support many participants recognized the need for a process different from that used to build support for the space shuttle and space station programs. Frosch was most clear on this point. Recalling his experience as NASA’s administrator, he noted that instead of promising something for everyone, we
must strive to establish a coalition that agrees on a specific space exploration goal. Even if different members of the coalition have different motivations for this goal, there must be agreement on the goal itself. Similarly, there was much discussion on the role of international partners in a coalition for support of a long-term goal. The smaller steps envisioned here offer many opportunities for partner governments to contribute and be involved as true stakeholders in the program. The successes, accumulated in many small steps, will help to build political support. That is, if projects are evaluated against the agreed goal, the workshop discussions envisioned that after many milestones are achieved, and numerous small, cumulative steps are taken, the long-term goal will become inevitable.

**THEME 5: SYNERGY SUPERSEizing THE HUMANS-VERSUS-ROBOTS DICHOTOMY**

In the ultimate achievement of a long-term goal for human exploration, numerous participants made statements echoing the spirit of the remarks made by Congressman Ralph Hall, quoted in Chapter 2: “There should no longer be a question of robotic versus human exploration—clearly both will be needed. . . .” Fink recalled his experience with the Augustine Committee,\(^7\) noting that in the early 1990s there was an unnecessary tension and debate on the subject of “manned versus unmanned” exploration. He noted that this debate has passed and that planning for exploration beyond low Earth orbit will have to consider how to best utilize both human and robotic assets. Other participants agreed, stating further that they believed the space program should move beyond complementarity and toward a synergy between robots and humans, as the concept of synergy best highlights the potential benefits associated with taking advantage of the strengths of each.

Exactly how best to realize this synergy is a matter that requires further discussion and can be dependent on what destination is chosen as the eventual goal for human exploration. In her prepared remarks, Newman articulated this point explicitly, noting that human-robotic missions could take the form of humans assisted by robotic explorers or robots/probes assisted by humans who are not co-located, depending on the location being explored. Frosch was even more detailed, discussing how robots and humans could be integrated if Mars were chosen as the human exploration goal; we could begin with teleoperations from Mars orbit and guided autonomy on the ground, after which we could move to the surface of Mars where humans can undertake tasks that robots cannot perform. Whatever the destination and whatever the specific means chosen, many participants stated that being guided by a principle of synergy between robots and humans provides the opportunity to explore the solar system in the most optimal manner.

The participants noted that there are additional benefits to the synergy of human and robotic assets. One is the fact that it provides the opportunity to communicate the space experience, as Jones expressed. Fink noted that this was a conclusion reached in the Augustine Report as well. Another is the opportunity that a human presence creates for unanticipated learning. Building on Fisk’s assertion that good science can be done with properly devised exploration efforts, Frosch again cited the desire for human participation in the exploration of the deep sea. Newman referred to this as humans enabling serendipity through the co-exploration of space with robots.

In summary, while a history of separation between human and robotic efforts is part of the context, many participants, notably including many scientists, seemed to believe that now is the time to put the dichotomy behind us and to find and exploit synergies between the two.

**THEME 6: THE LONG-TERM GOAL DRIVING ALL IMPLEMENTATION DECISIONS**

Many participants confirmed the context described in Chapter 2, i.e., that both the space shuttle and space station programs made too many promises to too many people and thus lost focus on any one technical mission. Yet if the human exploration program had a goal involving long-term human spaceflight, the station could have a very clear justification; to conduct microgravity and variable-gravity research and technology development to support the agreed goal. To many participants, this meant a higher priority for biological research in support of long-duration spaceflight. Indeed, participants argued that soundly based research on scientific and technical problems tied to human exploration beyond low Earth orbit should be the primary purpose of the ISS. The key to successful

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experiments lies in investigating gravity as an independent variable, whereby biological and physical processes in the weightless environment can be quantified. In addition to the microgravity research conducted on the ISS, participants argued that this approach means an additional focus on experiments utilizing fractional gravity—experiments that may be possible only with a variable-gravity research centrifuge aboard the ISS.

Others noted that learning how to stage and construct large systems, e.g., a large telescope, at a space station and move it to its operational orbit would realize and demonstrate the synthesis of robotic and human activities. Similarly, a human exploration goal could well raise new missions for the ISS, and ultimately, the goal of extending human presence beyond Earth orbit could define the exit strategies for the space station program. The thrust of these comments was that, given a human exploration goal, the ISS program should be modified to focus on supporting that goal, which would mean completing construction of needed facilities and choosing the right experiments to fly on the station. In other words, there would be very clear criteria for setting priorities across the program.

As with space station, the state of the shuttle program is a relevant part of the context of which workshop participants were well aware. The CAIB referred to the original promises and compromises required to gain approval for the shuttle program. These ensured there would be pressure for the vehicle to deliver more than it could. Participants argued that the shuttle program is now at a crossroad and the nation is faced with difficult choices—try to fix and continue with the shuttle or develop another launch vehicle. Discussions focused on the idea that a new human exploration goal could not only provide criteria for this decision, but could also make it possible to define a general exit strategy for the shuttle.

In summary, participants appeared to view the following activities as essential elements along the path to a goal for human exploration: (1) the continued robotic exploration of our solar system followed by the development of capable human-machine interfaces and teleoperators, (2) research on the ISS focused on addressing the questions posed by human exploration away from low Earth orbit, and (3) development of a space transportation system to replace the shuttle, all directed toward facilitating the eventual human exploration of some destination beyond low Earth orbit.

THEME 7: INSTITUTIONAL CONCERNS

These first six themes are cross-cutting concepts relevant to the nation’s future approach to civil space. The seventh theme collects the views offered by participants on needs and opportunities for successful implementation of future space policy.

Concerning the needs of all U.S. space activities, participants cited the Final Report of the Commission on the Future of the United States Aerospace Industry and pointed to the need for an “industrial base.” Critical cross-institutional or cross-sector activities—e.g., joint technology development, taking advantage of synergies, and better planning and development—are all dependent on the availability of a skilled industrial base. This base was viewed as being in decline.

Regarding the civil space program, workshop discussions primarily addressed two particular stakeholders in future civil space activities. They were (1) NASA, as the primary executive branch agency responsible for implementing space policy, and (2) the scientific community, one of NASA’s key constituents.

NASA

Workshop discussions focused on the following five aspects of NASA as an institution:

1. Lack of human spaceflight stakeholders. Participants were attracted to an intriguing observation about human spaceflight in comparison with the science program. In the science program scientists set the goals, e.g., scientific questions to be answered by desired missions, and the agency carries them out. In this way NASA and the scientists share the direction of the program. The scientists have a big stake in the agency program, but there is always tension between the scientists who want as much science as possible and who honor scientific values, and
the implementers who face the practicalities of resource limitations. Noel Hinners found this tension creative, resulting in better science, and noted the lack of similar independent stakeholders and creative tension in the current human spaceflight program. La Porte noted that his research on high-reliability organizations shows that they tend to have a strong presence of, and often active coordination with, outside stakeholder groups.

2. NASA’s changed role. Participants noted that at NASA’s beginning its job was to help make the United States a space-faring nation, but today the United States would be a space-faring nation even if NASA disappeared. Now, they suggested, the agency’s new role is to advance several space frontiers: science, human physiology, applications, technology, and human exploration.

3. Trust and honesty. Chapter 2 quotes Representative Boehlert, who has said that “we need to be honest about the purposes and challenges” of human spaceflight. Several participants cited less than forthright justifications for programs, from Apollo to the present. Several noted that more candid justifications of programs would help justify the risk of spaceflight; the public is not risk-averse for worthwhile programs. More openness would improve trust. In addition, Neureiter noted that failing to involve one’s partners at the very beginning of program decision making damages one’s credibility as a partner. Others agreed that NASA cannot afford to be seen as less than fully open and honest.

4. Management competence. The NASA ISS Management and Cost Evaluation (IMCE) Task Force report, part of the workshop’s context, found that the ISS program lacked the skills and tools to control costs and schedules. Noting the conclusions of the CAIB report, participants observed that in both the Challenger and Columbia accidents NASA management demonstrated failure to detect and remedy the early onset of failures that would threaten the safe operation of the space shuttle. Managers were not seen as learning across generations; they repeat mistakes. Participants also felt that NASA managers overpromised and got into trouble on the shuttle and then did the same thing 10 years later on the ISS.

5. Technical competence. Several participants commented that NASA tended to freeze old technology into human spaceflight programs. As a result, these programs may have trouble attracting good technical people who are at the cutting edge, or younger engineers and scientists. NASA was described as maintaining the shuttle and the station rather than developing new technology.

The Scientific Community

Fisk concluded the workshop by saying that he believed that this workshop could be a truly historic event if the scientific and technical communities, in the broadest sense, can say that as a group “we believe in a human spaceflight program, we believe this country should invest in it, and we will stand up and say how it can be done productively.” Participants saw this as a realistic possibility for several reasons. First, the timing seems good, because the robotic-versus-human dichotomy has begun to dissipate. Second, the tradition in space and Earth science, in which there exists a constructive tension between the agency and scientists who act as continuous stakeholders, was viewed by many as a model by which scientific exploration could strengthen human exploration. Third, participants seemed to agree that the science community could constructively help NASA identify and carry out the best science possible over the course of human exploration missions. Fourth, the discussions suggested that there is an important role for scientists to become involved as stakeholders in helping to integrate humans and robotics in the kind of synergistic way described above, thus producing the best experiments and missions possible and ensuring that bargains are kept across management generations. Indeed, this last point may represent one of the most important and hopeful ideas to emerge from the workshop.

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10See discussions in Chapter 8 on this point.
3.4 Plasma Physics of the Local Cosmos
A Report of the Committee on Solar and Space Physics

Executive Summary

Earth’s neighborhood in space—the local cosmos—provides a uniquely accessible laboratory in which to study the behavior of space plasmas (ionized gases) in a wide range of environments. By taking advantage of our ability to closely scrutinize and directly sample the plasma environments of the Sun, Earth, the planets, and other solar system bodies, we can test our understanding of plasmas and extend this knowledge to the stars and galaxies that we can view only from afar.

