
AN ASSESSMENT OF BALANCE IN NASA'S SCIENCE PROGRAMS

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Committee on an Assessment of Balance in NASA's Science Programs, National Research Council

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Preface

Congress, in the report accompanying the FY 2005 appropriation bill for NASA, directed "the National Academies' Space Studies Board (SSB) to conduct a thorough review of the science that NASA is proposing to undertake under the space exploration initiative and to develop a strategy by which all of NASA's science disciplines, including Earth science, space science, and life and microgravity science, as well as the science conducted aboard the International Space Station, can make adequate progress towards their established goals, as well as providing balanced scientific research in addition to support of the new initiative."[1]

In partial response to the congressional request, the National Research Council (NRC) has provided advisory assistance in (1) examining how science could be integrated into NASA's exploration efforts[2] and (2) reviewing NASA strategic planning roadmaps related to science[3] and plans for research on the International Space Station (ISS).[4] The first component of the NRC's response addressed the strategy for decision making about science programs and recommended a set of guiding principles for setting priorities. The second component, review of the roadmaps and plans for research aboard the ISS, addressed NASA's initial plans within specific discipline areas. These responses, in part, address initial directions proposed by NASA through early 2005.

After the NRC had completed the above steps, NASA's senior leadership implemented revisions of NASA's planning process and a rebalancing of programmatic priorities. Soon after being appointed in April 2005, NASA Administrator Michael Griffin indicated, in public statements, his general support of the role of science in NASA's Vision for Space Exploration ("the Vision").[5] He also embraced the value of pursuing an approach that encompasses both robotic missions and human spaceflight, and he expressed the importance of preserving balance across NASA's science programs. At the same time, Administrator Griffin altered the schedule of the agency's planning process and modified the original plans for NRC review of all NASA roadmaps and of NASA's integrated strategy so as to have the NRC review only the science roadmaps. Consequently, the NRC did not have an opportunity in 2005 to assess NASA's integrated strategy for pursuing both established scientific goals and science initiatives in support of human exploration, and thus the SSB's response to Congress was incomplete.

In February 2006, NASA released both the agency's FY 2007 budget request and a new agency strategic plan. These materials provide the first indication of NASA's integrated strategy and the choices that NASA has made among scientific programs within the context of the Vision. The present report provides the NRC's assessment of NASA's integrated strategy and proposed science program, as indicated in materials that accompany the NASA FY 2007 budget request, and it provides the third and final component of the NRC's advisory response to the FY 2005 congressional appropriations report mandate.

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[1] Conference Report on H.R. 4818, Consolidated Appropriations Act, 2005, H. Rept. 108-792, p. 1599.

[2] National Research Council, *Science in NASA's Vision for Space Exploration*, The National Academies Press, Washington, D.C., 2005.

[3] National Research Council, *Review of Goals and Plans for NASA's Space and Earth Sciences*, The National Academies Press, Washington, D.C., 2006.

[4] National Research Council, *Review of NASA Plans for the International Space Station*, The National Academies Press, Washington, D.C., 2006.

[5] The Vision for Space Exploration initiative was announced by President George W. Bush on January 14, 2004, and is outlined in *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

This report was prepared by the ad hoc Committee on an Assessment of Balance in NASA's Science Programs,[6] which was established under the auspices of the SSB. The committee was charged to consider whether the NASA science program, as articulated in the FY 2007 budget estimate and supplementary information and its out-year run-out, is:

1. Appropriately inclusive of all relevant science disciplines (Earth and planetary sciences, life and microgravity sciences, astronomy and astrophysics, and solar and space physics);
2. Robust and capable of making adequate progress toward scientific goals as recommended in NRC decadal surveys; and
3. Appropriately balanced to reflect cross-disciplinary scientific priorities within the appropriate directorate, as recommended in NRC decadal surveys and other relevant scientific reviews.[7]

The committee tasked the discipline-oriented standing committees of the SSB[8] to review the NASA program plans in their respective areas and to provide for the committee's consideration discipline-specific assessments of the match between previously established scientific goals and the ability of the science program described in the proposed FY 2007 budget to achieve those goals. The committee met on March 6-8, 2006, to hear from NASA and other government officials about the programs embodied in the FY 2007 budget proposals, to receive the reports of the SSB standing committee chairs, and to discuss the committee's response to its charge.[9] The committee also drew on the guiding principles recommended in the NRC report *Science in NASA's Vision for Space Exploration* to assess NASA's decision making across scientific programs and the integrated approach to the program, and the committee referred to published NRC decadal surveys[10] when assessing individual disciplines as well as NRC advice regarding the contribution of particular science disciplines in NASA's Vision.

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[6] See Appendix C for biographies of the committee members.

[7] See Appendix A for the full statement of task.

[8] The standing committees are the Committee on Astronomy and Astrophysics, the Committee on Planetary and Lunar Exploration, the Committee on Solar and Space Physics, the Committee on the Origins and Evolution of Life, and the Committee on Earth Studies.

[9] See Appendix B for the meeting agenda.

[10] The NRC decadal surveys have been widely used by the scientific community and by program decision makers because they (a) present explicit, consensus priorities for the most important, potentially revolutionary science that should be undertaken within the span of a decade; (b) develop priorities for future investments in research facilities, space missions, and/or supporting programs; (c) rank competing opportunities and ideas and clearly indicate which ones are of higher or lower priority in terms of the timing, risk, and cost of their implementation; and (d) make the difficult adverse decisions about other meritorious ideas that cannot be accommodated within realistically available resources.

Acknowledgment of Reviewers

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

Wesley T. Huntress, Jr., Carnegie Institution of Washington,
Tamara E. Jernigan, Lawrence Livermore National Laboratory,
Christopher McKee, University of California, Berkeley,
Simon Ostrach, Case Western Reserve University,
Robert Palmer, House Committee on Science (retired),
Robert Serafin, National Center for Atmospheric Research, and
Richard H. Truly, National Renewable Energy Laboratory (retired).

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

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Summary

Congress, in the report accompanying the FY 2005 appropriation bill for NASA, directed "the National Academies' Space Studies Board (SSB) to conduct a thorough review of the science that NASA is proposing to undertake under the space exploration initiative and to develop a strategy by which all of NASA's science disciplines, including Earth science, space science, and life and microgravity science, as well as the science conducted aboard the International Space Station, can make adequate progress towards their established goals, as well as providing balanced scientific research in addition to support of the new initiative."[1] This report provides the third and final component of the National Research Council's (NRC's) advisory response to that mandate. It presents the NRC's assessment of NASA's integrated strategy and proposed science program, as indicated in materials that accompany the NASA FY 2007 budget request.

More than four decades of extraordinary achievements of NASA science have captured the imaginations of people throughout the world, and those achievements continue to astonish us and expand our appreciation for the Earth, our solar system, and the universe beyond. The technology that must be created to accomplish such ambitious scientific endeavors finds its way into other terrestrial applications and stimulates other technological accomplishments. Consequently, NASA's science programs have succeeded on many levels, thereby winning valuable prestige and support for the agency from both the public and the government. NASA's science programs have served the nation broadly in ways that expand our intellect, enhance our culture, improve our economic security, and generally enrich the nation and the world.

Plans for programs in space and Earth science in NASA's Science Mission Directorate (SMD) differ markedly from planning assumptions of only 2 years ago. The impact on the SMD program is most dramatically illustrated when one compares the rate of growth that had guided science program planning in 2004 compared to the present. The total funding available for SMD programs in 2007-2011 is to be reduced by $3.1 billion below program projections that accompanied the FY 2006 budget (corresponding to a reduction of about 10 percent for the period FY 2006-2010). At the time that the Vision for Space Exploration ("the Vision") was announced in 2004, the programs that are now in SMD were projected to grow robustly from about $5.5 billion in 2004 to about $7 billion in 2008 to accommodate the development of new scientific missions. As recently as the time of the FY 2006 budget request, the SMD budget for FY 2007 was projected at $5.96 billion. The actual request for SMD in FY 2007 is $5.33 billion, which is about $200 million less than was appropriated in 2004 even before taking inflation into account. Subsequent years have a projected growth of 1 percent, which is again less than the projected rate of inflation. Changes in plans for microgravity life and physical sciences in the Exploration Systems Mission Directorate are more pronounced. That program was supported at about $950 million in 2002 and was expected to grow to over $1.1 billion in 2008, but the new plan calls for a reduction to under $300 million in 2007 with little growth thereafter.[2]

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[1] Conference Report on H.R. 4818 Consolidated Appropriations Act, 2005, H. Rept. 108-792, p. 1599. The Vision for Space Exploration initiative was announced by President George W. Bush on January 14, 2004, and is outlined in *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

[2] NASA budget numbers used in this report are from NASA's annual budget books or other information supplied to the committee by NASA.

The committee reviewed NASA's plans for research programs over the next 5 years in each of six areas—astrophysics, heliophysics, planetary science, astrobiology, Earth science, and microgravity life and physical sciences—and reached the following conclusions in response to the study charge.

Finding 1. NASA is being asked to accomplish too much with too little. The agency does not have the necessary resources to carry out the tasks of completing the International Space Station, returning humans to the Moon, maintaining vigorous space and Earth science and microgravity life and physical sciences programs, and sustaining capabilities in aeronautical research.

Recommendation 1. Both the executive and the legislative branches of the federal government need to seriously examine the mismatch between the tasks assigned to NASA and the resources that the agency has been provided to accomplish them and should identify actions that will make the agency's portfolio of responsibilities sustainable.

Finding 2. The program proposed for space and Earth science is not robust; it is not properly balanced to support a healthy mix of small, medium, and large missions and an underlying foundation of scientific research and advanced technology projects; and it is neither sustainable nor capable of making adequate progress toward the goals that were recommended in the National Research Council's decadal surveys.

The committee used four criteria to assess NASA's science programs in response to the committee's charge (see Chapter 1), and the committee's conclusions with respect to those criteria are as follows:

- *Capacity to make steady progress*. The proposed SMD mission portfolio will fall far short of what was recommended by the NRC's decadal surveys. The space and Earth science programs will be forced to terminate or delay numerous flight missions, curtail advanced technology preparations for other future missions, and significantly reduce support for the research projects of thousands of scientists across the country. The net result of these actions will be that NASA will not be able to make reasonable progress—in any of the major space research disciplines—toward the scientific goals that were set out for the decade, and our nation's leadership in Earth and space research and exploration will erode relative to efforts of other nations.
- *Stability*. The science program has become fundamentally unstable. As Figures 1.1 and 1.2 illustrate (see Chapter 1), there have been dramatic changes in the projected resource trajectories for all science programs over the past 3 years. Consequently, it has not been possible to follow an orderly plan for sequencing missions and projects, developing advanced technology, sizing and nurturing a research and technical community, or meeting commitments to other U.S. or international partners.
- *Balance*. The SMD program will become seriously unbalanced because the reductions in funding have fallen disproportionately on the small missions and the research and analysis (R&A) programs. The small missions such as the Explorers and the Earth System Science Pathfinders had already been reduced with the initiation of the Vision in FY 2005, to the point that their projected flight rate is now a fraction of what it had been throughout the history of the space program. The reductions in FY 2007 and the out-years compound the problem and also add a new target for reduction, the R&A program, which is the lifeblood of the space and Earth science community. Plans are to reduce R&A funding by 15 percent retroactively starting with the FY 2006 budget, with larger cuts in such programs as Astrobiology.
- *Robustness*. The proposed program is not robust because it undermines the training and development of the next generation of scientists and engineers—the generation that will be critical to the accomplishment of the agency's federal responsibilities, including the Vision. Space missions, regardless of whether they are for robotic or human exploration, generate an appropriate return on investment only if there is a high-quality, vibrant, experienced, and committed community of scientists and engineers to turn

each mission's data stream into new understanding that creates intellectual, cultural, and technological benefits. Because space exploration is a long-term endeavor that spans decades and generations, NASA will need a sustained long-term investment in human capital, facilities, technology development, and progressive scientific discoveries.

The committee identified four critical areas that are especially significant contributors to its second finding:

1. Research and analysis (R&A) budgets have been reduced.
2. Astrobiology research has been severely reduced.
3. Explorers and other small missions have been delayed or canceled.
4. Initial technology work on future missions and emphasis on technical innovation have been reduced.

Recommendation 2. NASA should move immediately to correct the problems caused by reductions in the base of research and analysis programs, small missions, and initial technology work on future missions before the essential pipeline of human capital and technology is irrevocably disrupted.

If at all possible, the restoration of the small missions, R&A programs, and the technology investment in future missions should be accomplished with additional funding for science. The scale of the short-term resource allocation problem is modest, probably slightly more than 1 percent of the total NASA budget, but addressing that problem will help correct the immediate threats to the health of the research program and also permit NASA and its stakeholders to conduct a vigorous, open assessment of longer-term priorities and plans. Given the funding shortages associated with elements of the human spaceflight program, the committee further urges that funding for science (both the amounts requested and any modest additions that might be made) be isolated from other NASA accounts to ensure that the money is actually spent on science.

Finding 3. The microgravity life and physical sciences programs of NASA have suffered severe cutbacks that will lead to major reductions in the ability of scientists in these areas to contribute to NASA's goals of long-duration human spaceflight.

Recommendation 3. Every effort should be made to preserve the essential ground-based and flight research that will be required to enable long-duration human spaceflight and to continue to foster a viable community that ultimately will be responsible for producing the essential knowledge required to execute the human spaceflight goals of the Vision for Space Exploration.

The scale of the short-term resource allocation required to revive this effort is also modest (less than 1 percent of the total NASA budget), yet addressing that problem will provide a continuing source of knowledge and community commitment that is absolutely critical for the success of this endeavor.

Finding 4. The major missions in space and Earth science are being executed at costs well in excess of the costs estimated at the time when the missions were recommended in the National Research Council's decadal surveys for their disciplines. Consequently, the orderly planning process that has served the space and Earth science communities well has been disrupted, and balance among large, medium, and small missions has been difficult to maintain.

Recommendation 4. NASA should undertake independent, systematic, and comprehensive evaluations of the cost-to-complete of each of its space and Earth science missions that are under development, for the purpose of determining the adequacy of budget and schedule.

As part of this recommended NASA review, a careful examination of the approaches to cost, schedule, and risk management should be made, and a comprehensive examination should be done of options to reduce cost while maintaining a mission's capability to achieve the science priorities for which it was recommended. The committee urges that steps be taken to allow all missions currently under development to make reasonable progress while the competitive assessment of projects across the SMD is underway. Major missions are an essential part of a balanced program—it is important to have large missions as well as medium and small missions—and finding ways to keep them on track and affordable is thus crucial.

Finding 5. A past strength of the NASA science programs, in both their planning and their execution, has been the intimate involvement of the scientific community. Some of the current mismatch between the NASA plans for the next 5 years and a balanced and robust program stems from the lack of an effective internal advisory structure at the level of NASA's mission directorates.

Recommendation 5. NASA should engage with its reconstituted advisory committees as soon as possible for the purpose of determining how to create in the space and Earth science program a proper balance among large, medium, and small missions, and research and analysis programs, and for evaluating the advice in and the consequences of the results from the comprehensive reviews of the major missions called for in Recommendation 4. Reconstitution and engagement of advisory committees for the microgravity life and physical sciences are equally important and should be given attention.

1
Introduction

The history of NASA's science programs is one of more than four decades of extraordinary achievements that have captured the imaginations of people throughout the world. Those achievements continue to astonish us and expand our appreciation for the universe as today's scientific spacecraft produce new evidence of what may once have been habitable environments on Mars, discoveries of water geysers spouting from the surface of a moon of Saturn, new insights into the formation of black holes, evidence of the importance of mysterious dark matter and dark energy, and insight into the structure of the universe near the time of its very beginning. Satellite-borne instruments that look back at Earth provide increasingly important ways to monitor natural hazards, climate variability, and both global and regional environmental changes, and through such measurements they help us understand the habitability of our own planet. The technology that must be created to accomplish such ambitious scientific endeavors finds its way into other terrestrial applications and stimulates other technological accomplishments. Consequently, NASA's science programs have succeeded on many levels, thereby winning valuable prestige and support for the agency from both the public and the government. NASA science has served the nation broadly in ways that expand our intellect, enhance our culture, improve our economic security, and generally enrich the nation and the world.

On January 14, 2004, President George W. Bush announced a new national Vision for Space Exploration ("the Vision") with the fundamental goal "to advance U.S. scientific, security, and economic interests through a robust space exploration program" that would involve human and robotic exploration of space, including sending humans back to the Moon and later to Mars.[1] In its June 2004 report, the President's Commission on Implementation of United States Space Exploration Policy[2] outlined a broad notional science agenda for implementing the Vision that was built around three themes:

- *Origins*—The beginnings of the universe, our solar system, other planetary systems, and life;
- *Evolution*—How the components of the universe have changed with time, including the physical, chemical, and biological processes that have affected it, and the sequences of major events; and
- *Fate*—What the lessons of galactic, stellar, and planetary history tell about the future and our place in the universe.

The breadth of NASA's science program is captured further in the administration's U.S. Ocean policy,[3] the 2001 U.S. Climate Change Research initiative,[4] and the 2003 Global Earth Observation initiative.[5] NASA's science program is thus intended to meet research priorities across an array of

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

[2] President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate and Discover* (also known as the Aldridge Commission report), June 2004, available at <govinfo.library.unt.edu/moontomars/docs/M2MReportScreenFinal.pdf>.

[3] See the information on the U.S. Ocean Action Plan at the Web site of the Committee on Ocean policy, <ocean.ceq.gov/>.

[4] See <www.climatevision.gov/statements.html>.

[5] See <www.whitehouse.gov/news/releases/2002/02/20020214-5.html> and <www.earthobservationsummit.gov/press_release_whfs.html>.

initiatives of national significance. For this report, the committee's statement of task did not encompass issues of balance and priorities among multiagency initiatives. Instead this report focuses exclusively on an analysis of the match between goals and proposed activity within NASA's own programs, and balance across disciplines within these programs, in support of the Vision as well as to meet broader national scientific objectives.

Congress, in the report accompanying the FY 2005 appropriations bill for NASA, expressed support for a broad view of science as part of its vision for NASA. It called for "a strategy by which all of NASA's science disciplines, including Earth science, space science, and life and microgravity science, as well as the science conducted aboard the International Space Station, can make adequate progress towards their established goals, as well as providing balanced scientific research in addition to support of the new initiative."[6] Finally, in the NASA Authorization Act of 2005,[7] Congress gave NASA program responsibilities as follows:

> The Administrator shall ensure that NASA carries out a balanced set of programs that shall include, at a minimum, programs in—
>
> (A) human space flight, in accordance with subsection (b);
> (B) aeronautics research and development; and
> (C) scientific research, which shall include, at a minimum—
> (i) robotic missions to study the Moon and other planets and their moons, and to deepen understanding of astronomy, astrophysics, and other areas of science that can be productively studied from space;
> (ii) earth science research and research on the Sun-Earth connection through the development and operation of research satellites and other means;
> (iii) support of university research in space science, earth science, and microgravity science; and
> (iv) research on microgravity, including research that is not directly related to human exploration.

Thus, a broad program of scientific studies continues to be an integral element of NASA's charter, but a challenge remains to accomplish a balanced scientific program within a broader, balanced portfolio of commitments that also must include human spaceflight and aeronautical research. In presenting NASA's proposed program and budget for FY 2007 to the House Science Committee on February 16, 2006, Administrator Griffin said, "The plain fact is that NASA simply cannot afford to do everything that our many constituencies would like the agency to do. We must set priorities, and we must adjust our spending to match those priorities. NASA needed to take budgeted funds from the Science and Exploration budget projections for FY 2007-11 in order to ensure that enough funds were available to the Space Shuttle and the ISS. Thus, NASA can not afford the costs of starting some new space science missions."

With respect to research in the microgravity sciences Griffin noted, "While NASA needed to significantly curtail projected funding for biological and physical sciences research on the [ISS] as well as various research and technology projects in order to fund development for the CEV [Crew Exploration Vehicle], the U.S. segment of the [ISS] was designated a National Laboratory in the NASA Authorization Act. . . . However, the research utilization of the ISS is limited primarily due to limited cargo and crew transportation."

Griffin stated clearly that the agency's decisions about support for science did not reflect an intention to move away from science as a core NASA mission, but he explained that the issue was about balancing priorities. He said, "My decision to curtail the rate of growth for NASA's Science missions is not intended in any way to demonstrate a lack of respect for the work done by the NASA science team.

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[6] Conference Report on H.R. 4818, Consolidated Appropriations Act, 2005, H. Rept. 108-792, p. 1599.
[7] Conference report to S. 1281, The NASA Authorization Act of 2005, H. Rept. 109-354, Section 101(a)(1).

On the contrary, NASA's science missions remain one of the Nation's crowning achievements, and NASA is a world leader with 54 satellites and payloads currently operating in concert with the science community and our international partners. My decision to slow the rate of growth for NASA's Science missions is simply a matter of how the Agency will use the available resources within the overall NASA portfolio."

The challenge for the committee, therefore, has been to recognize the multiple pressures on NASA, to weigh those in relation to science program goals and priorities that have been developed to meet stated national needs, and to fulfill the committee's charge to provide constructive advice about how to achieve a balanced and robust program in the face of these realities.

In responding to its charge, the committee used four criteria to measure the health of NASA's proposed science programs:

1. *Capacity to make steady progress*. A U.S. discipline-based research community (faculty, research scientists, postdoctoral trainees, and graduate students) and world-class research facilities need to be maintained at a level where the nation's highest science priorities identified in NRC decadal surveys can be achieved at a reasonable pace and a new generation of researchers is trained to enable our nation's leadership of the international community.
2. *Stability*. This aspect of the health of the community relates to the avoidance of rapid downsizing or expansion in short periods of time. The conduct of science is a generational enterprise. Reconstituting a lost research community can take a decade or more to accomplish.
3. *Balance*. The concept of balance across the disciplines means that at least the minimum health of each of the disciplines is maintained, although some disciplines may receive higher levels of support because of mission-related priorities. Balance is also used to refer to other aspects of NASA's research portfolio, including balance between opportunities for new initiatives and capacity to support ongoing programs and missions, and balance between capacity-building and longer-term scientific development relative to nearer-term mission-driven needs. A particularly important aspect of balance is the ability to sustain a mix of large, medium, and small programs and missions[8] and also research, data analysis, technology development, theoretical studies, and modeling.
4. *Robustness*. Sufficient human resources and research infrastructure need to be maintained to enable the nation to ramp up research activities within a year or two as national needs change or as major unexpected scientific breakthroughs occur.

The committee recognizes NASA's budgetary pressures and the administrator's need to set priorities and adjust specific program funding. However, any discussion about budget priorities and allocations across programs and projects must be viewed in the context of NASA's flight program development management practices, which have led to significant divergence between initial cost estimates and final project costs. Weaknesses in managing project costs over the life of a project have the effect of diminishing the resources available for conducting new science—even when total budget numbers appear higher than in previous years. As this report discusses below, meaningful planning to meet NASA's goals is not possible when costs of approved projects rise faster than the rate of change of available resources.

[8] See National Research Council, *Assessment of Mission Size Trade-offs in NASA's Earth and Space Science Missions*, National Academy Press, Washington, D.C., 2000.

NASA 2006 STRATEGIC PLAN

Every 3 years NASA produces a strategic plan. The latest plan was released in 2006 to accompany the agency's FY 2007 budget proposal.[9] According to the current strategic plan, the NASA vision statement is "to pioneer the future in space exploration, scientific discovery, and aeronautics research." This is a change from the 2003 NASA vision statement, which was "to improve life here, to extend life to there, to find life beyond."

The 2006 document lists six strategic goals, which clearly set forth near-term NASA priorities:

1. Fly the shuttle as safely as possible until its retirement, not later than 2010.
2. Complete the International Space Station in a manner consistent with NASA's international partner commitments and the needs of human exploration.
3. Develop a balanced overall program of science, exploration, and aeronautics consistent with the redirection of the human spaceflight program to focus on exploration.
4. Bring a new Crew Exploration Vehicle into service as soon as possible after shuttle retirement.
5. Encourage the pursuit of appropriate partnerships with the emerging commercial space sector.
6. Establish a lunar return program having the maximum possible utility for later missions to Mars and other destinations.

NASA's top priorities as reflected in its strategic plan are currently the shuttle and the space station, which together account for about 37 percent of the agency's overall budget. In its FY 2006 budget request NASA produced an out-year budget projection that showed shuttle costs decreasing by 2008. These funds were expected to become available for the early stages of development of the Crew Exploration Vehicle (CEV). NASA has now indicated that the shuttle budget will not decrease significantly in the 2007-2010 timeframe.

In addition, the original plan was for as much as a 4-year gap between shuttle retirement and the first operational flight of the CEV. However, NASA hopes to advance the planned operational date for the CEV to 2012. The combined effects of no expected shuttle savings and accelerated CEV development have increased the budget pressure on the agency. Consequently, the science budgets in both the Exploration Systems Mission Directorate (ESMD) and the Science Mission Directorate (SMD) have been reduced compared to earlier projections.

NASA SCIENCE PROVISIONS FOR FY 2007 AND BEYOND

The majority of NASA's science programs are managed in SMD, which is responsible for the space and Earth sciences, including development and operation of robotic science missions and supporting ground-based research, data analysis, and advanced technology development. ESMD is responsible for implementing the Vision's human spaceflight projects such as the CEV and the Crew Launch Vehicle, and future projects such as the Heavy Lift Launch Vehicle and the Lunar Surface Access Module. ESMD is also responsible for the life and physical sciences research that is to be conducted on the ISS and for development of lunar robotic missions in support of future human lunar missions. The Space Operations Mission Directorate (SOMD) is responsible for operation of the space shuttle and the ISS.

[9] The strategic plan is available at <www.nasa.gov/pdf/142303main_2006_NASA_Strategic_Plan_sm.pdf>.

NASA's FY 2007 budget request provides for a total of $16.8 billion, or an increase of 3.2 percent over the previous year.[10] Of those funds, 32 percent ($5.33 billion) are for SMD,[11] 24 percent ($3.98 billion) are for ESMD, 37 percent ($6.23 billion) are for SOMD, and 4 percent ($724 million) are for the Aeronautics Research Mission Directorate.[12] Some resources that had been planned for SMD and ESMD in the FY 2006 budget projections have been transferred to SOMD to compensate for the projected shortfall in support for the shuttle and the ISS programs.

Plans for SMD programs call for an increase of 1.5 percent in FY 2007 funding over FY 2006 and then annual increases of 1 percent in subsequent years. The impact on SMD program planning is most dramatically illustrated when one compares the rate of growth that had guided science program planning in 2004 compared to the present (see Figure 1.1). At the time that the Vision was announced, the SMD program[13] was projected to grow robustly from about $5.5 billion in 2004 to about $7 billion in 2008. The new projections provide for $5.38 billion in 2008 and less than inflationary growth thereafter. The effect of the reductions in SMD will be to reduce the total funds available in 2007-2011 by $3.1 billion compared to program projections made in the FY 2006 budget. Changes in plans for science in the ESMD are more pronounced (see Figure 1.2). The FY 2005 budget projections would have had that program level off at slightly more than $900 million per year starting in FY 2006, but the FY 2007 budget projects a drop to about $300 million per year for FY 2007-2011, corresponding to a 69 percent reduction.

Finally, NASA's longer-term planning for human exploration provides an important context in which to consider the long-term prospects for science. Although NASA has not yet released a specific strategic plan for exploration activities on the Moon, which are to begin in the 2018 timeframe, the resource demands to support development of the needed exploration systems will be considerable. Office of Management and Budget representatives described to the committee an exploration systems budget profile that would grow to $8.8 billion in 2011 and then to over $14 billion in 2015, not including provisions for science or aeronautics.

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[10] NASA's budget information is available at <www.nasa.gov/about/budget/index.html>.

[11] The fraction of the agency's budget allocated to space and Earth science surpassed 30 percent in 2001 and rose to 36 percent in 2004.