Solar and space physics research explores a diverse range of plasma physical phenomena encountered at first hand in the solar system. Sunspots, solar flares, coronal mass ejections, the solar wind, collisionless shocks, magnetospheres, radiation belts, and auroras are just a few of the many phenomena that are unified by the common set of physical principles of plasma physics. These processes operate in other astrophysical systems as well, but because these systems can be examined only remotely, theoretical understanding of them depends to a significant degree on the knowledge gained in the studies of the local cosmos. This report, Plasma Physics of the Local Cosmos, by the Committee on Solar and Space Physics of the National Research Council’s Space Studies Board attempts to define and systematize these universal aspects of the field of solar and space physics, which are applicable elsewhere in the universe where the action is only indirectly perceived.

The plasmas of interest to solar and space physicists are magnetized—threaded through with magnetic fields that are often “frozen” in the plasma. In many cases, the magnetic field plays an essential role in organizing the plasma. An example is the structuring of the Sun’s corona by solar magnetic fields in a complex architecture of loops and arcades—as seen in the dramatic close-up views of the solar atmosphere provided by the Earth-orbiting TRACE observatory. In other cases, such as the Sun’s convection zone, the plasma organizes the magnetic field. Indeed, it is the twisting and folding of the magnetic field by the motions of the plasma in the solar convection zone that amplifies and maintains the Sun’s magnetic field. In all cases, however, the plasma and the magnetic field are intimately tied together and mutually affect each other. The theme of magnetic fields and their interaction with plasmas provides an overall framework for this report. An overview is presented in Chapter 1, introducing the chapters that follow, each of which treats a particular fundamental set of phenomena important for our understanding of solar system and astrophysical plasmas.

The question of how magnetic fields are generated, maintained, and amplified, together with the complementary question of how magnetic energy is dissipated in cosmic plasmas, is explored in the second chapter of this report, “Creation and Annihilation of Magnetic Fields.” The focus is on the dynamo and on magnetic reconnection. Chapter 2 discusses the current understanding of the workings of these processes in both solar and planetary settings and identifies several outstanding problems. For example, understanding how the differential rotation of the solar interior arises represents a significant challenge for solar dynamo theory. In the case of planetary dynamos, important open questions concern the role of physical processes other than the Coriolis force in determining the morphology and alignment of the magnetic field (e.g., of Uranus and Neptune) and the influence of effects such as fluid inertia and viscous stress on Earth’s dynamo. With respect to magnetic reconnection, a significant advance in our understanding has been achieved with the development of the kinetic picture of this process. However, what triggers and maintains the reconnection process is the subject of great debate. Moreover, how reconnection operates in three dimensions is not well understood.

Chapter 3, “Formation of Structures and Transients,” examines some of the important structures that are found in magnetized plasmas. These include collisionless shocks, which develop when the relative velocity between different plasma regimes causes them to interact, producing sharp transition regions, and current sheets, which separate plasma regions whose magnetic fields differ in orientation and/or magnitude. A transient structure that occurs in a number of different plasma environments (solar active regions, the corona, the solar wind, the


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magnetotail) is the flux rope, a tube of twisted magnetic fields. Scientists have learned much about the plasma structures in our solar system but still have numerous questions. Studies of Earth’s bow shock have provided basic understanding of shock dissipation and shock acceleration in collisionless plasmas, but much work remains in extending this understanding to large astrophysical shocks. This will require understanding of strong interplanetary shocks in the outer heliosphere and, ultimately, direct observation of the termination shock. Flux ropes have also been extensively observed, but many unanswered questions remain: How are flux ropes formed and how do they evolve? What determines their size? How are they destroyed? What is their relation to magnetic reconnection?

Chapter 3 also examines magnetohydrodynamic turbulence, a phenomenon that is a classic example of the way in which magnetized plasmas couple strongly across multiple spatial and temporal scales. In turbulent coupling, energy is fed into the largest scales and then progressively flows down to smaller scales, eventually reaching the “dissipation scale,” where heating of the plasma occurs. Turbulence has been most completely studied in the solar wind, but questions remain concerning the detailed structure of heliospheric turbulence and how this structure affects energetic particle scattering and acceleration. Turbulent processes also occur in the Sun’s chromosphere as well as in Earth’s magnetopause and magnetotail. Outstanding problems include the role of turbulence in transport across boundary layers, the onset of turbulence in thin current sheets, and the coupling of micro-turbulence to large-scale disturbances.

Plasmas throughout the universe interact with solid bodies, gases, magnetic fields, electromagnetic radiation, and waves. These interactions can be very local or can take place over regions as large as the size of galaxies. Chapter 4 discusses four classes of plasma interaction. Electromagnetic interaction is exemplified by the coupling of a planetary ionosphere and magnetosphere by electrical currents aligned with the planet’s magnetic field. The aurora is a familiar and dramatic manifestation of the energy transfer that results from this coupling. Electromagnetic coupling is also believed to be important in stellar formation, through the redistribution of angular momentum between the protostar and the surrounding nebular material. Flow-object interactions refer to the processes that occur when plasma flows past either a magnetized or an unmagnetized object. Typical processes include reconnection, turbulent wakes, convective flows, and pickup ions. The third class of plasma interactions are those that involve the coupling of a plasma with a neutral gas, such as the exchange of charge between ions and neutral atoms or collisions between ions and neutrals in Earth’s auroral ionosphere, which drive strong thermospheric winds. The final category is radiation-plasma interactions, which is important for understanding the structure of the Sun’s corona: radiation-plasma interactions produce a monotonically decreasing temperature-altitude profile in the corona in great contrast to a falling-then-rising profile produced by the standard quasi-static models.

Chapter 5, “Explosive Energy Conversion,” treats the buildup of magnetic energy and its explosive release into heated and accelerated particles as observed in solar flares, coronal mass ejections, and magnetospheric substorms. Since the first observation of a solar flare in 1859 and the recognition that solar disturbances are associated with auroral displays and geomagnetic disturbances, magnetic energy release has been a central topic of solar-terrestrial studies. Because of their potentially disruptive influence on both ground-based and space-based technological systems, such explosive events are of practical concern as well as of great intrinsic scientific interest.

Both solar flares and coronal mass ejections (CMEs) result from the release of magnetic energy stored in the Sun’s corona. It is not understood, however, how energy builds up and is stored in the corona or how it is then converted into heating in flares or kinetic energy in CMEs. At Earth, magnetic energy stored in the magnetotail through the interaction of the solar wind and the magnetosphere is explosively released in substorms, periodic disturbances that convert this energy into particle kinetic energy. The details of how stored magnetic energy is transferred from the lobes of the magnetotail to the plasma sheet and ultimately dissipated remain subjects of intense debate. The storage and release of magnetic energy occur universally in astrophysical plasmas, as evidenced by the enormous flares from M-dwarfs and the stellar eruption observed in the young XZ-Tauri AB binary system. What is learned about the workings of magnetic storage-release mechanisms in our solar system is likely to contribute to our understanding of analogous processes in other, remote astrophysical systems as well.

The key mechanisms by which magnetized plasmas accelerate charged particles are reviewed in Chapter 6, “Energetic Particle Acceleration.” Shock acceleration occurs throughout the solar system, from shocks driven by solar flares and CMEs to planetary bow shocks and the termination shock near the boundary of the heliosphere. Particles are accelerated at shocks by a variety of mechanisms, and the resulting energies can be quite high, >100 MeV and even in the GeV range for solar energetic particles accelerated at CME-driven shocks. One topic of particular interest in current shock acceleration studies is the identity of the particles that form the seed population.
for the shock-accelerated ions. What, for example, are the sources and composition of the pickup ions that are accelerated at the termination shock to form anomalous cosmic rays?

Coherent electric field acceleration arises from electric fields aligned either perpendicular or parallel to the local magnetic field. Induced electric fields perpendicular to the geomagnetic field play a role in the radial transport and energization of charged particles in Earth’s magnetosphere and contribute to the growth of the outer radiation belt during magnetic storms. Parallel electric fields accelerate auroral electrons and accelerate plasma from reconnection sites; they are also involved in the energization of solar flare particles. Stochastic acceleration results from randomly oriented electric field perturbations associated with magnetohydrodynamic waves or turbulence. It plays a role in the acceleration of particles in solar flares, in the acceleration of interstellar pickup ions in the heliosphere, and possibly in the acceleration of relativistic electrons during geomagnetic storms.

All of these acceleration mechanisms may occur simultaneously or at different times. For example, direct energization of particles by electric fields, interactions with ultralow-frequency waves, and localized, stochastic acceleration may all contribute to the storm-time enhancement of Earth’s radiation belt. However, in this case as in others, distinguishing among the various acceleration mechanisms as well as determining the role and relative importance of each poses challenges to both the observational and the theory and modeling communities.

Plasma Physics of the Local Cosmos examines the universal properties of solar system plasmas and identifies a number of open questions illustrative of the major scientific issues expected to drive future research in solar and space physics. Recommendations regarding specific future research initiatives designed to address some of these issues are offered in another recent National Research Council report, The Sun to the Earth—and Beyond: A Decadal Research Strategy for Solar and Space Physics, which was prepared by the Solar and Space Physics Survey Committee under the auspices of the Committee on Solar and Space Physics.¹ The two reports are thus complementary. The Survey Committee’s report presents a strategy for investigating plasma phenomena in a variety of solar system environments, from the Sun’s corona to Jupiter’s high-latitude magnetosphere, while Plasma Physics of the Local Cosmos describes the fundamental plasma physics common to all these environments and whose manifestations under differing boundary conditions are the focus of the observational, theoretical, and modeling initiatives recommended by the Survey Committee and its study panels.

¹National 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. See also The Sun to the Earth—and Beyond: Panel Reports, 2003, the companion volume containing the reports of the five study panels that conducted the study.
3.5 Solar and Space Physics and Its Role in Space Exploration

A Report of the Committee on the Assessment of the Role of Solar and Space Physics in NASA’s Space Exploration Initiative

Executive Summary

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

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

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

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

From a purely scientific perspective, it is notable that the solar system, and stellar systems in general, are rich in the dynamical behaviors of plasma, gas, and dust that are organized and affected by magnetic fields. These dynamical processes are ubiquitous in highly evolved stellar systems, such as our own, and they play important roles in their formation and evolution. Magnetic fields produced in rotating solid and gaseous planets in combination with ultraviolet and x-ray photons from the planetary system’s central stars create plasma environments called asterospheres, or in the Sun’s case, the heliosphere. In its present manifestation, the heliosphere is a fascinating corner of the universe, challenging our best scientific efforts to understand its diverse workings. Consequently this “local cosmos” is a laboratory for investigating the complex dynamics of active plasmas and fields that occur throughout the universe, from the smallest ionospheric scales to galactic scales. Close inspection and direct


samplings within the heliosphere are essential parts of the investigations that cannot be carried out by a priori theoretical efforts alone.