[12] The remaining $492 million is for Cross-Agency Support Programs.

[13] SMD was established in August 2004. In this report, references to "the SMD program" that predate SMD's creation mean the programs that are now in SMD (space and Earth science).

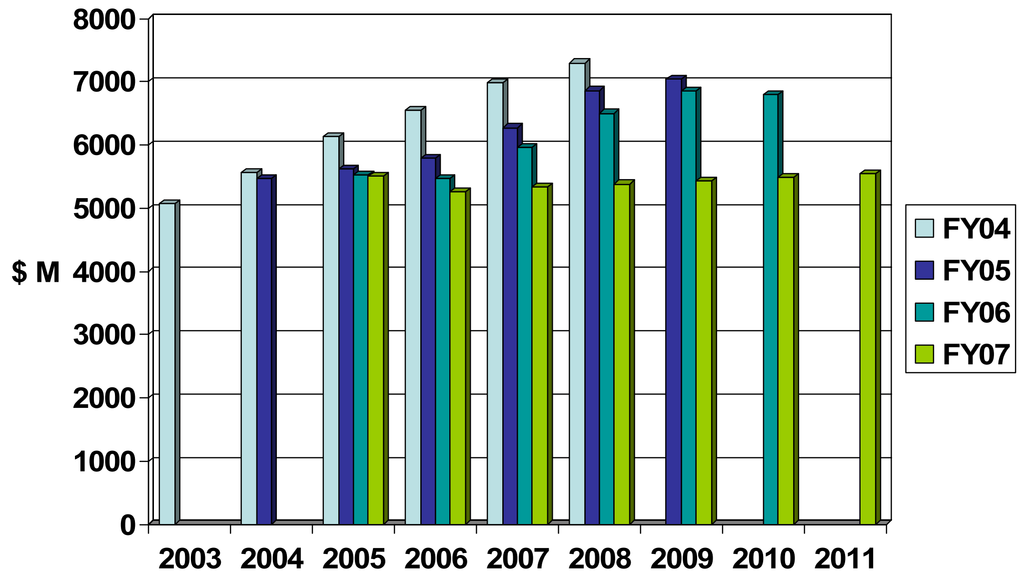

FIGURE 1.1 Five-year budget projections for space and Earth science as they were proposed by NASA for fiscal years 2004 through 2007. The actual appropriated level for the year in which the projections were proposed is also shown. Budget data provided by NASA.

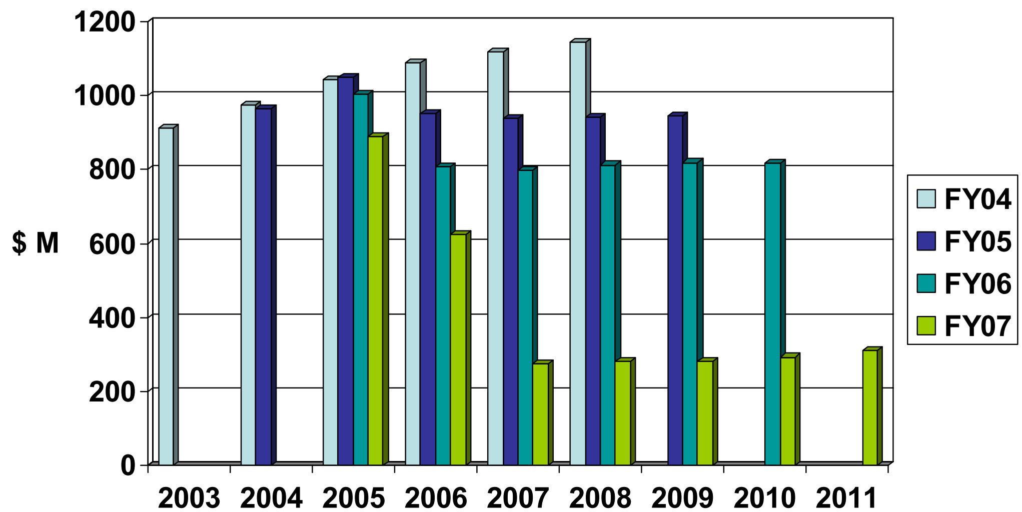

FIGURE 1.2 Five-year budget projections for microgravity life and physical sciences (human systems research and technology) as they were proposed by NASA for fiscal years 2004 through 2007. The actual appropriated level for the year in which the projections were proposed is also shown. Budget data provided by NASA.

2
Health of the Discipline Programs

To gather information and insight into the extent to which the proposed science programs are healthy—defined in Chapter 1 as being stable, balanced, robust, and maintaining the capacity to make steady progress—the committee turned to the discipline standing committees of the SSB. The standing committee chairs were asked to provide an assessment of these questions from the perspective of each science discipline. This chapter summarizes the committee's findings based on the briefings from the standing committee representatives.

ASTROPHYSICS

Goals

Since the 1960s, the U.S. astronomy community has conducted a sequence of decadal surveys that seek to prioritize ground- and space-based initiatives for the coming decade. These surveys have served the community and the nation well and are in large measure responsible for the steady stream of major scientific discoveries about the universe and its constituents over the intervening 40 years. In retrospect, the surveys' well-founded choices among many competing options largely succeeded in optimizing the scientific return from a finite expenditure of federal support.

The most recent survey, entitled *Astronomy and Astrophysics in the New Millennium* (AANM),[1] proposed an exciting program of research for the interval 2000 to 2010. Among the key scientific problems that were identified in the survey are the following:

- Determine the large-scale properties of the universe: the amount, distribution, and nature of its matter and energy, its age, and the history of its expansion;
- Study the dawn of the modern universe, when the first stars and galaxies formed;
- Understand the formation and evolution of black holes of all sizes;
- Study the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets; and
- Understand how the astronomical environment affects Earth.

The AANM report recommended balancing new initiatives with the ongoing program, maintaining the diversity of NASA missions, including the Explorer program, integrating theory challenges into missions, and coordinating programs with other federal agencies and international partners. Recommended major missions were the James Webb Space Telescope (JWST, formerly the Next Generation Space Telescope (NGST)), Constellation-X, Terrestrial Planet Finder (TPF) technology, and Single Aperture Far Infra-Red Observatory (SAFIR) technology. Moderate missions were the Gamma-ray Large Area Space Telescope (GLAST), Laser Interferometer Space Antenna (LISA), Solar

[1] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

Dynamics Observatory (SDO), Energetic X-ray Imaging Survey Telescope (EXIST),[2] and Advanced Radio Interferometry between Space and Earth (ARISE). Small missions were the Advanced Cosmic-ray Composition Experiment on the International Space Station and the Ultra-Long Duration Balloon program.

In recognition of the convergence of research frontiers in fundamental physics and cosmology, a second NRC study, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (Q2C),[3] was commissioned specifically to prioritize proposals in this cross-disciplinary area and to take account of exciting developments in cosmology that occurred just after the AANM report was completed. It added a mission to study inflationary cosmology and another to study dark energy (Super Nova Acceleration Probe),[4] as well as endorsing earlier recommendations.

More recently, an NRC "midcourse review" of progress in realizing the decadal survey goals concluded that despite the steady stream of discovery since publication of the AANM report, the science program outlined in AANM and Q2C remained valid and no new major, interdecade survey was needed.[5] It also concluded that it was imperative to maintain the breadth and balance of the program and that if an expensive Hubble Space Telescope re-servicing mission threatened the program, the community should be involved in assessing the relative value of the choices.

Prospects for Progress Toward Goals

In the FY 2006 NASA operating plan and FY 2007 budget, NASA has proposed major changes to the astrophysics component of the SMD program in FY 2006 and beyond. These result from reductions in out-year budgets in order to accommodate increases in projected costs of specific missions and programs, both internal to the astrophysics program and in other parts of the agency. The large and medium missions set prior to the 2007 program are summarized in Table 2.1.

The Hubble Space Telescope (HST) is now entering its 17th year of operation and is awaiting its fifth and final space shuttle servicing mission (SM-4), which is planned for 2008, pending a successful shuttle return to flight. According to NASA, the costs for SM-4 are \$166 million, \$216 million, and \$179 million in FY 2006, 2007, and 2008, respectively.

The James Webb Space Telescope (JWST, formerly NGST) was the highest-priority major mission in the AANM report, and it was affirmed by the NRC's 2005 midcourse review. A major issue in the present context is its cost. NGST was estimated in AANM to cost \$1 billion, not including the costs of technology development or operations.[6] The current estimate for JWST is \$4.5 billion (plus a \$0.5 billion international contribution), which includes all the technology development and 10 years of operations.[7] The operations budget is estimated to be \$1 billion, of which \$250 million is projected to be for R&A support for the users of the facility. Launch is now scheduled for 2013. Community support for JWST science appears to be unwavering; however, there is concern about the stability of the cost, schedule, and risk estimates and the implications of further cost growth and schedule slip for the rest of the astrophysics program.

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[2] EXIST later became the Black Hole Finder Probe.

[3] National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., 2003.

[4] SNAP later became the Joint Dark Energy Mission (JDEM).

[5] National Research Council, "Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision: Letter Report," The National Academies Press, Washington, D.C., 2005.

[6] Full-cost accounting for civil service personnel and NASA center operations has had a significant, though not easily quantifiable, impact on this, and other, mission budgets.

[7] For comparison, the total budget for HST after 15 years of operation is estimated to be \$11 billion in current-year dollars.

The Stratospheric Observatory for Infrared Astronomy (SOFIA) was recommended in the 1991 decadal survey as a complement to the Spitzer Space Telescope.[8] Due to reported development and operations cost growth and technical problems NASA has marked it for cancellation pending a review to be completed within months.

The Space Interferometry Mission (SIM) was also recommended in the 1991 decadal survey, and the performance that is necessary to achieve its science goals was set in a 2002 NRC letter report.[9] It was on schedule for attaining these goals prior to the 2007 budget for a cost of $1.1 billion. The proposed slip to 2016 and an increase in NASA's estimated total cost to $2.5 billion raise concerns about its future and its relevance as a precursor to TPF.

The Terrestrial Planet Finder (TPF), which was recommended in the AANM report as a technology program, has been deferred indefinitely.

Beyond Einstein is a program in which two observatories, Constellation-X and LISA, together with the JDEM probe, were called out in the 2005 NASA Roadmap as a first phase.[10] LISA has grown to become a major mission in the $2 billion class along with Constellation-X (which was advertised as $800 million in AANM for Phase C/D). JDEM has an associated budget of $600 million in the latest NASA plan. For FY 2006, funding for the entire Beyond Einstein program is down to about 25 percent of the level originally planned for FY 2006, according to NASA's FY 2006 initial operating plan. This amount appears to the committee to be inadequate to sustain the technology development teams. After a period of several years during which a community of researchers has been stimulated by expectations that Beyond Einstein would become a viable undertaking, there is now considerable uncertainty about the future of this program.

Explorer missions are an integral component of the astrophysics program. They provide relatively inexpensive, competed, rapid response to new opportunities and have an outstanding scientific success rate. A launch rate of at least one per year was projected.[11] They are seen as providing training for the next major mission principal investigators, and they traditionally involve younger scientists. The recent NRC report on principal-investigator-led missions called out Explorers for their strong technical and cost performance and value in training and engaging universities and small industry in NASA missions.[12] There have been significant cuts in the Explorer program in FY 2006 and 2007. A 2001 solicitation led to the selection of a Medium-class Explorer (MIDEX) mission, the Wide-field Infrared Survey Explorer (WISE). Its 2006 budget has just been halved in mid-year and its launch schedule slipped further to 2010. A 2003 solicitation led to the selection of the Nuclear Spectroscopic Telescope Array (NuSTAR) for extended Phase-A study. It was recently canceled 1 month prior to a technology review without any open, transparent assessment of scientific or management issues that could have been factors in that decision. The next planned 2007 solicitation has already slipped to 2008.[13]

Research and analysis (R&A) grants support peer-reviewed research projects by individual investigators or small teams. They perform data analysis and interpretation, theory and modeling, and complementary ground-based or suborbital studies that translate the measurements acquired by space missions into new scientific understanding and lay the scientific and technological foundations for future missions. NASA has announced a 15 percent cut in R&A. The immediate impact will lead to fewer

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[8] National Research Council, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991.

[9] National Research Council, "Review of the Redesigned Space Interferometry Mission," National Academy Press, Washington, D.C., 2002.

[10] Two more missions—Inflation Probe and Black Hole Finder Probe (BHFP)—also were recommended.

[11] For example, see "Explorer Program Plan," NASA Goddard Space Flight Center document GSFC-140-EXP-002, April 1999.

[12] National Research Council, *Principal-Investigator-Led Missions in the Space Sciences*, The National Academies Press, Washington, D.C., 2006.

[13] When NuSTAR was terminated the team was encouraged to reapply under the 2008 announcement of opportunity, but the team will have dispersed by then.

TABLE 2.1 Summary of Large and Medium Astrophysics Missions

Mission	Provenance[a]	Launch Date in Prior Plan	Launch Date in FY 2007 Plan
Stratospheric Observatory for Infrared Astronomy	DDAA	2008	Cancellation threatened
Space Interferometry Mission	DDAA	2012	Delayed to 2015/2016
Keck Telescope Outriggers			Canceled
Gamma-ray Large Area Space Telescope	AANM	2007	2007
Hubble Space Telescope Servicing Mission-4	DDAA	2008	2008 pending shuttle return to flight
Herschel-Planck	ESA	2008	2008
James Webb Space Telescope	AANM	2011	2013
Constellation-X[b]	AANM		Deferred
Joint Dark Energy Mission (formerly SNAP)[b]	Q2C		Deferred
Laser Interferometer Space Antenna[b]	AANM		Deferred
Black Hole Finder Probe (formerly EXIST)	AANM		Deferred
Inflation Probe	Q2C		Deferred
Terrestrial Planet Finder (technology development)	AANM		Deferred
Single Aperture Far Infra-Red Observatory (technology development)	AANM	Deferred	Deferred

[a] DDAA, *The Decade of Discovery in Astronomy and Astrophysics* (1991); AANM, *Astronomy and Astrophysics in the New Millennium* (2001); ESA, European Space Agency; Q2C, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (2003).
[b] Denotes a Beyond Einstein program mission.

funded grants following previous cuts in the program. The long-term prospect is worse, as the real-year funding is proposed to fall an additional 15 percent by 2011. The program preferentially supports younger scientists who will be especially affected by the cuts. HST, the Chandra X-ray Observatory, and the Spitzer Space Telescope are sources of funding that support mission-related data analysis and interpretation projects much like mission-independent R&A projects, and JWST will be a similar source of support after launch.