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

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

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

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

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

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

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

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

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

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

With those principles in mind, the decadal survey report recommended a specific sequence of high-priority
programs as a strategy for solar and space physics in the next decade. To accomplish this task, the survey report
presented an assessment of candidate projects in terms of their potential scientific impact (both in their own
subdisciplines and for the field as a whole) and potential societal benefit (i.e., with respect to space weather). The
survey report also took into consideration the optimum affordable sequence of programs, what programs would
benefit from being operational simultaneously, the technical maturity of missions in a planning phase, and what
programs should have the highest priority in the event of budgetary limitations or other unforeseen circumstances
that might limit the scope of the overall effort. The recommended sequence of missions was supported by a strong
base of Explorer missions, mission operations and data analysis (MO&DA), suborbital activities, and supporting
research and technology (SR&T) programs, which together provide the core strength of the Sun-Earth Connection
(SEC) program research base.

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

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

\(^5\)For a full discussion of the roles and relationships of spaceflight missions to supporting research and technology programs, see National

\(^6\)By “targeted basic” research the committee means research that is conducted at a relatively fundamental level but that is intended to provide
the scientific basis for specific future applications. The term “strategic research” has sometimes been used synonymously.
Recommendation 1. To achieve the goals of the exploration vision there must be a robust SEC program, including both the LWS and the STP mission lines, that studies the heliospheric system as a whole and that incorporates a balance of applied and basic science.

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

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

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

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

Even with an SEC program that preserves the priorities and sequence of recommended missions, there will be important consequences from delaying the pace at which missions are executed as a means of dealing with resource constraints. First, there will be losses of scientific synergy due to the fact that opportunities for simultaneous operation of complementary missions will be more difficult to achieve. Furthermore, a number of missions that were recommended in the decadal survey report will be deferred beyond the 10-year planning horizon. This could be the case for the Jupiter Polar Mission, Stereo Magnetospheric Imager, Magnetospheric Constellation, Solar Wind Sentinels, and Mars Aeronomy Probe. These issues will demand careful attention as NASA develops its overall plan for science in the exploration vision.
3.6 Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond

A Report of the Committee on Environmental Satellite Data Utilization

Executive Summary

There is no doubt that environmental satellite data have grown to be the most important source of information for daily global weather forecasting. In addition, these data are now also used by innumerable professionals and laypersons in pursuits as varied as oceanic, atmospheric, terrestrial, and climate research; environmental monitoring; aviation safety; precollege science education; and rapid-response decision support for homeland security, to name just a few. Compounding the pressure put on NOAA and NASA by expanding user communities to provide high-quality data products around the clock is the precarious state of the underfunded satellite data utilization program, which is struggling to keep up with demand for currently available data and the rapidly increasing sophistication of user requirements. The planned next-generation operational satellite systems, comprising both polar-orbiting and geostationary platforms, are designed to meet the needs of user communities whose complex applications are rapidly evolving.

Although the focus of this report is the use of satellite data for civilian rather than defense or national security purposes, a dual-use approach is expected as military and civilian satellite systems converge. The new systems will continue the record of climate-quality observations, but the increase in raw data will be unprecedented—perhaps an order-of-magnitude increase every 2 to 3 years. Expected to develop as a result of this expanded Earth-observing capability are novel ways of using satellite data that will have an increasing impact on citizens’ daily lives. Thus satellite data providers will have to continuously evolve, revise, and in some cases radically redefine their role as well as plan for increased research, operations, and infrastructure. The high-level training required by such personnel and the continuing education of users are equally important and also must be planned and provided for.

Meeting the challenges posed by the imminent and unprecedented exponential increase in the volume of satellite-system data requires an end-to-end review of current practice, including characterization of process weaknesses, an assessment of resources and needs, and identification of critical factors that limit the optimal management of data, plus a strategic analysis of the optimal utilization of environmental satellite data.

In this report, the Committee on Environmental Satellite Data Utilization (CESDU) offers findings and recommendations aimed at defining specific approaches to resolving the potential overload faced by the two agencies—NOAA and NASA—responsible for satellite data (see the preface for the committee’s statement of task). The committee has focused on the end-to-end utilization of environmental satellite data by characterizing the links from the sources of raw data to the end requirements of various user groups, although, given its limited scope, the committee could not thoroughly examine every link in the chain. CESDU’s goal is to characterize and provide sensible recommendations in three areas, namely, (1) the value of and need for environmental satellite data, (2) the distribution of environmental satellite data, and (3) data access and utilization. The committee’s findings are based on its members’ knowledge of trends in technology; past lessons learned; users’ stated requirements; and other supporting information. The committee hopes that this report will help NOAA and NASA identify and avoid impediments to optimal utilization of environmental satellite data.

Over the course of meetings held to collect information for this report, the committee heard presentations from several key agencies and organizations reflecting a broad range of professional perspectives. From these it distilled four consistent and recurring themes that significantly shaped its final findings and recommendations:

- A growing and diverse spectrum of individuals, companies, and agencies routinely utilize and depend on environmental satellite data and information;

• Products that best serve the public, together with effective use of public funds, create an ongoing evolution of requirements for data imposed on and by operational users;
• Improvements in available flight and ground technologies are being made that meet these new requirements—as demonstrated by research satellite missions and aircraft flights; and
• NOAA is committed to the collection of data with improved quality, reliability, latency, and information content.

The value of environmental satellite data derives from the unique, near-real-time, continuous global coverage from space of Earth’s land and ocean surfaces and its atmosphere—value that increases significantly as we accumulate satellite records that provide a historical perspective. In addition, the committee believes that, in the near future, environmental satellite data will be employed by a much wider spectrum of users—from individuals with real-time weather data displays in their home, car, truck, boat, plane, business, or campsite, to a wide range of companies with value-added products developed from those data, to farmers, mariners, truckers, and aviators dependent on weather, to numerical modeling centers that provide weather, crop, fire, drought, flood, health, climate, and other predictions and alerts. Indeed, evidence presented to the committee strongly suggests that we should look to and prepare for a future in which cable TV, wireless networks, personal digital assistants, direct satellite broadcast, and the Internet enable continuous, uninterrupted access to environmental satellite data, information, and knowledge as an essential element of commerce, recreation, and the conduct of everyday life for the majority of people.

Thus it will not be sufficient merely to collect greater amounts of environmental satellite data, although the expected orders-of-magnitude increase in the volume of collected data will in itself pose special challenges. The committee heard testimony about increasing requirements to recover more of the information content in the data, and also about an anticipated increase in the number and diversity of environmental satellite data users who will demand instantaneous access to the particular data and information they want. To achieve improved utilization of environmental satellite data will therefore require that as much effort and planning be devoted to the ground systems serving this user community as to the flight systems that originally collect the data. To successfully realize the future outlined above, the agencies responsible for archiving and distributing environmental satellite data must develop the essential visions, plans, and systems. The following findings of the committee and the recommendations based on them are offered to help NASA and NOAA in that process.

THE VALUE OF AND NEED FOR ENVIRONMENTAL SATELLITE DATA

Finding: Improved and continuous access to environmental satellite data is of the highest priority for an increasingly broad and diverse range of users. Their needs include real-time imagery for decision making in response to events such as forest fires, floods, and storms; real-time data for assimilation into numerical weather prediction models; recent imagery for assessment of crops and determination of impacts on the environment resulting from diverse human activities such as marine and land transportation; and data coverage spanning many years that allows assessment of patterns and long-term trends in variables, such as sea-surface temperature, land use, urbanization, and soil moisture. Users of environmental satellite data include individuals; federal government agencies; state and local managers, planners, and governments; commercial producers of added-value products; and Web, print, and TV/radio broadcasters.

Recommendation 1: To best serve the diverse user communities and to meet growing demand, the committee recommends that, as soon as is practical, agencies providing environmental satellite data and products collaborate, with NASA and NOAA taking the lead, to develop an explicit strategy and implementation plan for data distribution systems, user interfaces, and increased user engagement and education. The goals of this plan should be to facilitate access to current, historical, and future environmental satellite data and products in ways that acknowledge the range of skills and evolving needs of the user communities and to support these users by providing appropriate supporting information and educational material.
Finding: The national and individual user requirements for multiyear climate system data sets from operational environmental satellites, as currently delineated in the Climate Change Science Program strategic plan,¹ are placing special demands on current and future data archiving and utilization systems. These demands include more stringent requirements for accurate cross-platform radiometric calibration, new combinations of multiple satellite and instrument data, and algorithms for generating advanced biophysical variables. Detecting climate change trends often involves evaluating data at the limits of measurement precision, and so periodic, absolutely consistent reprocessing of climate data records is a fundamental requirement.

Recommendation 2: Creating climate data records (CDRs),² which quantify subtle but important global change trends, is not a task that can be accomplished solely in routine operational environments (such as with the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and Geostationary Operational Environmental Satellite (GOES)). The committee recommends that NASA, along with NOAA, select multidisciplinary, research-oriented, end-to-end science teams that will select those NPOESS, GOES, and other systems’ data products and variables that are scientifically important and technologically feasible for long-term CDR development. These science teams will design and maintain a proactive strategy for the stewardship and multidecadal production of the selected CDRs.

Finding: NOAA has limited experience with land data sets because historically its mission has focused on the oceans and atmosphere. Major advances in land remote sensing have occurred in the last decade, fostered primarily by the Earth Observing System developed by NASA, that are not reflected in NPOESS planning. The committee found that NOAA has so far not effectively utilized current satellite technologies and data sets for vegetation science, management, or applications. For example, of 58 environmental data records (EDRs) defined for NPOESS, only 6 are specifically for land, and of these only 2 are vegetation oriented. For the 2012 flight of GOES-R, only 20 of the approximately 170 environmental observation requirements (EORs) are land-surface related; of these, only 4 are vegetation related.

Recommendation 3: NOAA should convene an intergovernmental committee with NASA, the U.S. Department of Agriculture, the Department of the Interior, the Environmental Protection Agency, and other interested parties to select the variables for land vegetation data for generation from NPOESS, GOES, and other operational systems that will have high utility for both land management and the hydroecological sciences.

THE DISTRIBUTION OF ENVIRONMENTAL SATELLITE DATA

Finding: The constellations of satellites now in space and planned for the future include platforms launched by several nations, and more complete and comprehensive coverage of environmental data fields can be achieved by combining the data from these different national efforts.

Recommendation 4: The U.S. Environmental Satellite Data Program should work to facilitate user access to data from other nations’ satellites as well as its own and to facilitate synthesis of data across platforms by providing supporting metadata.


²A preliminary report by the NRC’s Board on Atmospheric Sciences and Climate (Climate Data Records from Environmental Satellites: Interim Report, National Academies Press, Washington, D.C., 2004, page 1) defines a climate data record as “a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change.” The report adds, “In addition we further segment satellite based CDRs into Fundamental CDRs (FCDRs) which are calibrated and quality controlled sensor data that have been improved over time, and Thematic CDRs (TCDRs), which are geophysical variables derived from the FCDRs, such as sea surface cloud temperature and cloud fraction.”
Finding: The Comprehensive Large Array-data Stewardship System is being designed by NOAA to catalog, archive, and disseminate all NOAA environmental satellite data produced after 2006. Given the magnitude of this effort—and considering the growing volume, types, and complexity of environmental satellite data; the increasingly large and diverse user base; and expectations for wider and more effective use of the data—the committee emphasizes the importance of NOAA’s (1) having a comprehensive understanding of the full scope of the technical requirements for data cataloging, archiving, and dissemination and (2) ensuring implementation based on that knowledge. Key to successful implementation of a strong system that will serve operational users and the nation well are detailed planning, proactive follow-through, and NOAA’s incorporation of lessons learned from previously developed, similarly scaled initiatives with similar systems requirements.

Recommendation 5:
   a. NOAA should conduct an immediate review of the entire Comprehensive Large Array-data Stewardship System (CLASS) program. This review should aggressively solicit and incorporate recommendations from the designers, builders, operators, and users of similar systems, particularly those systems comprised by the Earth Observing System Data and Information System.
   b. CLASS should be designated and developed as NOAA’s primary data archive system for environmental satellite data and other related data sets. NOAA should ensure that CLASS is designed to adequately serve the full spectrum of potential environmental satellite data users. In addition to end users, CLASS should be designed to disseminate data to the broadest possible community of data brokers and value-added providers. The CLASS architecture should explicitly include the public programmatic (e.g., Web services) interfaces that these third parties require.
   c. NOAA should plan for and identify resources required for an increased CLASS effort to fulfill the needs outlined in a and b above.

Finding: NOAA does not appear to be effectively leveraging the substantial and growing third-party resources available for creating, archiving, and distributing environmental satellite data products. In particular, the current CLASS effort appears to include end-user services (such as Web ordering, e-commerce, and product customization) that could just as easily be provided by third parties, while ignoring the lower-level programmatic interfaces that value-added providers require.

Recommendation 6:
   a. NOAA should consider both centralized and decentralized approaches to managing the generation and distribution of environmental satellite data products to ensure cost-effective and efficient utilization of existing human and institutional expertise and resources. Centralized handling should be provided for operationally critical core products and should include the acquisition, processing, distribution, archiving, and management of calibrated, navigated radiances and reflectances at the top and bottom (atmospherically corrected) of the atmosphere, as well as for selected key products and metadata. Specialized higher-level environmental data products could be handled (processed, reprocessed, and distributed) in a physically and organizationally distributed (and diverse) manner.
   b. NOAA should take maximum advantage of the exponentially decreasing costs of computing resources and allow for distributed implementations by third parties.
   c. NOAA should consider mutually beneficial partnerships and partnering models with the private sector (e.g., commercial value-added data and product services providers) that have the twin objectives of ensuring user-oriented open access to the data and providing the best value to end users.

Finding: Over the life of a project the cost of ownership of online (disk) storage is competitive with, and decreasing more rapidly than, that of offline (tape or optical) storage. The ability to store and process large volumes of satellite data online will thus become ubiquitous. More than any physical medium, Internet connections to these online data sources will prove a stable, economical, and widely available mechanism for data transfer.
Recommendation 7:
   a. NOAA’s default policy should be to maintain all public satellite data online, in archives that can be
      accessed (partitioned) to maximize throughput and replicated (mirrored) to ensure survivability.
   b. NOAA should transition to exclusively online access to satellite data. Distribution on physical media
      should be provided as a custom service by third parties.
   c. NOAA should plan for and identify resources to support handling of the anticipated increase in archival
      and dissemination requirements beyond 2010.

DATA ACCESS AND UTILIZATION

Finding: Data from diverse satellite platforms and for different environmental variables must often be retrieved
from different sources, and these retrievals often yield data sets in different formats with different resolution and
gridding. The multiple steps currently required to retrieve and manipulate environmental satellite data sets are an
impediment to their use.

Recommendation 8: Data access and distribution should be designed, and associated products tailored, to be
compatible with users’ processing, storage, distribution, and communications resources and their information
requirements.
   a. NOAA should improve access to its data by allowing users to focus searches by geographic region,
dates, or environmental variables, thus helping provide the means to search from one user interface across all
environmental satellite data held by U.S. agencies. Tailored subsets of data products should be made available
for routine distribution and/or in response to a specific request.
   b. Further, NOAA’s user interfaces should allow stored environmental satellite data sets and/or images to
be retrieved in a common data format and with geolocated gridding selected from a list of options by the user.
Subsetting and subsampling should be combined to provide a continuum of data products from broad-area,
low/moderate-resolution products to regional, high-resolution products.
   c. NOAA should concentrate on ensuring the commonality, ease, and transparency of access to environ-
mental satellite data and providing no-cost data streams in a few standardized, user-friendly formats selected
primarily to maximize ease of translation into community-specific formats.
   d. NOAA should support the development of third-party format translation services and the adaptation of
existing community-standard tools to NOAA-standard formats.
   e. The data that NOAA provides to users should be accompanied by metadata that documents data quality,
discusses possible sources of error, and includes a complete product “pedigree” (algorithm theoretical basis,
sensor and calibration, ancillary data, processing path, and validation status and component uncertainties).

Finding: Some major segments of the user community currently do not have the resources to fully utilize all of
the environmental satellite data available to them. The principal obstacles to expanded use have been inadequate
and/or discontinuous funding for applied research as a part of data utilization programs, the lack of support for
education and outreach programs, and the lack of trained professional brokers and facilitators available to work with
the various bidirectional interfaces between users and providers within the environmental satellite data utilization
system.

Recommendation 9: A continuous level of adequate resources, especially for applied research and educa-
tion of the work force in the use of environmental satellite data, is needed to exploit the huge investments
already made in the satellite system. Satellite data providers and the scientific research community should also
take a leading role in facilitating collaboration with their end-user partners. These efforts should include
outreach, training, and technical assistance for the more sophisticated user communities as well as for the
rapidly emerging nonscientific, nongovernmental user groups, with the ultimate goal being to enable straight-
forward and effortless user access to environmental satellite data and data products.
Finding: Early and ongoing cooperation with dialogue among users, developers of satellite remote sensing hardware and software, and U.S. and international research and operational satellite data providers is essential for the rapid and successful utilization of environmental satellite data. Active research and development is required to achieve operational sustainability—today’s research anticipates and underpins the satisfaction of tomorrow’s operational requirements. Many of the greatest environmental satellite data utilization success stories (see, e.g., the case study on the European Centre for Medium-range Weather Forecasts in Appendix D) have a common theme: the treatment of research and operations as a continuum, with a relentless team focus on excellence with the freedom to continuously improve and evolve.

Recommendation 10: To ensure the ongoing development of future operational environmental satellite data products that have high quality and value requires an ongoing evaluation of the U.S. effort to collect and provide environmental satellite data. An integrated, sustainable basis for the stewardship of future operational systems, sensors, and algorithms should be fostered by establishing close cooperation between the research and operational agencies responsible for the utilization of environmental satellite data (including their development, collection, processing and reprocessing, validation, distribution, and exploitation), with research and operations viewed as a continuum and not as two independent areas of effort. To meet evolving customer requirements, this cooperation between research and operational agencies should be coordinated in close partnership with the user community. Only a fully funded, end-to-end system, from satellite/sensor design to data assimilation/utilization, can fully optimize the investments that have been made.
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Short Reports

During 2004, the Space Studies Board and its committees issued two short reports. The main text of each is reprinted in this section.

4.1 Assessment of Options for Extending the Life of the Hubble Space Telescope: Letter Report


At the request of the National Aeronautics and Space Administration, the National Research Council recently established the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope. The committee’s statement of task charges it to assess the viability of a shuttle servicing mission, evaluate robotic and ground operations to extend the life of the telescope as a valuable scientific tool, assess telescope component failures and their impact, and provide an overall risk-benefit assessment of servicing options. The statement of task includes the possibility of transmitting an interim report to NASA prior to the submission of a final report.

The committee thanks you very much for your generous allocation of time in meeting with it on June 22, 2004. The information that you conveyed on the decision-making process that you and NASA followed when arriving at the Hubble-related decisions in January and in March 2004 was very important for us to hear directly from you. The additional information that you provided on NASA activities related to the shuttle return-to-flight program and robotic engineering in the broader context of long-term human space exploration was very useful, as was the extensive question-and-answer dialog that you enthusiastically engaged in with the committee.

Because you and your NASA colleagues have made clear to the committee that there is some urgency in issuing any recommendations related to Hubble, we are providing you with this interim report. It offers three principal findings and recommendations. These are based on the committee’s collective knowledge as well as input from other experts, both internal and external to NASA. This interim report does not address any one request in the statement of task in its entirety, but rather touches on aspects of task components 1, 2, and 4. Here the committee considers the

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1The committee roster, enclosure A, is not reprinted in this annual report. Additional background material on the motivation for the study, contained in enclosure B, is not reprinted in this annual report.

2See the statement of task, enclosure B, which is not reprinted in this annual report.