In summary, the reductions in the astrophysics program in 2006 and 2007 are severe. The sudden change in status is very disruptive to mission teams, especially affecting technology development and young scientists. The outlook threatens the long-term well-being of the field. Particularly disturbing is the decline in the launch rate. The only new U.S.-led astrophysics missions that are now scheduled for launch prior to JWST (now planned in 2013) are a moderate mission (GLAST in 2007) plus a Discovery mission (Kepler in 2008)[14] and an Explorer mission (WISE in 2010).

[14] See Table 2.3 for more about the Kepler mission.

HELIOPHYSICS

Goals

Heliophysics studies the vast region of our solar system that is driven directly by the Sun, including the Sun itself, the heliosphere out to the interstellar medium, and the magnetospheres and upper atmospheres of Earth and other planets. Utilizing information from space-based and complementary ground-based observations, together with supporting modeling and theoretical studies, this discipline seeks to study scientific problems such as the following:

- Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona;
- Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium;
- Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences;
- Understanding the basic physical principles manifest in processes observed in solar and space plasmas; and
- Developing near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamic processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere and upper atmosphere.

Also known as solar and space physics, this research was carried out prior to 2004 in a division of the NASA Space Science Enterprise known as Sun-Earth Connections (SEC), then in 2004-2005 as a part of the Earth-Sun Division of SMD, and now in the Heliophysics Division of SMD.

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*.[15] The survey report recommended a research program for NASA and the National Science Foundation (NSF) that would also address the operational needs of the National Oceanic and Atmospheric Administration (NOAA) and the Department of Defense (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 2004, that survey was re-examined in *Solar and Space Physics and Its Role in Space Exploration*,[16] which considered whether changes might be appropriate in view of the Vision. The 2004 report confirmed the scientific and operational importance of solar and space physics research (including its direct relevance to gaining an understanding of space radiation risks to human space exploration), repeated the call for a balanced program of applied and basic science and of a mix of mission sizes and R&A, and reaffirmed the mission priorities that were set out in the decadal survey. The report recognized that there might be delays in the pace at which missions would be executed as a consequence of resource constraints, and it noted that such delays would have impacts in the form of losses of scientific synergy between complementary missions and slips of some important missions beyond the 10-year planning horizon.

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

[16] National Research Council, *Solar and Space Physics and Its Role in Space Exploration*, The National Academies Press, Washington, D.C., 2004.

Prospects for Progress Toward Goals

In FY 2005 NASA proposed to remove several hundred million dollars of program content from the basic science mission line of SEC, the Solar Terrestrial Probe (STP) line, over the next 5 years. There were also large cuts in the Explorer line, which is managed by the Heliophysics Division for solar and space physics and for astrophysics, and there would have been an almost immediate shutdown of a portion of the SEC spacecraft fleet of operating missions (dubbed the Great Observatory for Sun-Earth Connections).

Congress restored some of the funding for SEC science in FY 2006, by restoring some mission operations and data analysis (MO&DA) support that spared the SEC Great Observatory from complete disruption. However, little program content was restored to the STP or Explorer lines, and the other main heliophysics mission line, Living With a Star (LWS), was held flat. The next LWS program mission, Solar Dynamics Observatory, has experienced cost growth compared to original projections, and accommodating that growth is impacting the rate at which later missions can progress. Thus, the FY 2006 budget continued to hold heliophysics at lower levels compared to the budgets that had been described by NASA to the solar and space physics decadal survey committee in 2002-2003.

Compared to the 2004 expectations, there now are several notable elements missing from the program proposed for 2007 and beyond (see Table 2.2):

- The discipline's only large ("flagship") mission is the Solar Probe. This program has just completed a science definition team study and is ready for development. However, there are no provisions for Solar Probe development in 2007-2011.
- The Heliophysics program of basic research is built on the timely and regular execution of moderate-sized missions in the STP line. It was anticipated that a balanced set of missions in solar, heliospheric, magnetospheric, and ionospheric-thermospheric research would commence with a new mission every 18 months to 2 years. The first new STP mission in this plan (Magnetospheric Multiscale, MMS) was to launch in about 2009. The FY 2007 program defers the MMS launch until 2013. The second and third STP missions (Geospace Electrodynamic Connections and Magnetospheric Constellation, respectively) are deferred indefinitely (until at least 2015 and beyond).
- The "small" mission category for heliophysics has always included Explorer and sounding rocket elements. The FY 2007 plan proposes even larger cuts to the Explorer line than was the case in FY 2005. For FY 2007-2011, the committee estimates that about $1 billion has been removed from the combined heliophysics and astrophysics Explorer line, corresponding to a reduction of more than 55 percent in FY 2007 and more than 40 percent over the 5-year period. High priority was assigned in the 2003 decadal survey to a revitalization of the sounding rocket program and the University Explorer-class missions. No such funding is evident in the FY 2007 plan.
- The lowest cost category program for solar and space physics was termed the "vitality" element of the program. Here the top priority for NASA was enhancement in the Supporting Research and Technology (SR&T) program, of which R&A is a major element. Instead, the FY 2007 plan proposes to cut the R&A component of SR&T by 15 percent.

The overarching implication of NASA's new plan is that the health of the discipline is in serious jeopardy. The 2003 decadal survey recommendations were based on a balanced set of programs that could pursue essential applied science and important basic research at a meaningful pace. However, there are no new basic research missions in solar, heliospheric, or ionosphere-thermosphere-magnetosphere science. There can be no new starts for several years in the Explorer program, and it is unlikely that an Explorer announcement of opportunity can come out until 2008 at the earliest. Even the LWS program has seen deferrals of the geospace mission components so that the key scientific element of simultaneity of solar and geospace observations has been jeopardized.

TABLE 2.2 Summary of Large and Medium Heliophysics Missions

Mission	Provenance[a]	Launch Date in Prior Plan	Launch Date in FY 2007 Plan
Solar-Terrestrial Relations Observatory (STEREO)	SEB	2006	2006, 2-month delay
Solar Dynamics Observatory	AANM and SEB	2008	2008, 4-month delay
Solar-B	SEB	2006	2007, 4-month delay
Magnetospheric Multiscale	SEB	2009	2013
Juno Jupiter Polar Orbiter	SEB and NFSS	2010	2011
Radiation Belt Storm Probes	SEB	2010	2012, moved ahead of GEC
Ionosphere-Thermosphere Probe	SEB		Deferred >2015
Geospace Electrodynamic Connections	SEB		Deferred >2015
Magnetospheric Constellation	SEB		Deferred >2015
Solar Probe	SEB		Deferred >2015

[a]AANM, *Astronomy and Astrophysics in the New Millennium* (2001); NFSS, *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2003); and SEB, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2003).

PLANETARY SCIENCE

Goals

Planetary science encompasses the study of the major and minor planetary bodies in our solar neighborhood. Planetary science tries to understand not only the basic physical properties of these bodies, but also the processes responsible for the formation and evolution of the diverse planetary environments found throughout the solar system. Utilizing information from in situ and remote-sensing observations, together with supporting laboratory and theoretical studies, this discipline seeks to answer questions such as:

- How did the Sun's retinue of planets originate and evolve?
- How did life develop in the solar system?
- How do basic physical and chemical processes determine the main characteristics of the planets?

In 2001, the U.S. planetary science community initiated a major study to outline pressing scientific questions and prioritize future solar system exploration missions. The results of their efforts are embodied in the 2003 report *New Frontiers in the Solar System: An Integrated Exploration Strategy* (hereafter, the solar system exploration [SSE] decadal survey).[17] The scientific priorities identified in this study are still valid and supported by the SSE community. Following guidelines provided by NASA, the SSE decadal survey's recommendations for robotic spacecraft missions to Mars and to other solar system bodies are prioritized separately and categorized as large (flagship), medium, and small. These mission priorities are founded on conservative budgetary assumptions, a fact recognized in the report's

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

recommendations for a constrained Mars program and the launch of three medium and, possibly, one flagship mission per decade for the rest of the solar system. Recognizing the wide range of capabilities to be gained from reliable power sources, the availability of radioisotope power systems was considered extremely important.

Prospects for Progress Toward Goals

The results from robotic missions to Mars and elsewhere in the solar system have done much to provide the scientific and popular stimulus for the human exploration activities envisaged by the Vision. However, the major transfer of funds from the SSE program as a result of NASA's rebalancing exercise in 2006 and a second major redistribution of funds that is proposed in the FY 2007 plan pose serious threats to the long-term health and robustness of the program. The large and medium missions set prior to the 2007 program are summarized in Table 2.3.

As a result of these changes, the status of the SSE program is as follows:

- Continued support remains for Discovery and New Frontiers missions that are in operation.
- Plans to initiate the development of the Europa Geophysical Explorer—the SSE decadal survey report's only flagship mission for the decade 2003-2013—are indefinitely deferred. Failure to initiate a Europa mission, or any other flagship mission, will create gaps in the scientific, engineering, and management workforces that will hinder NASA's ability to develop large missions in the future even if the budgetary environment improves.
- Continued support remains for those Mars missions currently in operation—e.g., the Mars Exploration Rovers and Mars Reconnaissance Orbiter. Similarly, plans to launch Phoenix—the first Mars Scout mission—in 2007, and the Mars Science Laboratory in 2009, continue as planned. A second Mars Scout is scheduled for launch in 2011.
- Work on all post-2011 Mars missions, including high-priority missions such as Mars Sample Return and a network of atmospheric and seismic monitoring stations, is terminated or deferred. The atmospheric monitoring stations will be needed to understand turbulent flow that heavy loads—e.g., those required by a sample-return mission or, in the longer term, by human exploration activities—will encounter in the descent through Mars's thin, but highly variable, atmosphere.
- R&A programs suffer an initial cut of approximately 15 percent and then lose ground against inflation over the 5-year run-out period. Unlike the practice in other parts of NASA where a portion of mission funding is dedicated to data analysis studies, most of the analysis and interpretation of data from ongoing solar system missions is funded from within the general R&A budget. Thus, the proposed cuts not only will impact basic research activities, but also will limit community participation in analysis of the valuable data that are streaming back from the current Mars and Cassini missions.
- There will be a heavy reduction of investment in technology development activities not specifically related to missions in development. As with its data analysis activities, NASA's SSE program uses R&A funding to identify and develop the technologies needed for advanced missions. The reduction in technology development activities will have a major impact on future missions in the Discovery and New Frontiers lines. Technology development is not within the resources allocated to development of these mission lines due to their funding and schedule constraints.
- A healthy mix of small, medium, and flagship missions is still essential for the SSE program. Plans for a potential mix of missions that includes a future flagship mission (to Europa) will be needed to guide future radioactive power supply/radioisotope thermoelectric generator technology development activities. There also is considerable concern about the availability of Pu-238. Although this is not a NASA-specific issue, it is a problem that can impact both space science and human exploration activities.

TABLE 2.3 Summary of Large and Medium Planetary Science Missions

Mission	Provenance[a]	Launch Date in Prior Plan	Launch Date in FY 2007 Plan
Dawn (Discovery 9)	NFSS[b]	2006	2007
Phoenix (Mars Scout 1)	NFSS[c,d]	2007	2007
Kepler (Discovery 10)	NFSS[b]	2008	2008
Mars Science Laboratory	NFSS	2009	2009
Mars Scout 2	NFSS[c,d]	2011	2011
Juno (New Frontiers 2)	NFSS	<2012	<2012
Discovery 11	NFSS[b,e]	2012	2012
Europa Geophysical Orbiter	NFSS	>2012	Deferred
New Frontiers 3	NFSS	2013	Deferred
Mars Upper Atmosphere Orbiter	NFSS[f]	2013	Deferred
Mars Long Lived Lander Network	NFSS	2020	Deferred
Mars Sample Return	NFSS	>2020	Deferred

[a] NFSS, *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2003).
[b] The Discovery line of small missions was prioritized in NFSS. But the individual missions within this line are not specified since they are selected via a competitive process at a recommended (but not currently realized) flight rate of one every 18 months; missions are numbered in order of launch date.
[c] The Mars Scout line of small missions was prioritized in NFSS. But the individual missions within this line are not specified since they are selected via a competitive process.
[d] A community-wide solicitation for the second Mars Scout launch opportunity is currently underway.
[e] A community-wide solicitation for the eleventh Discovery launch opportunity is currently underway.
[f] The assumption made here was that the scientific goals of this mission, as described in NFSS, are being implemented by an appropriately selected secondary payload on a Mars telecommunications satellite or a more broadly based science mission. Either possibility is now moot. The science goals for this NFSS mission are also compatible with implementation by a Mars Scout mission. As such, this mission is a potential candidate for the second Mars Scout launch opportunity.

The combined impact of these various factors will result in a solar system exploration program that for several years will appear robust to the outside observer, but is actually running on the investment of the past and will enter the next decade with nothing ready to fly, no technology base to support visionary initiatives, and an atrophy and erosion of the current talent base and infrastructure that make ambitious robotic missions possible. The space research community is witnessing a reenactment of the actions taken in the 1970s, when, after the start of Viking and Voyager missions at the beginning of the decade, no further planetary missions were put into the pipeline. Only Magellan broke the 11-year drought until Mars Observer and Galileo were launched in the 1990s.

ASTROBIOLOGY

Goals

NASA's astrobiology program is built around three overarching scientific questions:

1. How does life begin and evolve?
2. Does life exist elsewhere in the universe?
3. What is life's future on Earth and beyond?