3Information about the independent review of the committee’s report under the supervision of the NRC’s Report Review Committee is provided in enclosure C, which is not reprinted in this annual report.
degree of importance that a Hubble servicing mission would have for science, as well as some of the key factors involved in selecting a servicing mission option. Its aim is to provide useful guidance to NASA that can be utilized during the time that the committee (as well as NASA) continues to investigate the servicing options in greater detail.

The work of the committee will continue during the coming weeks, and we expect to finish drafting a final report by late summer or early fall. The final report will address in detail all four of the requests in the study’s statement of task.

IMPORTANT OF A HUBBLE SERVICING MISSION

The Hubble Space Telescope (HST) is arguably the most important telescope in history. Much of Hubble’s extraordinary impact was foreseen when the telescope was being planned. It was predicted, for example, that the space telescope would reveal massive black holes at the centers of nearby galaxies, measure the size and age of the observable universe, probe far enough back in time to capture galaxies soon after their formation, and provide crucial keys to the evolution of chemical elements within stars.

All of these predicted advances have been realized, but the list of unforeseen Hubble accomplishments may prove even greater. Hubble did discover “adolescent” galaxies, but it also saw much farther back in time to capture galaxies on the very threshold of formation. Einstein’s theory of general relativity was bolstered by the detection of myriad gravitational lenses, each one probing the mysterious dark matter that pervades galaxies and clusters of galaxies. Gamma-ray bursts had puzzled astronomers for more than 20 years; in concert with ground and X-ray telescopes, Hubble placed them near the edge of the visible universe and established them as the universe’s brightest beacons, outshining whole galaxies for brief moments. Perhaps most spectacularly, Hubble confirmed and strengthened preliminary evidence from other telescopes for the existence of “dark energy,” a new constituent of the universe that generates a repulsive gravity whose effect is to drive galaxies apart faster over time. The resulting acceleration of universal expansion is a new development in physics, possibly as important as the landmark discoveries of quantum mechanics and general relativity near the beginning of the 20th century.

Closer to home, Hubble has zeroed in on our own cosmic past by uncovering virtual carbon copies of how the Sun and solar system formed. Dozens of protoplanetary disks have been found encircling young stars in nearby star-forming regions of the Milky Way. The sizes and densities of these disks show how surplus dust and gas collect near infant stars to form the raw material of planets. Dozens of large, Jupiter-like planets have been discovered, initially by other telescopes but recently by Hubble using a new and more precise method. Measuring the tiny drop in light as a planet transits the disk of its parent star, the new technique could lead to a method for discovering Earth-like planets—a discovery with tremendous long-term implications for the human race.

Riveting as they are, these scientific returns from Hubble are far from their natural end. With its present instruments the telescope could continue probing star formation and evolution, gathering more data on planetary systems, revealing planetary and cometary phenomena in our own solar system, and exploring the nature of the universe at much earlier times. However, two new instruments, already built for NASA’s next planned servicing mission (SM-4), would amplify the telescope’s capabilities by allowing qualitatively new observations in two underexploited spectral regions. Such rejuvenation via new instruments has occurred after every Hubble servicing mission, and the next one promises to be no different. Wide Field Camera-3 (WFC3) would increase Hubble’s discovery efficiency for ultraviolet and near-infrared imaging by factors of 10 to 30. The UV channel coupled with the camera’s wide field of view will image the final assembly of galaxies still taking place in the universe. The near-infrared channel of WFC3 favors discovery of the very youngest galaxies, whose light is maximally red-shifted. The available UV, visible, and near-IR channels will combine to give a sweeping, panchromatic view of objects as diverse as star clusters, interstellar gas clouds, galaxies, and planets in our own solar system.

The second new instrument, the Cosmic Origins Spectrograph (COS), will increase Hubble’s observing speed for typical medium-resolution ultraviolet spectroscopy by at least a factor of 10 to 30, and in some cases by nearly two orders of magnitude. Ultraviolet spectra carry vital clues to the nature of both the oldest and the youngest stars, yet UV rays are totally invisible from Earth’s surface. COS will fill important gaps in our understanding of the birth and death of stars in nearby galaxies. Even more impressive, COS will use the light of distant quasars to spotlight

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4Throughput multiplied by the area of the field of view.
hitherto undetectable clouds of dispersed gas between nearby galaxies, thereby mapping in unprecedented detail the properties of the so-called “cosmic web.”

**Finding.** Compelling scientific returns will result from a servicing mission to the Hubble Space Telescope that accomplishes the scientific objectives of the originally planned NASA servicing mission SM-4.

**Recommendation.** The committee urges that NASA commit to a servicing mission to the Hubble Space Telescope that accomplishes the objectives of the originally planned SM-4 mission, including both the replacement of the present instruments with the two instruments already developed for flight—the Wide Field Camera-3 and the Cosmic Origins Spectrograph—and the engineering objectives, such as gyroscope and battery replacements. Such a servicing mission would extend the life of this unique telescope and maximize its productivity.

Other potential options to extend the useful life of Hubble—for example, by servicing components such as batteries and gyroscopes but without replacing instruments—will be studied by the committee as part of its charge. However, such a reduced level of servicing has not been featured in the repair strategies that the committee has heard about to date. The scientific impacts of reduced levels of servicing below that envisioned in SM-4 will be considered in the committee’s final report.

**SERVICING MISSION OPTIONS**

A wide range of factors must be considered when assessing the risk and effectiveness of HST servicing and deorbiting options. These options range from robotically attaching a deorbit module to Hubble to performing a mission (human or robotic) that replaces both scientific instruments and also services or repairs a number of engineering components. You discussed many of these options with us on June 22. One essential task is to enable the ultimate safe deorbiting of the spacecraft so that humans on Earth will not be at risk during its reentry. The present plan is to launch and robotically attach a deorbit module to the telescope around the year 2013.\(^5\) Consistent with this plan, NASA issued a Request for Proposals (RFP) on June 1, 2004, for a Hubble disposal vehicle.\(^6\)

Another risk concerns robotic servicing and possible replacement of telescope instruments. You told the committee that a robotic mission “will be really tough.” NASA has proposed that a deorbit module might be attached to the spacecraft at the time of robotic servicing, although the recently issued RFP does not specifically require either servicing or instrument replacement.\(^7\)

The committee has been given detailed information on the plans for robotic servicing currently under consideration by NASA at its Goddard Space Flight Center. A subgroup of the committee visited Goddard and examined the current activities. The robotic servicing development effort at Goddard was officially initiated in 2004 and is a very recent undertaking. While considerable advances have been made in just a few months, there has been little time for NASA to evaluate and understand the technical and schedule limitations of robotic servicing.

The committee was gratified by your assurance that the robotic efforts will be adequately supported by the required resources in a timely manner. During the next year the robotic servicing mission project will have to achieve key milestones (including a critical design review in the summer of 2005) that will clarify the feasibility of a robotic servicing mission. Substantial resources will be required in Fiscal Year 2005 to accomplish this.

The committee finds the proposed robotic mission to be highly complex due to the inherent difficulties with supervised autonomy in the presence of time delays; the integration of vision and force feedback in six-degree-of-freedom assembly and disassembly tasks with high-degree-of-freedom, dexterous manipulators; and the coordinated control of the high-inertia HRV\(^8\) with a long-reach robotic arm grappling with a high-inertia payload. Robotic

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\(^5\)This is the earliest date at which Hubble would be expected to reenter the atmosphere without intervention.

\(^6\)The RFP can be found at the following URL: http://www2.epsc.gov/spg/NASA/GSFC/OPDC20220/HST%2DDDM%2D0002%2DGDJ/ listing.html.

\(^7\)The RFP requires only submissions for a vehicle to provide end-of-life controlled reentry or other safe disposal of the HST; the RFP invites but does not require that submissions include life extension or servicing capabilities.

\(^8\)Hubble Robotic Vehicle.
emplacement of a deorbit module and replacement of instruments and subsystems on Hubble will require a rendezvous with a non-cooperative vehicle together with a human in a telerobotic loop that has a substantial (on the order of 2-second) time delay.

The committee was informed about several current U.S. and foreign space programs that involve various concepts for robotic spacecraft rendezvous, capture, and servicing. Related U.S. experimental programs are currently scheduled for November 2004 (U.S. Air Force) and September 2006 (DARPA). The committee has been informed that NASA is participating in some aspects of the DARPA program but this does not yet include a commitment to Hubble robotics servicing mission demonstrations. To the best of the committee’s current understanding, difficult challenges of the Hubble robotic scenario (such as the time delay and a non-cooperative target) are not currently covered explicitly in either the Air Force or the DARPA programs. Based on information provided to the committee and the knowledge of members who have deep experience with shuttle flights and spacecraft servicing, the committee believes that the proposed robotic mission to Hubble will essentially be an experimental test program that is expected to accomplish specific programmatic objectives at the same time.

**Finding.** The proposed Hubble robotic servicing mission involves a level of complexity, sophistication, and technology maturity that requires significant development, integration, and demonstration to reach flight readiness.

**Recommendation.** As an early step, NASA should begin immediately to take an active partnership role that includes HST-related demonstrations in the robotics space experiments that are now under way in other agencies in order to ensure that the returns from these experiments can be beneficial to a potential robotic Hubble servicing mission.

The four HST shuttle servicing missions already completed have demonstrated that crew servicing and instrument replacement can be highly successful. Of course, there is risk to the astronaut crew in any human flight mission. As you informed the committee, some 25 to 30 additional shuttle missions are planned to complete the International Space Station (ISS). Based on its current assessment of the conclusions and recommendations contained in the Columbia Accident Investigation Board (CAIB) report and the Stafford-Covey reports (latest dated May 19, 2004), the committee concludes that a shuttle flight to the HST is not precluded by or inconsistent with the recommendations from these two NASA advisory groups.

The committee finds that the CAIB report makes clear distinctions between missions to the ISS and non-ISS missions. The CAIB report notes that the degree of difficulty is somewhat greater when conducting a non-ISS shuttle mission. This is partially due to the fact that a non-ISS mission such as one to Hubble would not have as long a “safe haven” opportunity as would a mission docking with the space station. The shuttle repair capabilities at a non-ISS location would also be less robust than at the ISS itself. Even so, the CAIB report does not prescribe operational constraints on how to conduct a non-ISS mission, but rather only general risk mitigation steps that should be followed. The CAIB consciously accepted lower risk mitigation efforts for non-ISS missions (such as a mission to Hubble). The committee was cognizant and most appreciative of your extensive discussions with us related to the ownership that you, and NASA, have for the shuttle return-to-flight and for astronaut safety in the nation’s civil space program. You stressed that total elimination of risk in crewed space flight is “impossible” and that you and NASA are “not risk averse.” From information it has received, including the risk information to date, the committee concludes that there would be little additional investment in time and resources required over the next year for NASA to keep open an option for a human servicing mission to Hubble.

According to briefings received by the committee, the risk assessments for viable Hubble servicing alternatives, both human and robotic, have not yet been completed or reported by NASA. The Hubble project office is currently investigating risks associated with robotic mission scenarios. Additionally, the committee was told that probabilistic

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9A non-cooperative vehicle is a vehicle that is not equipped with transponders or active sensors, meaning that it cannot respond to electronic interrogation from other spacecraft or emit signals enabling its identification or localization.
10Defense Advanced Research Projects Agency.
14Ibid.
risk assessment results for shuttle flights should be available in the fall or winter of this year. Such a study will be important in improving the comparisons between the risks of human flights to the ISS and to Hubble.

Finding. Because of inherent uncertainties in the early stages of development of a robotic mission to the Hubble Space Telescope, as well as the uncertain current status of the shuttle return-to-flight program, the key technical decision points for committing to a specific service scenario are at least a year in the future.

Recommendation. At the same time that NASA is vigorously pursuing development of robotic servicing capabilities, and until the agency has completed a more comprehensive examination of the engineering and technology issues, including risk assessments related to both robotic and human servicing options, NASA should take no actions that would preclude a space shuttle servicing mission to the Hubble Space Telescope.

We would be pleased to brief you and your staff regarding the views expressed in this letter. We remain committed to completing our final report in an expedited fashion.

Signed by

Louis J. Lanzerotti
Chair, Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope
4.2 Review of Science Requirements for the Terrestrial Planet Finder: Letter Report

On September 23, 2004, SSB/BPA Panel to Review the Science Requirements for the Terrestrial Planet Finder-Chair Wendy L. Freedman sent the following letter to Anne L. Kinney, director of the Universe Division, Science Mission Directorate, NASA Headquarters.

This letter report reviews the science goals of the current Terrestrial Planet Finder (TPF) project as well as NASA’s plan for acquiring the necessary precursor knowledge to successfully meet those goals. This review by the Panel to Review the Science Requirements for the Terrestrial Planet Finder complements recommendations made in the National Research Council report Astronomy and Astrophysics in the New Millennium (referred to here as the 2000 decadal survey) and was conducted in response to your request of January 29, 2004, asking for a science assessment of the TPF project. Your original letter of request was followed by one dated April 15, 2004, announcing NASA’s intention to proceed with both coronagraphic and interferometric planet finder missions on an accelerated schedule. Both are included in this letter report’s attachment. The Space Studies Board and the Board on Physics and Astronomy, in response to your requests, developed the following charge:

This panel will review NASA’s current scientific objectives for the Terrestrial Planet Finder (TPF) mission and prepare a brief letter report conducting an independent scientific assessment as to whether these objectives remain consistent with the priority given to the mission by the Astronomy and Astrophysics Survey Committee.

In carrying out this charge, the panel will consider (1) the scientific goals of the mission as developed by the NASA TPF-Science Working Group; (2) plans for acquiring the necessary precursor scientific knowledge; and (3) the rationale for the mission that formed the basis of the priority assigned by the NRC’s decadal survey report Astronomy and Astrophysics in the New Millennium.

This charge, to which NASA raised no objection, governed the scope of the current letter report; the panel emphasizes here that it was not constituted to carry out a technical assessment of the current TPF project plans and did not attempt to do so.

The panel met at the Keck Center of the National Academies in Washington, D.C., on May 18, 2004, to conduct the review (see the attachment for a panel roster and the meeting agenda). Drawing extensively on the current membership of the NRC’s Committee on Astronomy and Astrophysics, the panel’s membership covered a broad range of astronomical expertise. The panel also included members with specific expertise in coronagraphy and extrasolar planets.

The panel received presentations from Zlatan Tsvetanov (NASA) on the programmatic plans for TPF and from Charles Beichman (JPL) on the scientific and engineering plans for the project. Also participating in the discussion were Marc Kuchner (Princeton University), Alan Boss (Carnegie Institution of Washington), Dan Coulter (NASA), and Garth Illingworth (University of California, Santa Cruz).

The 2000 decadal survey report ranked the Terrestrial Planet Finder third in its list of major NASA missions behind the James Webb Space Telescope (then called the Next Generation Space Telescope) and the Constellation-X Observatory and sixth overall:

The main goal of TPF is nothing less than to search for evidence of life on terrestrial planets around nearby stars. The present concept calls for a space-based infrared interferometer of enormous sensitivity, capable of nulling out the light from the host star. TPF’s angular resolution will also enable it to peer into the innermost regions of protoplanetary disks, galactic nuclei, starburst galaxies, and galaxies at high redshift. By a large margin, TPF is the most costly and the most technically challenging mission discussed in this report. Both SIM and NGST involve key technologies that must be demonstrated if TPF as currently envisioned is to go forward. The committee’s recommendation of this mission is predicated on the assumptions that TPF will revolutionize major areas of both planetary and nonplanetary science, and

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that, prior to the start of TPF, ground- and space-based searches will confirm the expectation that terrestrial planets are common around solar-type stars. NASA should pursue a vigorous program of technology development to enable the construction of TPF to begin in this decade. (p. 39)

The original mission that was considered by the 2000 decadal survey ranked highly based on its potential science impact on terrestrial planet finding and on the astrophysics reach afforded by the high angular resolution at infrared wavelengths. However, the widely recognized technical challenges of the interferometer prohibited the decadal survey committee from prioritizing it as a flight mission. Rather, that committee gave TPF its high ranking as a technology development activity with the aim of pushing the technology forward in this decade, and enabling the mission to be flown in the following decade. Specifically, “The committee attributes $200 million [in FY2000 dollars] of the $1,700 million total estimated cost of TPF to the current decade . . . .” (p. 37).

At the time of NASA’s initial request in January 2004 for the current vision, the TPF project was considering both a free-flying infrared interferometer and an optical coronagraph, with the goal of downselecting to a single architecture in the near future. The course of the TPF project has since changed in order to take advantage of the new opportunities presented by NASA’s new space exploration goals and to maximize the scientific potential for terrestrial planet finding. Specifically, the TPF project team is now proposing to fly TPF-C (an optical telescope with a coronagraph) followed by TPF-I (a free-flying infrared interferometer) within its planet-finding portfolio. The level-1 requirement for TPF-C’s wavelength coverage is proposed to be 0.5 to 0.8 µm, with “stretch” goals of 0.5 to 1.05 µm. The level-1 requirement for TPF-I’s wavelength coverage is proposed to be 6.5 to 13 µm, with “stretch” goals of 6.5 to 17 µm.

The primary scientific goal of the TPF mission (direct detection and spectroscopic analysis of Earth-like planets in orbit about some of the nearest main-sequence stars) arguably requires both TPF-C and TPF-I. This requirement was not well understood at the time the TPF mission was presented to the decadal survey committee, because understanding was imperfect then concerning the spectrum that our own Earth would present to a nearby solar system. Furthermore, the identification of biomarkers (i.e., spectroscopic features indicative of chemical balances attributable to biogenic activity) requires observations in spectra that span not only the optical but also the mid-infrared (IR) bands. Assuming there are planets to be found within the range of these telescopes, the combination of the two could provide evidence suggesting the presence of living organisms outside our solar system.

The TPF-C coronagraph is being designed to be able to identify planets that are Earth-sized or slightly smaller within the habitable zones of about 35 single, solar-type (F, G, K) stars within about 10 parsecs of the Sun. Liquid water is required for Earth-like life, and O₂ is under most circumstances a good indicator of photosynthetic life. Equipped with a modest-resolution spectrometer, the coronagraph should be able to identify several near-IR absorption bands of H₂O, along with the 0.76-µm “A” band of O₂ in light passing through the atmosphere of such planets. Hence, this mission has the capability by itself of at least suggesting whether life is present on planets around other stars.

Flying an IR interferometer, TPF-I, several years after the coronagraph is launched (potentially in a joint mission with the European Space Agency, as is under current discussion with NASA) could help to advance the science goals of the field in several ways. The currently envisioned free-flier concept for the interferometer would make long baselines possible and could enable this mission to extend the search for planets to more than 150 single, solar-type stars—a fourfold increase over the TPF-C sample. This larger search space would, of course, be critical if the frequency of Earth-like planets is low. Even if Earth-like planets are abundant, and the coronagraph is able to see many of them, the additional information obtained by the interferometer will likely prove crucial in characterizing these planets and determining whether any of them could harbor life. Thus the spectroscopic information provided by the interferometer is complementary to that provided by the coronograph. For example, with sufficient cooling, the interferometer is expected to be able to observe the strong 15-µm band of CO₂. The presence of CO₂ is perhaps the best indicator that a planet being observed is terrestrial (i.e., rocky) and that it has an atmosphere, as opposed to being an airless body similar to Mercury or the Moon. CO₂ is also required for photosynthesis, both aerobic and anaerobic, and hence it is a requirement for many Earth-like forms of life. Even more importantly, the IR interferometer will have

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1Terrestrial planets are planets similar in size and composition to Earth. In our solar system Mercury, Venus, and Mars (as well as Earth) are considered to be terrestrial planets.

the capability to detect the 9.6-µm ozone band. Ozone, formed photochemically from oxygen, may be a more sensitive indicator of photosynthetic life than is oxygen itself. The TPF-C and TPF-I data together will provide simultaneous information for the same molecules in different states (e.g., the presence of oxygen from the A-band, as well as ozone at 9.6 µm or CO₂ at both the near and the thermal infrared), thereby removing some of the degeneracies in the interpretation of TPF-C or TPF-I data alone. The simultaneous detection of ozone (TPF-I) and methane (TPF-C)—oxidizing and reducing gases—implies that life may be present. What can be learned from the combination of TPF-C and TPF-I data is therefore far greater than what either mission alone would yield.