The program consists of four independent R&A elements—the exobiology and evolutionary biology program, the Astrobiology Science and Technology Instrument Development program, the Astrobiology Science and Technology for Exploring Planets program, and the NASA Astrobiology Institute (NAI). Together, these were funded in FY 2006 at a combined level of $65 million, already down 13 percent from the FY 2005 program. The FY 2007 budget would cut the program again, to half its current level. This is projected to be a permanent reduction in the size of the program

Prospects for Progress Toward Goals

The cuts in FY 2006 are expected to be absorbed by protecting existing contracts and grants, but selecting no new awards. Each of the four program elements has had a proposal solicitation in FY 2006, and so those proposers would all be shut out of the program. The deeper cuts for FY 2007 will require a combination of no new awards plus the reduction or cancellation of some existing contracts and grants.

The decadal surveys for astrophysics and for solar system exploration both embraced astrobiology as a key component of their programs, with the questions encompassed by astrobiology serving as overarching themes for the programs as a whole. The missions put forward in the solar system exploration survey are all key missions in astrobiology, whether they are labeled as such or not. And issues and missions related to astrobiology represent one of the key areas of interest identified in the astronomy and astrophysics communities.

Astrobiology provides the intellectual connections between otherwise disparate enterprises. NASA's astrobiology program creates an integrated whole and supports the basic interdisciplinary nature of the field. Further, the Vision is, at its heart, largely an astrobiology vision with regard to the science emphasis.[18] In developing the future of the program, the missions actually feed forward from the basic science. Astrobiology is just beginning the type of synthesis and integration that will allow it to provide science input for future mission development. Without it, the science and the scientific personnel will not be in place to support the missions when they do fly.

At a time of increasing desire for cross-disciplinary programs, astrobiology represents an outstanding example of the development of a successful new interdisciplinary area. Universities across the country have established new programs in astrobiology and appointed numerous faculty members. A generation of undergraduate and graduate students has been inspired by the intellectual challenges and the Vision to undertake courses and research projects in broad areas of space science. The United States has

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[18] The NASA document, *The Vision for Space Exploration,* cited a number of actions that were to be taken to implement the Vision, including the following scientific activities with an emphasis on searches for life:

- Conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration;
- Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids, and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources; and
- Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars.

been the leader in this developing field and has triggered large efforts in other countries, notably in Britain, Spain, Australia, and Russia. The strong U.S. leadership will be lost under the current plan.

In a new discipline that has a larger than average number of early career participants, the proposed cuts will have a disproportionate impact on young people (students, postdoctoral fellows, and junior faculty) and will strongly discourage new entries into space research. Highly trained and creative people are the heart of the space program. Yet training of the very best people takes years, and drastic cuts now will mean that scientists will not be there to support future missions. The proposed halving of the program is a complete reversal of years of NASA efforts and will be counterproductive to any long-term space exploration strategy.

EARTH SCIENCE

Goals

In response to requests from NASA, NOAA, and the U.S. Geological Survey (USGS), the National Research Council has begun a decadal survey of Earth science and applications from space that is due to be completed in late 2006. The guiding principle for the study, which was developed in consultation with members of the Earth science community, is to set an agenda for Earth science and applications from space, including everything from short-term needs for information, such as environmental warnings for protection of life and property, to longer-term scientific research that is essential for understanding our planet and is the lifeblood of future societal applications. Indeed, the decadal survey study committee has already concluded in its interim report that:

> Understanding the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important for society as it seeks to achieve prosperity and sustainability.[19]

Among the key tasks in the charge to the decadal survey committee is the request to:

- Develop a consensus of the top-level scientific questions that should provide the focus for Earth and environmental observations in the period 2005-2020; and
- Develop a prioritized list of recommended space programs, missions, and supporting activities to address these questions.

A unique aspect of the NASA Earth science program is the extent to which it supports other federal agencies. NOAA, the USGS, and the Department of Defense depend on NASA for development of new Earth observation technologies for weather, climate, and land imaging and for observations and technologies to support operational oceanography. Agencies such as the U.S. Department of Agriculture, the Department of the Interior, the Environmental Protection Agency, and the Department of Transportation depend on current NASA sensors and NASA's ability to develop decision support systems and resource management tools for national and international agriculture assessments, forestry and parks monitoring, pollution assessment, and land, air, and ocean transportation planning. NASA uniquely complements research conducted under the sponsorship of the National Science Foundation, allowing basic science to test hypotheses about natural phenomena at scales that would not be possible using ground-based technologies. NASA's role is significant in the international arena in similar ways.

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[19] National Research Council, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*, The National Academies Press, Washington, D.C., 2005, p. 1.

Recognizing the near-term challenges during the time that the decadal survey was being conducted, the NRC survey committee examined urgent issues that required attention prior to publication of the final decadal survey report. Released in April 2005, the survey committee's interim report, *Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation*, identified the following issues that required immediate attention:

- Proceeding with some NASA missions that have been delayed or canceled,
- Evaluating plans for transferring needed capabilities from some canceled or descoped NASA missions to the National Polar-orbiting Operational Environmental Satellite System (NPOESS),
- Developing a technological base for exploratory Earth observation systems,
- Reinvigorating the Explorer missions program,
- Strengthening R&A programs, and
- Strengthening the approach to obtaining important climate observations and data records.

Prospects for Progress Toward Goals

The interim report stated that the nation's "system of environmental satellites is at risk of collapse" (p. 2). That statement, which may have seemed somewhat extreme at the time, was made before the Hydros and Deep Space Climate Observatory[20] missions were canceled, before the Global Precipitation Mission (GPM) was delayed for 2½ years, before the NPOESS Preparatory Program (NPP) mission was delayed for 1½ years, before the NPOESS program breached the Nunn-McCurdy cost growth threshold[21] and was delayed for at least several years, and before significant cuts were made to NASA's R&A program. In less than a year since the interim report was issued, matters have become progressively worse. The missions set prior to the 2007 program are summarized in Table 2.4.

The interim report endorsed the Hydros mission; subsequently, but before the FY 2007 budget was released, Hydros was not confirmed for development. Nor was the Deep Space Climate Observatory, which was not addressed by the interim report but had been supported by an earlier NRC panel.[22] The interim report stated that the Global Precipitation Mission should proceed immediately and without further delay. The NASA FY 2007 action delays the mission by 2½ years.

The interim report not only recommended that NASA and NOAA complete the fabrication, testing, and space qualification of an atmospheric sounding instrument for a geostationary orbit (GIFTS—Geostationary Imaging Fourier Transform Spectrometer), but it also recommended that they support the international effort to launch this instrument by 2008. While NOAA has completed some of the space qualification of GIFTS, the FY 2007 plan does not provide the additional funding that would be necessary to complete GIFTS.

The interim report called for the release of the next announcement of opportunity (AO) for the Earth System Science Pathfinder (ESSP) program in FY 2005; however, the earliest AO for the next ESSP will be FY 2008.

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[20] The Deep Space Climate Observatory was formerly called Triana.

[21] Title 10 USC § 2433 (known as the Nunn-McCurdy legislation) requires that Congress be notified about any major military procurement program that is likely to exceed its baseline cost by more than 15 percent and requires that any program that is likely to exceed its baseline cost by more than 25 percent be subjected to a cancellation review. On January 12, 2006, the Air Force notified Congress that NPOESS had cost growth in excess of 25 percent, thereby triggering such a review.

[22] National Research Council, "Review of Scientific Aspects of the NASA Triana Mission: Letter Report," National Academy Press, Washington, D.C., 2000, available at <www.nap.edu/catalog/9789.html>.

TABLE 2.4 Summary of Earth Science Missions

Mission	Provenance	Launch Date in Prior Plan	Launch Date in FY 2007 Plan
Global Precipitation Mission	Approved NASA mission	2008 in FY 2005, then went to 2010 in FY 2006	2.5-year delay to early 2013
Landsat Data Continuity Mission	Approved mission	FY 2006 budget had NASA providing an imager for flight on the first NPOESS platform, then thought to be end of 2009	Now a free-flyer with launch in early 2011
GLORY Atmospheric Aerosol Observatory	Approved mission	FY 2006 budget initially canceled mission; later restored—entered development in November 2005	January 2009
NPOESS Preparatory Program	NASA-NOAA mission	2007	18-month delay to May 2008
Ocean Surface Topography Mission (OSTM)	Approved NASA mission	April 2008	June 2008
Geostationary Imaging Fourier Transform Spectrometer	NASA-NOAA-DOD (Navy)	Canceled in FY 2006 budget	N.A.
Ocean Vector Winds	Approved NASA mission; continuity with QuikScat	2008 in FY 2005 budget; canceled in FY 2006 budget	N.A.
Wide-Swath Ocean Altimeter	NASA	Option for OSTM mission; canceled in FY 2006 budget	N.A.
Earth System Science Probe (ESSP)-Cloudsat	Selected via ESSP-2 AO in 1998	May 2005	April 2006
ESSP-OCO	Selected via ESSP-3 AO in 2001	2008	2008
ESSP-Aquarius	Selected via ESSP-3 AO in 2001	2009	2009
ESSP-Hydros	Selected as an alternate via ESSP-3 AO in 2001	2011	Not confirmed for development
ESSP-Next AO		Originally planned for 2004	2008?

The most serious impacts on the long-term strategy and capacity-building efforts in Earth science will result from the severe cuts in the R&A program. Although the proposed R&A cuts across NASA are approximately 15 percent, the cuts for FY 2007 appear to be closer to 20 percent in key elements of the Earth sciences. Such reductions will impair the ability of the research community to make substantial scientific progress, reduce the capacity to train new scientists to succeed those who retire, and forestall the ability to respond to new challenges as national needs change.

Another impact is to reduce scientific research on missions that have already been launched and are providing novel observations of Earth with unprecedented opportunities to learn about our planet. Cutting the research after all of the expense of building and launching the missions means that much of the up-front, and most expensive, part of the mission will be wasted.

The added delays will have multiple impacts: (1) there will be increased costs downstream that will further undermine the possibilities for a revitalized future Earth science program, and (2) there will be a strong disincentive to keeping or attracting good scientists in the field. Procurement stretch-outs increase overall program costs, result in less out-year money for the future, and lead to missed synergies and gaps in observations associated with delay in execution. For example, the 2-year delay in the Global Precipitation Mission (GPM) will create a gap between its operation and that of the Tropical Rainfall Measurement Mission (TRMM), whose science operations were extended last year in part because of their valuable role in meteorological forecasts of severe weather events. The delay of GPM also endangers a carefully planned partnership with the Japanese space agency, JAXA.[23]

Finally, there are several recent administration initiatives that are part of a comprehensive vision for Earth science research that will be handicapped. NASA is expected to be an important participant in the U.S. Climate Change Research initiative announced in 2001,[24] which is intended to advance understanding of the climate system and climate change. NASA also has a key role in the integration of remote sensing observations into regional and global observatories proposed as a part of the U.S. Global Earth Observation (GEO) initiative,[25] which is a multinational effort dedicated to developing and instituting a Global Earth Observation System of Systems, but that role is threatened as well.

MICROGRAVITY LIFE AND PHYSICAL SCIENCES

Goals

There has not been a formal decadal survey in the space life sciences, although several past reports from the NRC have addressed scientific priorities for space biology and medicine.[26] The 1998 report recommended two top priorities for the program:

1. Research aimed at understanding and ameliorating problems that may limit astronauts' ability to survive and/or function during prolonged spaceflight, and
2. Research to understand fundamental biological processes in which gravity is known to play a direct role.

With respect to research to help develop countermeasures for the effects of spaceflight on crew members, all of the reports emphasized that meaningful clinical trials cannot be executed with astronauts, given that the sample numbers are small and the fact that NASA continues to fail to collect and archive clinical data in a meaningful or useful manner.

The NRC report *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies*,[27] which was published in 2000, addressed the mission enabling and enhancing technologies that will require an improved understanding of fluid and material behavior in a reduced-gravity environment. The NRC report *Assessment of Directions in Microgravity*

[23] Among other items, JAXA is developing the dual-frequency precipitation radar that is at the heart of the GPM mission.

[24] See <www.climatevision.gov/statements.html>.

[25] See <www.whitehouse.gov/news/releases/2002/02/20020214-5.html> and <www.earthobservationsummit.gov/press_release_whfs.html>.

[26] National Research Council, *A Strategy for Research in Space Biology and Medicine in the New Century* (1998), *Review of NASA's Biomedical Research Program* (2000), and *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences* (2002), all published by National Academy Press, Washington, D.C.

[27] National Research Council, *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies*, National Academy Press, Washington, D.C., 2000.

and Physical Sciences Research at NASA,[28] published in 2003, summarized the accomplishments of the field and re-emphasized those areas of research that are important to the exploration of space. Among the areas identified in the latter report for their likely high impact on NASA's technology needs were the following:

- Research regarding aspects of spacecraft fire safety,
- Multiphase flow and heat transfer,
- Computational materials science,
- Complex fluid rheologies,
- Interfacial processes, and
- Physiological flows.

While the microgravity physical science community has not conducted a decadal survey that recommended a program strategy and priorities in the fashion of the space science communities, the studies noted above provide the same kind of broad scientific assessment of appropriate research directions.

A 2005 NRC review of NASA plans for research on the ISS in light of the new Vision focused on research areas that are critical to the human exploration mission and for which the ISS was uniquely suited.[29] To this end, several areas of ISS research were identified:

- Effects of radiation on biological systems,
- Loss of bone and muscle mass during spaceflight,
- Psychosocial and behavioral risks of long-term space missions,
- Individual variability in mitigating a medical and/or biological risk,
- Fire safety aboard spacecraft, and
- Multiphase flow and heat transfer issues in space technology operations.

Consequently, the 2005 report reaffirmed the general message relating to microgravity life and physical sciences research at NASA that has been communicated in prior NRC reports regarding the importance of research for the development of new technologies and the mitigation of space-induced risks to human health and performance both during and after long-term spaceflight. The report stated (p. 1),

> The loss of these programs is likely to limit or impede the development of such technologies and of physiological and psychological countermeasures, and the panel notes that once lost, neither the necessary research infrastructures nor the necessary communities of scientific investigators can survive or be easily replaced.