Since the 2000 decadal survey the TPF project has made progress in technology development and scientific definition of the mission. NASA reported that shortly after the survey, a number of detailed studies of TPF system architectures showed that an extremely precise coronagraphic imaging telescope could achieve some—though not all—of the science goals outlined originally for the interferometer approach. The TPF team believes that it will be ready to move TPF-C into Phase-A development by 2006, pursuant to an ambitious schedule to launch the coronagraphic imaging telescope by 2014. Because of its greater complexity, TPF-I is currently planned to follow about 6 years later. The technology development plans for both TPF-C and TPF-I are aggressive. However, a promising development is that the High Contrast Imaging Test Bed at the Jet Propulsion Laboratory has successfully imaged a region next to a simulated star within which an average contrast of 1.5 × 10⁻⁹ has been achieved. If this result proves applicable to the broader TPF-C mission, the mission’s development may meet the 2006 goal for entering Phase A.

Nevertheless, TPF-C would satisfy only part of the science requirements previously ascribed to the interferometric version of TPF that was ranked in the 2000 decadal survey. TPF had two goals of equal importance: planet finding and astrophysics. As emphasized in the 2000 survey: “To ensure a broad science return from TPF, the committee recommends that, in planning the mission, comparable weight be given to the two broad science goals: studying planetary systems and studying the structure of astronomical sources at infrared wavelengths” (p. 12). The 2000 decadal survey’s companion volume of panel reports specified that TPF cover a range from 3 to 30 µm for general imaging, and 7 to 20 µm for planet finding, with an angular resolution of 7.5 × 10⁻⁷ arcsec at 3 µm.¹ TPF-I is necessary not only to enhance the project’s planet-finding ability but also to complete the astrophysical goals laid out in the 2000 decadal survey.

A conceptual ancillary science case for TPF-C has been developed with the addition of a 5-arcminute wide-field camera. The science achieved with this camera would be synergistic with that made possible by the James Webb Space Telescope and a 30-m ground-based telescope. An example involves extremely deep observations, significantly more sensitive than the Hubble Space Telescope ultradeep field, of the annular region around the stars targeted for the planet search. TPF-C might have additional astrophysics reach, but the TPF project has not allowed broader astrophysics goals to drive the design or the cost of the TPF-C optical telescope assembly. Ancillary science for the TPF-I mission is not as clearly developed at this point, although ideas include extended spectral coverage for exoplanetary science or fine-resolution studies of high-red-shift galaxies and protostellar disks.

The 2000 decadal survey report was also very explicit about the importance of studies to be carried out prior to designing TPF. NASA’s plans for acquiring the necessary precursor science include (1) an assessment of the extent of exozodiacal dust in other planetary systems and the effects of this dust on the detectability of terrestrial planets, (2) a determination of the biomarkers that would be optimal indicators that life exists on such planets, and (3) an estimation of the minimum number of stars in the sample necessary to detect terrestrial planets with confidence.

Both the Spitzer Space Telescope, which was launched in 2003, and new ground-based IR interferometry (using the Keck interferometer or Very Large Telescope Interferometer telescopes) should address the extent of exozodiacal dust. The NASA TPF Working Group presented a reasonable case that the combination of visible (obtainable with a coronagraphic mission) and infrared (obtainable with an interferometric mission) biomarkers would be a far stronger discriminant of life than either set of wavelength-dependent biomarkers separately. Launching both TPF-C and TPF-I would provide this combination of evidence.

The greatest unknown remains the number of stars TPF-C needs to be able to observe, in order to assure that it will detect terrestrial planets.³ Achieving the primary scientific goal for the TPF mission is still hampered, perhaps

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crucially, by a lack of information about how common Earth-mass, let alone Earth-like, planets are around the sorts of F-, G-, and K-type stars identified for the TPF sample. Estimates of the probability that Earth-like planets exist vary widely. The fraction of these planets that will have even remotely Earth-like atmospheres is also unknown, but must strictly be less than 1 (i.e., over most of its lifespan Earth’s atmosphere has been chemically quite different from its composition today). The fraction of stars with planets bearing Earth-like atmospheres is a matter of conjecture at this point. This is precisely why the 2000 decadal survey report recommended that strong constraints on these fractions be established before the TPF conceptual design is finalized. As envisioned by the survey, the mission could be designed to accommodate whatever fraction nature provides, thus maximizing the chances of success.

Thus, the precursor science is of paramount importance to the success of TPF. The target stars must be surveyed with any and all available resources before a detailed preliminary design is finalized. These searches can be undertaken with both ground- and space-based precursor missions, such as SIM and other lower-sensitivity projects (e.g., the planned “extreme” adaptive optics coronagraph for the Gemini Observatory). The Kepler mission may place strong constraints on the frequency of Earth-mass planets around Sun-like stars. Unfortunately, on NASA’s proposed schedule these missions may not produce results before the design of TPF-C is completed. The panel concludes that accelerating the schedule for TPF-C development carries considerable risk of settling on a design that the results obtained with SIM, Kepler, and microlensing and other observations will subsequently reveal to be incapable of seeing terrestrial planets. Therefore, the panel urges NASA to plan the development of TPF-C at a pace that allows the design to take into account the results of SIM, Kepler, and other observations as outlined above. A TPF flight mission could then be well positioned for a high ranking, possibly including both TPF-C and TPF-I, in the next decadal survey.

The 2000 decadal survey took into account, among other things, the broad programmatic implications of TPF. The proposed addition of TPF-C represents a major new mission of the Great Observatory class and is proposed for launch in 2014, 3 years after the James Webb Space Telescope. The panel agrees that TPF as envisioned in the 2000 decadal survey remains an exciting mission scientifically. The combination of TPF-C and TPF-I will cover at a minimum the planet-finding goals as laid out in that report.

Although NASA gave the panel no cost estimates, presenters did suggest a few bounds that lead toward a conclusion that the mission cost of TPF-C will be at least the cost of the current James Webb Space Telescope. According to NASA, the decision to fly both TPF-C and TPF-I was triggered by NASA’s new space exploration goals, in which planet finding received a very high priority. Neither the 2000 decadal survey nor any prior NRC reports had considered the added value for terrestrial planet finding of having an optical mission such as TPF-C as a complement to TPF-I.

The panel finds that the current scientific goals of the TPF project are consistent with those envisioned in the 2000 decadal survey, *Astronomy and Astrophysics in the New Millenium*. But the panel does not consider that this finding justifies advancing at this time the priority that can be accorded TPF as combined TPF-C and TPF-I missions. A decision after the fact to initiate a major project such as TPF-C implicitly reorders without due process the prioritized list developed by the 2000 decadal survey. Any such decision about prioritization should be made with the input of a broadly constituted committee that has sufficient time to weigh all of the scientific and technical issues.

In summary, the panel reaffirms that TPF, as envisioned in the 2000 decadal survey, remains an exciting mission scientifically. The panel concludes that, with the addition of TPF-C, there is considerable potential for interesting ancillary science in addition to the science connected with the search for life-bearing planets. The panel also concurs with the 2000 decadal survey on the importance of precursor missions (e.g., SIM and Kepler) toward enhancing TPF’s overall scientific productivity. It is critical that their results continue to drive the development of the project. The panel also concurs with the 2000 decadal survey’s recommendation that the astrophysics goals of TPF be weighted comparably to the planet-finding goals.

Yet although the proposed new camera for TPF-C possesses interesting capabilities, the associated science case has been neither carefully developed nor critically reviewed. The panel recommends that NASA solicit input from the astronomical community in order to develop the strongest possible science case. A strong science case would enhance TPF’s competitiveness in any priority-setting process, whether conducted in the context of the next decadal survey of astronomy and astrophysics or in an exercise of smaller scope conducted before the next survey.

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1 Precursor studies will constrain the fraction of Sun-like stars that are orbited by Earth-like planets. This information determines the minimum volume of space that needs to be searchable by TPF-C in order to reasonably ensure that it will directly detect at least one Earth-like planet, thus driving the physical design of the telescope.
Finally, the panel is concerned about the process by which NASA’s decision to propose two TPF missions and to start one of them this decade was reached. The statement of task asked for input on the likely impacts on the 2000 decadal survey priorities, and these are large. The plan for TPF-C is clearly not consistent with the 2000 decadal survey’s recommendations regarding TPF.

Even though NASA has rearranged the order of missions occasionally in the past when funding or technology concerns warranted such changes, TPF-C is so expensive and challenging that the panel believes that, from the perspective of astronomy and astrophysics, it must be placed in the broader context of the other highly ranked space missions identified in the 2000 decadal survey. The panel is very concerned about breaking with a process for developing a strategy that has served astronomy and astrophysics very well—the broadly debated, carefully balanced, and widely endorsed portfolio that the 2000 decadal survey presented. If implementation of TPF-C were to delay, or even preclude, other highly ranked astronomy and astrophysics missions, such an outcome would represent a substantial tipping of the portfolio’s scientific balance. The panel urges NASA to consider the addition of TPF-C within the broader context of the entire astronomy and astrophysics program.

Signed by

Wendy L. Freedman
Chair, Panel to Review the Science Requirements for the Terrestrial Planet Finder

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*The panel acknowledges that the TPF mission is of interest to disciplines throughout the space sciences, and that the mission could conceivably be of higher priority to other disciplines.*
5
Congressional Testimony

5.1 The President’s Vision for Space Exploration: Perspectives from a Recent NRC Workshop on National Space Policy

Statement of Lennard A. Fisk, chair of the Space Studies Board, University of Michigan, and Thomas M. Donahue Collegiate Professor of Space Science, University of Michigan, before the Committee on Science, U.S. House of Representatives, on March 10, 2004.

INTRODUCTION

Chairman Boehlert, Ranking Member Gordon, and members of the committee, thank you for inviting me to testify today. My name is Lennard Fisk. I am the Thomas M. Donahue Collegiate Professor of Space Science at the University of Michigan, and I appear before you today in my capacity as the Chair of the National Research Council’s Space Studies Board. In discussing the President’s vision for space exploration this morning I will be telling you about a workshop that the National Research Council held last November under the sponsorship of the Space Studies Board and the Aeronautics and Space Engineering Board. The purpose of the workshop was to discuss the question: What should be the principal purposes, goals, and priorities of the U.S. civil space program? As I will tell you, there are many ideas from that workshop that are well embodied in the President’s vision for space exploration. There are also some views on implementation, which you may wish to consider. There are, however, some notable differences from what participants at our workshop thought was an appropriate approach that I would like to call to your attention.

I have brought with me and would submit for the record a list of the workshop participants and a copy of the report, titled Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy, which summarizes our discussions. As you can see from the list, the participants represented a broad range of experiences in the space program, having participated in leadership positions in NASA, industry, and the military, as well as the science community. The discussions were informed and lively, and what impressed me most was the extent to which people agreed on the key issues.

IS THE PRESIDENT’S VISION NEEDED?

The participants in the NRC workshop stated several times over the course of the meeting that NASA needed a clear vision, direction, and goal for the human spaceflight program.
Furthermore, these participants were inclined to agree that such a goal should be the human exploration of the solar system beyond low-Earth orbit. They viewed exploration as the acquisition of new knowledge: knowledge of space as a place for human activity, knowledge of our solar system, and knowledge of the universe beyond our solar system. They also saw exploration as a basic human desire, innate in our genetic code, and noted that human spaceflight can be the modern realization of that basic trait.

**IS NASA APPROACHING THE VISION CORRECTLY?**

The important question, of course, is how does the nation proceed in order to achieve a space exploration goal? How do we ensure success? Our workshop recognized that exploration of our solar system is a long-term endeavor, which needs to be accomplished with a series of incremental steps. In this sense, the human exploration efforts can learn from the successes of NASA’s science programs. Workshop participants observed that certain key factors have contributed to the success of the science program: there are clear goals in the science program established by the science community’s interest in pursuing the most challenging scientific questions; there is strategic planning; and there has been a steady sequence of accomplishments. The science program is executed via a series of individual steps that can accumulate success, from which progress can be measured and momentum sustained.

So what are these steps for human exploration? Our workshop participants envisioned a number of key efforts—the development of building block technology, the dedication of ISS research to solving questions posed by long-term spaceflight, eventual phasing out of the space shuttle, and the use of robotic precursor missions to both the Moon and Mars. These steps also are part of NASA’s new roadmap for space exploration.

In 1997 the Space Studies Board published a report which I think offers several complementary ideas for a roadmap for space exploration. Titled *The Human Exploration of Space*, the report reviews three important areas of consideration that the Board felt were necessary to address at the initial stages of a program in human exploration. First is the enabling science for human exploration. This defines the conditions necessary to maintain the health and safety of astronauts and to ensure their optimal performance. Research areas that are enabling science can be classified according to their degree of urgency. Critical research issues, or “showstoppers,” are those for which inadequate scientific data lead to unacceptably high risks to any program of extended space exploration. The second area of consideration is the science that is enabled by a human exploration program, specifically human missions to the Moon and Mars. The third area of consideration is one of management and organization—what should be the relationship between the scientific community and NASA, between scientists and engineers within NASA, as a program of human exploration moves forward?

The 1997 SSB report identifies the following as those showstopper, critical research issues: the long- and short-term effects of ionizing radiation on human tissue; the radiation environment inside proposed space vehicles; the benefits and costs of different radiation shielding techniques; the detrimental effects of reduced gravity and transitions in gravitational forces on all of the body’s systems and on bones, muscles, and mineral metabolism; and the psychological effects of long-duration confinement in microgravity with no escape possible. These and several other issues related to the human biological response to space exploration are detailed and prioritized in two more recent National Academies reports: *A Strategy for Research in Space Biology and Medicine in the New Century*, published by the Space Studies Board; and *Safe Passage: Astronaut Care for Exploration Missions*, published by the Institute of Medicine.

As for the connection between scientists and engineers, I was struck at our workshop by how members of the scientific community appeared willing to embrace the idea that the human spaceflight program can be a contributor to real scientific progress. I think our participants would echo the conclusions of the 1997 report which called for an integrated science program to accompany human missions to the Moon and Mars, as well as the close coordination between human spaceflight and science program staff in the implementation of an exploration program. Participants at our workshop said many times that the reason the process of setting research priorities by the scientific community has had a positive impact on NASA’s science programs is that it creates within the scientific community, a community that in the language of Congress can be considered the constituency of the science programs, a sense of ownership in the program. That feeling of ownership creates what we called a constructive tension between NASA and the science community, which ultimately empowers the program to excel. We observed this sense of ownership to be missing from the human spaceflight part of NASA, but that does not have to remain the case.
Robotic precursor missions to the Moon and Mars can provide an opportunity to engage this issue of cooperation between science and exploration, develop new technologies for space exploration, and significantly enhance and optimize the scientific return of eventual human missions. A 2002 report by the Space Studies Board, New Frontiers in the Solar System: An Integrated Exploration Strategy, highlighted an extremely exciting opportunity for science from the Moon, by making a sample return mission to the Moon’s South Pole-Aitken Basin one of its top priorities. By studying the internal structure of the Moon at this location, which is the oldest and deepest impact structure preserved on the Moon, we can investigate how major impacts on the Earth from early solar system space debris shaped the evolution of our planet. The solar system exploration strategy report also identifies important scientific opportunities for the exploration of Mars.

Participants at our workshop argued that precursor missions to the Moon and Mars should seek to move past a previously long-standing dichotomy that has existed between robotic and human spaceflight over most of NASA’s existence. Part of the goal of these missions should be to develop the technology that will allow for the greatest possible human-robotic interaction. Workshop discussions emphasized the concept of synergy—not just complementarity—between robots and humans. We must learn how to best take advantage of the strengths of both, separately and in cooperation.

FURTHER COMMENTS ON SCIENCE

There are other critical research challenges which deserve equal attention and consideration in addition to the biological and physiological questions I mentioned. Specifically, I refer to two issues highlighted in our 1997 Human Exploration report: (a) the characteristics of cosmic-ray particles and the extent to which their levels are modulated by the solar cycle and (b) the frequency and severity of solar flares. These issues arise from questions about the nature of the role of the Sun in our solar system and how the Sun creates and controls the environment into which we intend to send astronauts. The recent NRC decadal science strategy for solar and space physics identified key missions within NASA’s Sun-Earth Connections program that are critical to understanding these fundamental processes and consequently to understanding the volatile space environment. That report recommended that the Sun-Earth Connections program of NASA be charged with, and provided the resources needed for, developing a predictive understanding of the Sun and the space environment it controls. I would urge you to carefully consider the impact of any prioritization that would hinder or delay the development of our understanding of and our ability to predict the space environment.

A LACK OF BALANCE IN THE SCIENCE PROGRAMS

It was the opinion of many at our workshop that the science roadmaps, decadal strategy surveys, and mission plans in astronomy and astrophysics, solar and space physics, and solar system exploration, which have been so carefully developed by scientists and engineers in the external community and in NASA, and NASA’s careful attention to these details in execution of its programs, have resulted in science being NASA’s greatest current strength. In fact, since the Apollo era came to a close one might argue that NASA’s science efforts have been responsible for a major fraction of the agency’s greatest successes. The pertinent question then is: Can NASA preserve the strengths of its science programs and at the same time energize a new human spaceflight program that seeks to include the science of exploration as part of an overall new thrust for the agency?

This is, of course, a question of balance—balance between a new exploration priority and continuing successful science programs. I would encourage you to consider whether or not the science disciplines have been divided unnecessarily into those that are perceived as essential for exploration and those that are not. Our reports argue that the Sun and the planets and moons of the solar system are all equally worthy of exploration. They also suggest that research to study both the origins of planetary systems and life and the structure and evolution of the universe are highly important. In Earth science, NASA has a responsibility under the Space Act and its amendments to use its capabilities to understand our home planet and predict its future. While NASA may now have a priority to explore, I would expect that it still also has the responsibility to deliver to the policy makers and the public a sufficient understanding of how we can be good stewards of our planetary home.
HOW TO MOVE FORWARD

The matter of balance between new exploration priorities and science opportunities, between new priorities and responsibilities, is very difficult to tackle. I believe the best way to approach this matter, as is emphasized in our workshop report, is to move forward on the human exploration front at a deliberate pace. Our workshop discussions embraced the idea that NASA should pursue a long-term goal via a series of small steps, and they identified learning as the critical factor that should drive implementation decisions.

There are several subjects about which we need to learn more. We must learn about the technology we will employ in this endeavor. We must learn more in several areas before we can be sure we have minimized the health risks to astronauts. And all of us, the scientific community, NASA, the Congress, and the nation as whole, must learn how to organize our space program to engage this effort. The workshop report describes concerns that the infrastructure of our space program was formed and sized to support Apollo and it asks “Is the current infrastructure properly configured for a bold initiative?” The report notes that the space program workforce, in the broadest sense, is aging; the attitudes seem risk averse; process seems more important than ingenuity. Can this mind-set be changed? An aging workforce and infrastructure are also a feature of the space science community. Where are the bold new minds that will lead us into the future?

Finally, there is the matter of cost. A sense at the workshop was that it is too premature to estimate how much an exploration initiative would cost—exactly because we have a great deal to learn and because our past experiences have told us that we should be careful in estimating costs too early. This is at the heart of why our participants emphasized a deliberate approach—we should identify critical research and technology development issues and devise, even at this early time, some kind of roadmap for progress in those areas. We must also examine the full breadth of NASA’s science programs to determine what research already underway may contribute to that progress; what research is currently planned that may contribute to that progress; and what new research is necessary, and we must support them all with the resources necessary to achieve success. Only through this balanced approach, with roadmaps for technology development and scientific progress that are related to each other and flexible enough to adapt to change and to learning can we have a guidepost against which we measure our progress, articulate our successes, and identify our next steps.

This approach to success through a series of individual steps implies a kind of “go-as-you-pay” approach to exploration to allow for affordable and flexible exploration that changes in response to learning. In this sense then, go-as-you-pay is complemented by the practice of pay-as-you-learn.

CONCLUSION

In closing, Mr. Chairman, I would like to again thank you for inviting me to testify today. I would be happy to address any questions you and the committee may have about our report or the discussions that took place at our workshop. A renewed opportunity for human exploration in the solar system creates an exciting moment in our nation’s history. I can tell you that there is indeed great excitement in the space community, which I believe is reflected in our report. I think further that the leaders of the scientific community may be ready to stand up and say “we believe this country should invest in this activity, and we are ready to make the case to the world that this is a valid use of this nation’s resources.” I am hopeful that we as scientists are ready to engage this process actively to help guide its implementation and direct it toward success.
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