Prospects for Progress Toward Goals

In 2005, the NASA programs in the former Office of Biological and Physical Research (OBPR) were expected to support a broad scientific community in microgravity biological and physical research. With the announcement of the Vision, the OBPR and its budget were absorbed into the EMSD, and most of the resources were refocused toward development of infrastructure for human Moon and Mars missions. Budget estimates provided by NASA indicate that the microgravity life and physical science program is to be reduced by $3.8 billion from a total original budget of $5.5 billion for 2007 to 2011 (i.e.,

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[28] National Research Council, *Assessment of Directions in Microgravity and Physical Sciences Research at NASA*, The National Academies Press, Washington, D.C., 2003.

[29] National Research Council, *Review of NASA Plans for the International Space Station*, The National Academies Press, Washington, D.C., 2006.

a 69 percent reduction). Annual budgets for all microgravity research over the period FY 2007-2011 range from $275 million to $312 million per year, compared to an FY 2005 level of $910 million. The majority of the funds, $170 million per year, will be allocated to the Human Health and Performance (HHP) program, and only about $30 million per year will be allocated for fundamental biological and physical research. At the present time, the remaining funds for microgravity research on the ISS appear to be in a state of flux. Congress has directed that NASA use 15 percent of its ISS research budget for "ground-based, free-flyer, and ISS life and microgravity science research that is not directly related to supporting the human exploration program," but how funding will be determined and allocated is uncertain.

NASA has been given an overriding mandate for an enormously complex mission—long-term human spaceflight through deep space to Mars. Therefore, requirements-driven or strategic research that will enable the success of that mission becomes crucial. However, not carrying out fundamental research that is necessary to overcome critical obstacles to the completion of the mission would be equally improper. It is not clear that it will be possible for astronauts to survive long-term missions in deep space due to the lethal effects of high-energy radiation and the serious debilitating effects of the microgravity environment on human physiology. It is also unlikely that these problems will be fully understood or that effective countermeasures will be developed unless fundamental, problem-focused research is supported in these areas. Much of this research will need to be carried out in ground-based studies and model systems, given the need to generate large enough samples and experimental variables to produce statistically significant and scientifically meaningful results. A few limited studies with astronauts in the ISS using existing drugs and technologies are unlikely to solve these problems.

As a result of the budget cuts, much of the research community that was recruited and nurtured over the past decades now finds itself facing award terminations or uncertainty about the potential future of microgravity research.[30] Many of the leading scientists in the field have redirected their research into other areas where future research support is more stable. This is particularly true for university researchers, given that it takes 4 to 5 years for a faculty member's students to complete doctoral research.

ESMD representatives explained to the committee that the program can be revitalized later in the decade when the financial pressures of completing the ISS and the CEV become less intense. However, the committee notes that an entirely new generation of investigators will have to be recruited into the field at that time because the current researchers will have gone to other fields and will not return to a field with uncertain funding or a demonstrated lack of long-term commitment to its members and trainees. Given that the current research community is the product of some three decades of development and nurturing, the committee has concerns about how long it will take to regenerate a viable new research community and whether any investigators can be found to mentor the new researchers that NASA will need to recruit. One way to mitigate the demise of the microgravity research community is to maintain a credible ground-based program that can involve many more investigators at a lower cost than would be incurred with only a small number of flight programs. In fact, this continuing ground-based program would provide a much stronger basis for selecting only those programs that offer the promise of the greatest gain from a flight experiment should future funds and facilities for microgravity experiments become available.

The current HHP program focuses on development and testing of existing technologies to meet NASA's long-term needs. Given that the biological effects of radiation or of microgravity conditions that will be experienced by astronauts on their journey through space to Mars, or when they are living for extended periods on the Moon, are not currently well understood, no existing treatments have been developed and tested for these conditions. There is a small possibility that some interventions that have been developed for other purposes may provide some countermeasure function. However, the biological mechanisms underlying the body's responses to the stresses of high-energy radiation and microgravity are

[30] According to NASA representatives, 64 life sciences grants were canceled in 2005, impacting a total of 140 scientists, 45 post-doctoral trainees, and 70 graduate students. In the physical sciences, 176 physical sciences grants were canceled in 2005 impacting a total of 190 scientists, 125 post-doctoral trainees, and 154 graduate students.

not well enough understood to enable development of a rational approach to selecting these agents for testing. Even if this were possible, replication of relevant conditions (e.g., radiation effects) on the ISS is not, and the number of astronauts is too small to develop appropriate controlled studies with large enough sample sizes to produce statistically significant results. Thus, the most reasonable approach would be to fund the critical ground-based research necessary to develop appropriate models and understand fundamental biological mechanisms leading to the effects of radiation and microgravity on humans.

Analysis of the NASA FY 2007 budget suggests that funds will not be provided for the physical and biological research necessary to identify and define problems that are critical to human survival and function in long-term spaceflight or to develop new technologies and countermeasures to overcome these challenges. It is also not clear that NASA is effectively linking its ongoing applied research program on development of microgravity countermeasures for humans to fundamental life science research activities that are likely critical for its future success. Based on what is known about the effects of high-energy radiation and microgravity on human physiology over the long term, entirely new scientific breakthroughs likely will be needed to make it possible for humans to travel to Mars and return alive. This type of breakthrough will require fundamental life science research that combines ground-based and flight experiments, and rigorous clinical trials and analysis.

Given the likely limitations of the ISS, including lack of funding for microgravity life and physical sciences research, the small number of astronauts who will be living in this environment, and the small percentage of their time available for biology-based research activities, even if the ISS research areas noted above can be supported, the committee reiterates the conclusions of prior NRC studies that a robust ground-based program is critical to help solve problems that are relevant to NASA's planned human spaceflight. Studies necessary to identify the critical problems, to develop new and more effective countermeasures, and to subject them to clinical trials will still need a strong ground-based program, especially given statistical limitations related to the small sample sizes from studies done on the ISS. The effects of radiation on human health constitute one area that cannot be resolved by studies conducted on the ISS because the ISS is in relatively low Earth orbit. Therefore, continued research on ground-based radiation effects and preparation for research on the Moon will be necessary to make long-term human spaceflight to Mars a possibility in the future.

If significant support is not restored for the more fundamental life and biomedical sciences research necessary to understand the biological mechanisms responsible for the deleterious effects of spaceflight on human physiology (most notably, effects of radiation, microgravity, bone and muscle loss, and behavioral adaptation), then it is highly likely that:

1. The risks of eventually sending humans to Mars will be enormously increased;
2. There will be significant difficulty in maintaining long-term human installations on the Moon; and
3. An entire generation of space biologists will be lost, thus profoundly impacting the human space exploration program.

In terms of space-based research, the committee generally concurs with the findings and recommendations of the recent NRC review of plans for research on the ISS,[31] including the following areas where there are particular needs:

- Involvement of a broad base of experts and a rigorous and transparent prioritization process to develop and maintain a set of research experiments to be conducted aboard the ISS that would enable the full suite of exploration missions;

[31] National Research Council, *Review of NASA Plans for the International Space Station*, The National Academies Press, Washington, D.C., 2006.

- Scheduled periodic reviews of the ISS utilization plan with a broad group of stakeholders (internal and external, scientific and operations) to ensure that the plan remains appropriate and that it promotes an integrated approach to attaining the ultimate program goals;
- Long-duration experiments designed and conducted on the ISS to characterize temporal muscle atrophy and bone loss in the spacecraft environment;
- Evaluation of restoration of the animal habitat and glove box for muscle and bone studies, and of the utility of the animal centrifuge as a unique fractional gravity research tool and a potential countermeasure in the context of a martian outpost scenario;
- Critical analysis of both disaggregated and aggregated data (such as the data in the Longitudinal Study of Astronaut Health and the Life Sciences Data Archive[32]) to derive confidence bands for medical risks;
- Development of ground-based programs focused on understanding the effects of high-energy radiation (similar to that present in deep space) on whole-animal physiology and survival, as well as development of countermeasures or shielding protocols for protection of astronauts against these lethal effects;
- Additional hypothesis-driven, long-duration research on the ISS to refine confidence bands such that a reasonable statistical likelihood exists that the crew members' adaptation during a long-duration mission will fall within a clinically acceptable range;
- Research into predictors of individual response on the ISS or during extended-duration spaceflight to allow individual tailoring of countermeasures;
- Use of previous recommendations (e.g., those of the Institute of Medicine bioastronautics roadmap committee[33]) to sequence additional needed experiments and to address in a timely fashion those critical issues that could be important for the design of architectures for future missions;
- Research or testing necessary to ensure fire safety at the design level and to mitigate the risks associated with fire safety for exploration missions; and
- Studies relevant to multiphase flow and heat transfer systems operating in microgravity environments, e.g., the motion of films and fluid particles at interfaces.

The one area where the ISS is absolutely critical is in providing a laboratory where the effects of fractional gravity can be studied in animals, and eventually in humans. As suggested in past NRC reports, it is therefore critical that equipment that can create fractional gravity environments (e.g., a centrifuge) be reinstated in NASA's plan and budget for future missions.

[32] Institute of Medicine, *Safe Passage: Astronaut Care for Exploration Missions,* National Academy Press, Washington, D.C., 2001, p. 3.

[33] Institute of Medicine, *A Risk Reduction Strategy for Human Exploration of Space: A Review of NASA's Bioastronautics Roadmap*, The National Academies Press, Washington, D.C., 2006.

3
Findings and Recommendations

Finding 1. NASA is being asked to accomplish too much with too little. The agency does not have the necessary resources to carry out the tasks of completing the ISS, returning humans to the Moon, maintaining vigorous space and Earth science and microgravity life and physical sciences programs, and sustaining capabilities in aeronautical research.

Both the Vision, when it was announced in 2004, and the NASA Authorization Act of 2005 were based on administration projections of total NASA funding that have not been requested subsequently. Furthermore, demands have grown for resources for flights of the space shuttle, completion of the ISS, and efforts to shorten the gap between retirement of the space shuttle (mandated for 2010) and availability of a new crew exploration vehicle (mandated by 2014), as well as for higher costs of science missions. As a result the resources are inadequate to accomplish NASA's broad missions of national importance.

Recommendation 1. Both the executive and the legislative branches of the federal government need to seriously examine the mismatch between the tasks assigned to NASA and the resources that the agency has been provided to accomplish them and should identify actions that will make the agency's portfolio of responsibilities sustainable.

Finding 2. The program proposed for space and Earth science is not robust; it is not properly balanced to support a healthy mix of small, medium, and large missions and an underlying foundation of scientific research and advanced technology projects; and it is neither sustainable nor capable of making adequate progress toward the goals that were recommended in the National Research Council's decadal surveys.

In Chapter 1, the committee lists four criteria by which it assessed NASA's science programs in response to the committee's charge. The committee's conclusions with respect to those criteria are as follows:

- *Capacity to make steady progress*. The proposed SMD mission portfolio will fall far short of what was recommended by the NRC's decadal surveys. The space and Earth science program will be forced to terminate or delay numerous flight missions, curtail advanced technology preparations for other future missions, and significantly reduce support for the research projects of thousands of scientists across the country. The net result of these actions will be that NASA will not be able to make reasonable progress—in any of the major space research disciplines—toward the scientific goals that were set out for the decade, and our nation's leadership in Earth and space research and exploration will erode relative to efforts of other nations.
- *Stability*. The science program has become fundamentally unstable. As Figures 1.1 and 1.2 illustrate (see Chapter 1), there have been dramatic changes in the projected resource trajectories for all science programs over the past 3 years. Consequently, it has not been possible to follow an orderly plan for sequencing missions and projects, developing advanced technology, sizing and nurturing a research and technical community, or meeting commitments to other U.S. or international partners.

- *Balance*. The SMD program will become seriously unbalanced because the reductions in funding have fallen disproportionately on the small missions and the R&A programs. The committee estimates that the proposed 15 percent reductions in R&A budgets are equivalent to less than 2 to 3 percent of the funding for flight missions. The small missions such as the Explorers and the Earth System Science Pathfinders had already been reduced with the initiation of the Vision in FY 2005, to the point that their projected flight rate is now a fraction (possibly lower than 30 percent) of what it had been throughout the history of the space program. The reductions in FY 2007 and the out-years compound the problem and also add a new target for reduction, the R&A program, which is the lifeblood of the space and Earth science community. Plans are to reduce R&A funding by 15 percent retroactively starting with the FY 2006 budget, with larger cuts in such programs as Astrobiology.
- *Robustness*. The proposed program is not robust because it undermines the training and development of the next generation of scientists and engineers—the generation that will be critical to the accomplishment of the agency's federal responsibilities, including the Vision. Space missions, regardless of whether they are for robotic or human exploration, generate an appropriate return on investment only if there is a high-quality, vibrant, experienced, and committed community of scientists and engineers to turn each mission's data stream into new understanding that creates intellectual, cultural, and technological benefits. Because space exploration is a long-term endeavor that spans decades and generations, NASA will need a sustained long-term investment in human capital, facilities, technology development, and progressive scientific discoveries.

The committee identified four critical areas that are especially significant contributors to its second finding.

1. *Research and analysis (R&A) budgets have been reduced*. R&A projects conducted at universities, NASA centers, and within industry support a trained, knowledgeable workforce; they form the basis for the science and technology required for future missions; and they support analysis and interpretation of data from existing missions. Although these programs involve a relatively small fraction of total resources, cuts to the R&A grants program cause disproportionately large damage to the viability of the space sciences disciplines as well as to future programs. By reducing these programs, NASA reduces the return on its investment in past missions and cripples its ability to execute future missions in an economical and scientifically productive manner.
2. *Astrobiology research has been severely reduced*. Astrobiology—the study of the origin, evolution, and ubiquity of life in the cosmos, including the conditions necessary for life on other planets—is a discipline that NASA created and fostered for decades with its exobiology program and to which it gave major new emphasis a decade ago through the use of dedicated R&A funds.[1] NASA has stimulated the establishment of new courses and degree or certificate programs at several institutions, created new faculty lines, stimulated new areas of cross-disciplinary research and teaching, and inspired more diverse and capable students to become engaged in the new field. The search for life elsewhere is central to NASA's overall mission, but the overall program is now proposed to be cut in half, causing valuable expertise and research to be lost. NASA's ability to reconstitute its astrobiology capability in the future will be impeded by the message that the field is a bad career choice.
3. *Explorers and other small missions have been delayed or canceled*. Explorer, ESSP, and Mars Scout missions are among the smallest missions in NASA's science portfolio, and because of their centrality to science research, all of the NRC decadal survey reports have considered them vital and inviolable. These small missions fill critical science gaps in areas that are not addressed by strategic missions, serve as precursors to larger missions, support the rapid implementation of attacks on very

[1] In its 2003 review of the astrobiology program (National Research Council, *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*, The National Academies Press, Washington, D.C., 2004) the SSB Committee on the Origins and Evolution of Life concluded that "Astrobiology is a good recent example of the United States leading the rest of the world into a new discipline area and new forms of research."

focused topics, provide for innovation and the use of new approaches that are difficult to incorporate into the long planning cycles needed to get a mission into the strategic mission queues, and provide a particularly substantial means to engage and train science and engineering students in the full life cycle of space research projects. The steady successes and productivity of the small missions are strong arguments for their role in a balanced overall mix of mission sizes.[2]

4. *Initial technology work on future missions and emphasis on technical innovation have been reduced.* As a 1998 NRC report, *Assessment of Technology Development in NASA's Office of Space Science,*[3] noted, development and utilization of new technologies have always been pivotal elements of the space program. Advances in spaceflight and space science, and the beneficial applications of new knowledge from space research, have been driven, or constrained, by the pace of growth in technological capabilities and their innovative exploitation to open new fields and pursue new scientific questions. As space research strives today to tackle increasingly complex scientific problems and to do so by accomplishing more with less, the effective development, adaptation, and adoption of new technologies are every bit as important as in the past, and probably more so. New opportunities also now exist to create truly innovative new technologies to meet NASA's needs by pursuing interdisciplinary approaches that span engineering, physical sciences, and the life sciences. Reductions in the resources to provide these kinds of long-lead-time technology investments will delay readiness for future missions and increase their technological, schedule, and cost risk, and hence decrease the likelihood of their success in the long term.

Recommendation 2. NASA should move immediately to correct the problems caused by reductions in the base of research and analysis programs, small missions, and initial technology work on future missions before the essential pipeline of human capital and technology is irrevocably disrupted.

If at all possible, the restoration of the small missions, R&A programs (including astrobiology), and the technology investment in future missions should be accomplished with additional funding for science. The committee does not intend to compound the disruptions by impacting other parts of the space science portfolio such as the larger missions. The scale of the immediate resource allocation problem is modest, probably slightly more than 1 percent of the total NASA budget, but addressing that problem will help correct the immediate threats to the health of the research program and also permit NASA and its stakeholders to conduct a vigorous, open assessment of longer-term priorities and plans. Given the funding constraints associated with elements of the human spaceflight program, the committee further urges that funding for science be isolated from other NASA accounts to ensure that the money is actually spent on science.

Finding 3. The microgravity life and physical sciences programs of NASA have suffered severe cutbacks that will lead to major reductions in the ability of scientists in these areas to contribute to NASA's goals of long-duration human spaceflight.

For much of its history, building the ISS was justified in terms of the life and physical sciences research that it would enable. As the space station's research capabilities have been scaled back, NASA has also reduced support for these research areas. However, if the agency is to pursue long-duration human lunar, and ultimately Mars, missions, it will have to answer fundamental questions about issues such as how the human body reacts to long-duration spaceflight, what microgravity and radiation countermeasures are mandatory for astronaut survival and mission effectiveness, and how materials and

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[2] National Research Council, *Assessment of Mission Size Trade-offs in NASA's Earth and Space Science Missions*, National Academy Press, Washington, D.C., 2000, and National Research Council, *Principal Investigator-Led Missions in the Space Sciences*, The National Academies Press, Washington, D.C., 2006.

[3] National Research Council, *Assessment of Technology Development in NASA's Office of Space Science,* National Academy Press, Washington, D.C., 1998.

new technological systems act in the space environment.[4] Current NASA funds for human health research focus on testing and improving existing technologies that are unlikely to meet NASA's long-term needs. NASA is not planning to support sufficient fundamental problem-oriented research on Earth or in space necessary to identify and define problems that are critical to human survival and performance in long-term spaceflight, or to develop new scientifically grounded technologies and countermeasures to overcome these challenges.

The proposed FY 2007 program implements a drastic reduction in the life and physical sciences program to about one-third of its former size, thereby eliminating whole research areas and research communities and reducing the scientific use of the ISS to a fraction of its previously expected level. By NASA's count, 240 grants already have been terminated, with the result of removing support from more than 500 postdoctoral fellows and graduate and undergraduate students, and additional cuts are planned for the fall of 2006. The research that was to be conducted under these grants, including important ground-based research, is fundamental to the development of sufficient understanding of human physiology and of technology in the environment of space so as to be able to undertake long-duration human spaceflight.

NASA has rationalized these reductions based on the need to use the funds for the development of the Crew Exploration Vehicle, which is to replace the space shuttle. In many ways, then, the reductions in life and microgravity sciences programs are the most egregious example of the unfortunate choices that NASA has had to make because the overall funding for the agency is inadequate for its many responsibilities. NASA is being compelled to accommodate near-term necessities at the expense of the future of human spaceflight. The committee has serious doubts about whether the necessary research community can be reconstituted rapidly enough later so that it can meet NASA's needs in time to support critical exploration risk assessments, systems choices, and development.

Recommendation 3. Every effort should be made to preserve the essential ground-based and flight research that will be required to enable long-duration human spaceflight and to continue to foster a viable community that ultimately will be responsible for producing the essential knowledge required to execute the human spaceflight goals of the Vision for Space Exploration.

The scale of the short-term resource allocation required to revive this effort is modest (less than 1 percent of the total NASA budget), yet addressing that problem will provide a continuing source of knowledge and community commitment that is absolutely critical for the success of this endeavor.

Finding 4. The major missions in space and Earth science are being executed at costs well in excess of the costs estimated at the time when the missions were recommended in the National Research Council's decadal surveys for their disciplines. Consequently, the orderly planning process that has served the space and Earth science communities well has been disrupted, and balance among large, medium, and small missions has been difficult to maintain.

NASA is known for its flagship missions, such as the Hubble Space Telescope, and will be known in the future for such flagship missions as the James Webb Space Telescope. These missions have strong endorsements in the decadal strategy surveys for their disciplines, and NASA is to be commended for pursuing these missions as a high priority in response to NRC advice.

A problem has arisen, however, in the execution of a number of the missions. Decadal surveys offer advice on the full range of science in their discipline. They rank missions to be pursued by category—large, medium, and small; they offer advice on R&A programs; and they balance the aspirations of the various subdisciplines. They perform this ranking and offer this advice based on NASA estimates of the costs of the missions and of the overall funding that is likely to be available for the

[4] National Research Council, *Review of NASA Plans for the International Space Station*, The National Academies Press, Washington, D.C., 2006.

discipline. A number of missions in development, however, are costing substantially more than they were estimated to cost at the time of the decadal survey that recommended them, with the result that it is not now possible to execute the broad range of programs recommended in the decadal surveys for these disciplines on the recommended timescales. In particular, within the current funding constraints, it is not possible to maintain the proper balance among large, medium, and small missions, or with R&A programs, nor is it possible to maintain a vibrant program in all the various subdisciplines.

The specific causes of problems with the execution of the larger missions are complex and difficult to discern. Some mission costs were undoubtedly underestimated and/or were developed with inadequate reserves at the time the missions were recommended. However, deficiencies in program execution (including inadequate assessment of technical risk, problems with systems planning or development, changing technical and management requirements, changing internal NASA costs, and growing launch costs) have also contributed substantial additional burdens to the program. Put as simply and directly as possible, the committee believes that NASA needs to improve the execution of its flight programs.

Recommendation 4. NASA should undertake independent, systematic, and comprehensive evaluations of the cost-to-complete of each of its space and Earth science missions that are under development, for the purpose of determining the adequacy of budget and schedule.

As part of this recommended NASA review, a careful examination of the approaches to cost, schedule, and risk management should be done, and a comprehensive examination should be made of options to reduce cost while maintaining a mission's capability to achieve the science priorities for which it was recommended. The committee urges that steps be taken to allow all missions currently under development to make reasonable progress while the competitive assessment of projects across the SMD is underway. Major missions are an essential part of a balanced program—it is important to have large missions as well as medium and small missions—and finding ways to keep them on track and affordable is thus crucial.

Finding 5. A past strength of the NASA science programs, in both their planning and their execution, has been the intimate involvement of the scientific community. Some of the current mismatch between the NASA plans for the next 5 years and a balanced and robust program stems from the lack of an effective internal advisory structure at the level of NASA's mission directorates.

Under normal circumstances, internal NASA committees would be providing tactical advice, and the NRC committees would follow their long-standing role of validating NASA's choices with respect to the decadal and other surveys. However, these are not normal circumstances. External scientific involvement was absent in the construction of the program that accompanied the FY 2007 budget; had an advisory structure existed, it could have warned NASA of the outcry that would accompany cuts to the R&A budgets and other decisions. Unless an adequate, effective, and representative advisory process is instituted, this process will repeat itself. As a 2004 NRC report stated, a scientific community "that has some 'ownership' in the program creates 'constructive tension' that pushes the programs to excel."[5]

Recommendation 5. NASA should engage with its reconstituted advisory committees as soon as possible for the purpose of determining how to create in the space and Earth science program a proper balance among large, medium, and small missions, and research and analysis programs, and for evaluating the advice in and the consequences of the results from the comprehensive reviews of the major missions called for in Recommendation 4. Reconstitution and engagement of advisory committees for the microgravity life and physical sciences are equally important and should be given attention.

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[5] National Research Council, *Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy*, The National Academies Press, Washington, D.C., 2004, p. 1.

Appendixes

A
Statement of Task

An ad hoc committee of the National Research Council's (NRC's) Space Studies Board (SSB) will conduct an assessment of balance in NASA's science programs as a third and final component of its response to Congressional language in the FY 2005 appropriations bill for NASA. That bill directed the SSB to "conduct a thorough review of the science that NASA is proposing to undertake under the space exploration initiative and to develop a strategy by which all of NASA's science disciplines, including Earth science, space science, and life and microgravity science, as well as the science conducted aboard the International Space Station, can make adequate progress towards their established goals, as well as providing balanced scientific research in addition to support of the new initiative" (Joint Explanatory Statement: (NASA Excerpts) Conference Report on H.R. 4818 Consolidated Appropriations Act, 2005).

The committee, which will include some members of the Space Studies Board, will conduct a fast-track assessment of the programs embodied in NASA's FY 2007 budget estimates and supplementary information. The study will consider whether the science program, as articulated in the FY 2007 budget estimate and supplementary information and its out-year run-out, is:

(1) Appropriately inclusive of all relevant science disciplines (Earth and planetary sciences, life and microgravity sciences, astronomy and astrophysics, and solar and space physics);
(2) Robust and capable of making adequate progress towards scientific goals as recommended in NRC decadal surveys; and
(3) Appropriately balanced to reflect cross-disciplinary scientific priorities within the appropriate directorate, as recommended in NRC decadal surveys and other relevant scientific reviews.

In reviewing the NASA program, the committee will use the guiding principles recommended in the NRC report, *Science in NASA's Vision for Space Exploration*, to assess NASA's decision-making across scientific programs and the integrated approach to the program. The committee will also refer to published NRC decadal science strategy surveys when assessing individual disciplines as well as NRC advice regarding the contribution of particular science disciplines in NASA's Vision for Space Exploration.

The committee will prepare a short report of approximately 10 to 20 pages. The report will summarize the previous two components of the SSB's response to Congress,[1] in the context of the additional insight provided by NASA's 2007 budget submission, and include the third and final component that assesses the scientific program as it is presented in NASA's FY 2007 budget.

[1] The first component is presented in *Science in NASA's Vision for Space Exploration* (National Research Council, 2005). The second component is covered in *Review of Goals and Plans for NASA's Space and Earth Sciences* (National Research Council, 2005 [prepublication]) and in *Review of NASA Plans for the International Space Station* (National Research Council, 2005 [prepublication]).

B
Meeting Agenda

MONDAY, MARCH 6, 2006

Closed Session

8:00 a.m.	Discussion	
12:00 p.m.	Lunch	

Open Session

1:00 p.m.	FY 2007 budget overview: The view from the Hill	
	Senate Committee on Commerce, Science, and Transportation Majority	Jeff Bingham
	House Committee on Science Majority	David Goldston
	House Subcommittee on Space and Aeronautics Majority Minority	Bill Adkins Richard Obermann
2:00 p.m.	FY 2007 budget overview: The view from the Executive Branch	
	Office of Science and Technology Policy Office of Management and Budget	Robie Samanta Roy Amy Kaminski
3:00 p.m.	Break	
3:15 p.m.	FY 2007 budget overview: The view from the NASA/SMD	Mary Cleave
4:45 p.m.	Discussion	
5:30 p.m.	Adjourn	

TUESDAY, MARCH 7, 2006

8:30 a.m.	Standing Committee Assessments of FY 2007 Budget Implications	
	Committee on Solar and Space Physics	Dan Baker

	Committee on Planetary and Lunar Exploration	Reta Beebe
	Committee on Origins and Evolution of Life	Bruce Jakosky
	Committee on Earth Studies	Berrien Moore
10:05 a.m.	Break	
10:20 a.m.	FY 2007 budget overview: The view from the ESMD	Carl Walz
11:20 a.m.	Standing Committee Assessments of FY 2007 Budget Implications, *continued*	
	Committee on Astronomy and Astrophysics	Roger Blandford
	Committee on Space Biology and Medicine	Don Ingber
	Committee on Microgravity Research	Dennis Ready
12:00 p.m.	Lunch	
1:00 p.m.	Discussion—Implications of FY 2007 Budget on Science Programs	
3:00 p.m.	Break	
3:15 p.m.	[Closed session for splinter group to prepare outline of draft report on "Balance in NASA's Science Programs"]	
	Other SSB business	
	Berlin Ministerial Conference	Jean-Claude Worms
	Project updates: ESAS, LOIS, Workforce, others	
	Discussion of new studies: Science on the Moon, Astronomy and Astrophysics Progress Review	
5:30 p.m.	Adjourn	

WEDNESDAY, MARCH 8, 2006

Closed Session

8:00 a.m.	Discussion
3:00 p.m.	Adjourn

C
Biographical Sketches of Committee Members and Staff

LENNARD A. FISK, *Chair*, is the Thomas M. Donahue Collegiate Professor of Space Science in the Department of Atmospheric, Oceanic, and Space Sciences at the University of Michigan. He heads the Solar and Heliospheric Research Group. From 1987 to 1993, he was the associate administrator for Space Science and Applications and chief scientist of NASA. From 1977 to 1987, he served as a professor of physics and vice president for Research and Financial Affairs at the University of New Hampshire. Dr. Fisk is a member of the National Academy of Sciences, and he currently serves as chair of the NRC Space Studies Board.

GEORGE A. PAULIKAS, *Vice Chair*, retired in 1998 after 37 years at the Aerospace Corporation, after serving as a member of the technical staff, department head, laboratory director, vice president, senior vice president, and executive vice president, during which time he made many technical contributions to the development of national security space systems. He is vice chair of the NRC Space Studies Board.

SPIRO K. ANTIOCHOS, an astrophysicist, is head of the Solar Theory Section, Space Science Division at the Naval Research Laboratory (NRL), and adjunct professor in the Department of Atmospheric, Oceanic, and Space Sciences at the University of Michigan. He has served as a postdoctoral fellow at the National Center for Atmospheric Research and as a research associate at Stanford University, and he was chair of the Solar Physics Division, American Astronomical Society (1991-1993). He currently serves on the Space Studies Board.

DANIEL N. BAKER is director of the Laboratory for Atmospheric and Space Physics and is a professor of astrophysical and planetary sciences at the University of Colorado. He is also the director of the Center for Limb Atmospheric Sounding and is a member of the Center for Integrated Plasma Studies. He was formerly leader of the Space Plasma Physics Group at Los Alamos National Laboratory and chief of the Laboratory for Extraterrestrial Physics at NASA Goddard Space Flight Center. Dr. Baker currently serves as chair of the Committee on Solar and Space Physics and is a member of the Space Studies Board.

RETA F. BEEBE is a research professor in the Astronomy Department at New Mexico State University, Las Cruces. Dr. Beebe manages the Atmospheres Discipline Node of NASA's Planetary Data System, and she was a member of the Galileo imaging team and lead scientist for the team using the Hubble Space Telescope to provide context images for the Galileo project. She now serves as chair of the NRC Committee on Planetary and Lunar Exploration and she chaired the Solar System Exploration Survey Panel on Giant Planets (2004-2005). She is a member of the Space Studies Board.

ROGER D. BLANDFORD is Pehong and Adele Chen Professor of Physics and director of the Kavli Institute for Astrophysics and Cosmology at Stanford University. His research interests cover cosmology, black hole astrophysics, gravitational lensing, galaxies, cosmic rays, neutron stars, and white dwarfs. He served on the 1991 Astronomy and Astrophysics Survey Committee Panel on Scientific Opportunities and UV/Optical Astronomy from Space. Blandford is a member of the National Academy of Sciences, and he currently co-chairs the NRC Committee on Astronomy and Astrophysics and is a member of the Space Studies Board.

RADFORD BYERLY, JR., is a research scientist at the Center for Science and Technology Policy Research, University of Colorado. He formerly worked at the National Institute of Standards and Technology (then the National Bureau of Standards), served as chief of staff of the U.S. House of Representatives Committee on Science and Technology, and was director of the University of Colorado's Center for Space and Geosciences Policy. He is a member of the NRC Space Studies Board.

JUDITH A. CURRY is chair of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. Her research interests include remote sensing, climate of the polar-regions, atmospheric modeling, and air/sea interactions. She participates in the World Meteorological Organization's World Climate Research Program and chairs the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Studies Working Group on Polar Clouds. She currently serves on the NRC Space Studies Board.

JACK D. FARMER is a professor in the Department of Geological Sciences at Arizona State University. He previously worked as a research scientist at the NASA Ames Research Center and was a member of NASA's 2003 Mars Pathfinder Landing Site Steering Committee. His research covers microbial biosedimentology and paleontology, early biosphere evolution, and astrobiology. He currently serves on the NRC Space Studies Board.

JACQUELINE N. HEWITT, professor of physics, is the director of MIT's Kavli Institute for Astrophysics and Space Research. She has held positions at MIT's Haystack Observatory and at Princeton University. Hewitt is a former member of the NRC Committee on Astronomy and Astrophysics (1997-2000), the Task Group for Space Astronomy and Astrophysics' Panel on Galaxies and Stellar Systems (1996-1997), and the Panel on Radio and Submillimeter-wave Astronomy (1998-2001). She is a member of the Space Studies Board.

DONALD E. INGBER is the Judah Folkman Professor of Vascular Biology in the departments of Pathology and Surgery at Harvard Medical School and Children's Hospital Boston. He is also a member of the Children's Hospital Vascular Biology Program, Harvard Materials Research Science and Engineering Center, Harvard-MIT Health Science and Technology Division, Harvard-Dana Farber Cancer Center, and MIT Center for Bioengineering. He also helped found two biotechnology start-ups and has consulted for pharmaceutical, biotechnology, venture capital, and private investment companies. He is a member of the NRC Space Studies Board.

BRUCE M. JAKOSKY is a professor of geology and associate director for science at the University of Colorado's (UC) Laboratory for Atmospheric and Space Physics. He is also the director of UC's Center for Astrobiology. He began his Mars research working on the Viking mission to Mars in 1975, and he has been involved with a number of spacecraft missions, including Clementine, Mars Observer, Mars Global Surveyor, and the Mars Surveyor 2001 Orbiter.

KLAUS KEIL is the interim dean for the School of Ocean and Earth Science and Technology at the University of Hawaii. He has served in the past as director of the Hawaii Institute of Geophysics and Planetology, as a professor in and as chair of the Department of Geology at the University of New Mexico (UNM), as director of the UNM Institute of Meteoritics, and as a researcher at the NASA Ames Research Center. He is a member of the NRC Space Studies Board.

DEBRA S. KNOPMAN is vice president and director of the RAND Corporation Infrastructure, Safety and Environment (ISE) Division. She is an expert in issues on energy, the environment, water resources, and public administration. She was previously the director of the Center for Innovation and the Environment at the Progressive Policy Institute, the Deputy Assistant Secretary for Water and Science at the Department of the Interior, a hydrologist at the U.S. Geological Survey, and a staff member for the U.S. Senate Environment and Public Works Committee. She is a member of the Space Studies Board.

CALVIN W. LOWE is president of Bowie State University, a position that he assumed in 2002 after serving as vice president for research and dean of the Graduate College at Hampton University. Prior to his arrival at Hampton, he served 3 years as chair of and as a professor in the physics department at the Alabama Agricultural & Mechanical University in Huntsville. He is a member of the NRC Space Studies Board.

BERRIEN MOORE III is a professor and director of the Institute for the Study of Earth, Oceans, and Space, University of New Hampshire. Dr. Moore's research focuses on the carbon cycle, global biogeochemical cycles, and global change as well as policy issues in the area of the global environment. He currently serves on the Space Studies Board and co-chairs the Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future. Dr. Moore served as chair of the NRC Committee on Global Change Research (1995-1998) and chair of the Committee on International Space Programs (1996-1998).

FRANK E. MULLER-KARGER is a professor of biological oceanography, and he directs the Institute for Marine Remote Sensing at the College of Marine Science at the University of South Florida in St. Petersburg. Dr. Muller-Karger conducts research on marine primary production using satellite remote sensing, large data sets, networking, and high-speed computing. He was appointed by President George W. Bush to serve on the U.S. Commission on Ocean Policy, and he currently serves on the NRC Ocean Studies Board.

SUZANNE OPARIL is a professor of medicine, physiology, and biophysics and director of the Vascular Biology and Hypertension Program in the Division of Cardiovascular Disease at the University of Alabama at Birmingham (UAB). Dr. Oparil has served as president of the American Federation of Clinical Research and previously served as chair of the Public Policy Committee of that organization, where she formulated science policy positions that affect biomedical research at the national level. She is a member of the Institute of Medicine and of the NRC Space Studies Board.

RONALD F. PROBSTEIN is the Ford Professor of Engineering, emeritus, Massachusetts Institute of Technology. His career is centered on scientific applications of fluid mechanics, both theoretical and experimental, to numerous areas of conceptual, economic, or societal importance, including hypersonics, rarefied gas dynamics, dust comets, desalination, physicochemical hydrodynamics, synthetic fuels, in situ soil remediation with electric fields, and slurry rheology. He is a member of both the National Academy of Sciences and the National Academy of Engineering and is a member of the NRC Space Studies Board.

DENNIS W. READEY is the Herman F. Coors Distinguished Professor of Ceramic Engineering, Metallurgical and Materials Engineering Department, and the director of the Colorado Center for Advanced Ceramics at the Colorado School of Mines. Previously he served as chair of the Department of Ceramic Engineering at Ohio State University, program manager in the Division of Physical Research of what is now the Department of Energy, group leader of the basic ceramics group at Argonne National Laboratory, and a group leader in the research division of the Raytheon Company. He has been a member of the National Materials Advisory Board and is currently a member of the NRC Space Studies Board.

HARVEY D. TANANBAUM is director of the Smithsonian Astrophysical Observatory's Chandra X-ray Center (CXC). He was project scientist for the Uhuru X-ray satellite and served as the scientific program manager for the Einstein Observatory, the first large imaging X-ray telescope. Dr. Tananbaum is a member of the National Academy of Sciences and a member of the NRC Space Studies Board, and he served on the NRC Committee on Space Astronomy and Astrophysics (1981-1984) and the Committee on the Physics of the Universe (2001-2002).

J. CRAIG WHEELER is the Samuel T. and Fern Yanagisawa Regents Professor of Astronomy at the University of Texas, Austin, and past chair of the department. His research interests cover supernovas, black holes, and astrobiology. He has published more than 200 scientific papers, an astronomy text, and a novel and has edited five books. He is a member of the Space Studies Board and served as the co-chair of the NRC Committee on the Origin and Evolution of Life (2002-2005). He is president-elect of the American Astronomical Society.

A. THOMAS YOUNG is a retired executive vice president of Lockheed Martin Corp. Mr. Young previously was president and COO of Martin Marietta Corp. Prior to joining industry, Mr. Young worked for 21 years at NASA, where he directed the Goddard Space Flight Center, was deputy director of the Ames Research Center, and directed the Planetary Program in the Office of Space Science at NASA headquarters. Mr. Young received high acclaim for his technical leadership in organizing and directing national space and defense programs, especially the Viking program. He is a member of the National Academy of Engineering. Mr. Young currently serves on the NRC Space Studies Board.

Staff

JOSEPH K. ALEXANDER, study director, served previously as director of the Space Studies Board (1998-2005), deputy assistant administrator for science in EPA's Office of Research and Development (1994-1998), associate director of space sciences at the NASA Goddard Space Flight Center (1993-1994), and assistant associate administrator for space sciences and applications in the NASA Office of Space Science and Applications (1987-1993). Other positions have included deputy NASA chief scientist and senior policy analyst at the White House Office of Science and Technology Policy.

DWAYNE A. DAY, Space Studies Board research associate, has served as a study director for an SSB study on the hazards of radiation to human space explorers and has supported several other NRC studies on the NASA workforce, science portfolio, and International Space Station. He has previously worked as an investigator for the Columbia Accident Investigation Board. Prior to that, he worked for the Congressional Budget Office and at George Washington University's Space Policy Institute.

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Acronyms and Abbreviations

AANM	*Astronomy and Astrophysics in the New Millennium*
AO	announcement of opportunity
ARISE	Advanced Radio Interferometry between Space and Earth
BHFP	Black Hole Finder Probe
CEV	Crew Exploration Vehicle
DDAA	*The Decade of Discovery in Astronomy and Astrophysics*
DOI	Department of the Interior
DOT	Department of Transportation
EPA	Environmental Protection Agency
ESMD	Exploration Systems Mission Directorate (NASA)
ESSP	Earth System Science Pathfinder
EXIST	Energetic X-ray Imaging Survey Telescope
FY	Fiscal Year
GIFTS	Geostationary Imaging Fourier Transform Spectrometer
GLAST	Gamma-ray Large Area Space Telescope
GPM	Global Precipitation Mission
HHP	Human Health and Performance program
HST	Hubble Space Telescope
ISS	International Space Station
ITM	Ionosphere-Thermosphere-Mesosphere
JAXA	Japan Aerospace Exploration Agency
JDEM	Joint Dark Energy Mission
JWST	James Webb Space Telescope
LISA	Laser Interferometer Space Antenna
LWS	Living With a Star program
MIDEX	Medium-class Explorer
MMS	Magnetospheric Multiscale mission
MO&DA	mission operations and data analysis

NAI	NASA Astrobiology Institute
NASA	National Aeronautics and Space Administration
NFSS	*New Frontiers in the Solar System: An Integrated Exploration Strategy*
NGST	Next Generation Space Telescope
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Program
NuSTAR	Nuclear Spectroscopic Telescope Array
OBPR	Office of Biological and Physical Research (NASA)
OCO	Orbiting Carbon Observatory
OMB	Office of Management and Budget
OSTM	Ocean Surface Topography Mission
Q2C	*Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*
R&A	research and analysis
SAFIR	Single Aperture Far Infra-Red Observatory
SDO	Solar Dynamics Observatory
SEB	*The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*
SEC	Sun-Earth Connections
SIM	Space Interferometry Mission
SMD	Science Mission Directorate (NASA)
SNAP	SuperNova Acceleration Probe
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOMD	Space Operations Mission Directorate (NASA)
SR&T	Supporting Research and Technology
SSE	Solar System Exploration
STEREO	Solar-Terrestrial Relations Observatory
STP	Solar-Terrestrial Probe
TPF	Terrestrial Planet Finder
TRMM	Tropical Rainfall Measurement Mission
USGS	U.S. Geological Survey
WISE	Wide-field Infrared Survey Explorer