# SCIENCE IN NASA'S VISION FOR SPACE EXPLORATION

NATIONAL RESEARCH COUNCIL
*OF THE NATIONAL ACADEMIES*

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Committee on the Scientific Context for Space Exploration
Space Studies Board
Division on Engineering and Physical Sciences
NATIONAL RESEARCH COUNCIL
*OF THE NATIONAL ACADEMIES*

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## SPACE STUDIES BOARD

# Preface

This report stems from several key events that influenced U.S. space policy in 2004. On January 14, 2004, President George W. Bush announced major new goals for human and robotic exploration of space that would include sending humans back to the Moon and later to Mars.[1] On the same day the National Academies released the report of a November 2003 space policy workshop that independently addressed many of the issues covered in the new Bush space policy.[2] In its June 2004 report the President's Commission on Implementation of United States Space Exploration Policy recommended that NASA "ask the National Academy of Sciences to engage its constituent scientific community in a re-evaluation of priorities to exploit opportunities created by the space exploration vision."[3] NASA Administrator Sean O'Keefe subsequently wrote to the presidents of the National Academy of Sciences and the National Academy of Engineering proposing that the National Academies and NASA consider how to "collectively address" the commission's recommendations. He also announced a new strategic planning process in which NASA would develop a "strategic roadmap" for each of the agency's highest-level goals. Finally, Congress in its FY2005 appropriation bill for NASA directed "the National Academies' Space Studies Board 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."[4]

This report provides a partial response by the National Academies to the recommendations of the President's Commission and the requests from Administrator O'Keefe and the Congress. To further assist in response to the various requests, the NRC will organize separate, independent reviews of NASA's new strategic roadmaps.

This report was prepared by the ad hoc Committee on the Scientific Context for Space Exploration[5] according to the following charge:

> An ad hoc committee will prepare a short report regarding the role of science in the context of NASA's new vision for space exploration. The committee will draw on relevant past NRC science strategies and will do the following:
>
> 1. Develop a guiding statement of how scientific efforts will mesh into the new vision for space exploration,
> 2. Review available "decadal" surveys and similarly relevant science strategy reports and comment on their timeliness and relevance in the context of the committee's definition of science,
> 3. Recommend major goals and roles of science in the context of space exploration, and

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

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

[4] Joint Explanatory Statement: (NASA Excerpts) Conference Report on H.R. 4818 Consolidated Appropriations Act, 2005.

[5] See Appendix B for committee member biographies.

4. Recommend a set of guiding principles for integrating science into space exploration.

Many members of the committee had participated in Space Studies Board (SSB) discussions of aspects of these issues going back to the Board's first post-Columbia-accident meeting in March 2003, and many also participated in the November 2003 NRC space policy workshop. The committee includes senior members of the space science and astrophysics community who were contributors to the various NRC decadal science strategy surveys that constitute an important portion of prior scientific advice on these issues. Board members who chair several of the SSB's relevant discipline standing committees also were able to share a sense of the views of the members of the standing committees for consideration in preparing this report.

The committee met on November 17-19, 2004, at the National Academies' Beckman Center in Irvine, California. During the meeting the committee reviewed developments since publication of the report on the 2003 NRC space policy workshop, held extended discussions with NASA's Associate Administrator for Science and the NASA Director of Advanced Planning, and received briefings on relevant aspects of the report of the President's Commission and on related space exploration planning in Europe. The committee also received input from the disciplinary standing committees of the Space Studies Board regarding recent relevant NRC science strategy reports and the implications of the strategy reports for the new space exploration goals. All of those discussions served to inform the committee's deliberations, which then led to this consensus report.

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:

Michael J.S. Belton, Belton Space Exploration Initiatives, LLC,
Don P. Giddens, Georgia Institute of Technology,
Michael D. Griffin, Johns Hopkins University,
Noel Hinners, Lockheed Martin Astronautics (retired),
John P. Huchra, Harvard-Smithsonian Center for Astrophysics,
Frank B. McDonald, University of Maryland,
Robert J. Serafin, National Center for Atmospheric Research, and
Norman Sleep, Stanford University.

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 Louis J. Lanzerotti, Bell Laboratories, Lucent Technologies, and New Jersey Institute of Technology. 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.

# Contents

# Summary

We live in an extraordinary period of exploration. Over the last few decades, humanity has used space as a vantage point from which to dramatically advance the exploration of our planet, the solar system, and the universe. In this transformative era, our understanding of every aspect of the cosmos has been reshaped as a result of a process driven by science—the desire to gain a fundamental and systematic understanding of the universe around us. Many aspects of exploration share this characteristic and constitute a form of science as well. This synergism establishes an overarching perspective from which to view science as an integral part of NASA's vision for space exploration.

On January 14, 2004, NASA received specific instructions from President George W. Bush to undertake a space exploration program with a clear set of goals, including implementation of "a sustained and affordable human and robotic program to explore the solar system and beyond."[1] We have an opportunity, then, to pursue critical scientific questions that remain just beyond our grasp and to extend the human presence across the solar system and thus become a true space-faring civilization. The opportunities for future discovery are vast, encompassing our home planet Earth, the Moon and Mars and other places in the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond. Indeed, there is an extraordinary richness to the opportunities, but of course also a sobering reality, given the need to consider the limitations of available resources.

The issue thus is not what to pursue ultimately, but rather what to pursue first. Accordingly, the Committee on the Scientific Context for Space Exploration recommends the following *guiding principles*:[2]

- Exploration is a key step in the search for fundamental and systematic understanding of the universe around us. Exploration done properly is a form of science.
- Both robotic[3] spacecraft and human spaceflight should be used to fulfill scientific roles in NASA's mission to explore. When, where, and how they are used should depend on what best serves to advance intellectual understanding of the cosmos and our place in it and to lay the technical and cultural foundations for a space-faring civilization. Robotic exploration of space has produced and will continue to provide paradigm-altering discoveries; human spaceflight now presents a clear opportunity to change our sense of our place in the universe.
- The targets for exploration should include the Earth where we live, the objects of the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond.
- The targets should be those that have the greatest opportunity to advance our understanding of how the universe works, who we are, where we came from, and what is our ultimate destiny.
- Preparation for long-duration human exploration missions should include research to resolve fundamental engineering and science challenges. More than simply development problems, those challenges are multifaceted and will require fundamental discoveries enabled by crosscutting research that spans traditional discipline boundaries.

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[1] *A Renewed Spirit of Discovery, the President's Vision for U.S. Space Exploration*, The White House, January 2004.

[2] These principles share much in common with those recommended in the National Research Council report *Science Management in the Human Exploration of Space* (National Academy Press, Washington, D.C., 1997).

[3] In this report the term "robotic" broadly encompasses all uncrewed space missions, observatories, probes, landers, and the like.

*The appropriate science in a vibrant space program is, therefore, nothing less than that science that will transform our understanding of the universe around us, and will in time transform us into a space-faring civilization that extends the human presence across the solar system.*

NASA has embarked on a strategic planning activity that is built around 13 top-level agency objectives (see Chapter 2). The committee has reviewed the objectives, particularly those relating to science, and finds them to be comprehensive and appropriate. They have the potential to encompass all of the scientific topics that should be pursued under NASA's broad mission statement, which in turn is supported by the recent policy directives governing NASA. However, to be thorough and effective, strategic planning will require much forethought and the involvement of a diverse scientific community, because many of the scientific and technological challenges cut across several of the agency's objectives.

The breadth of NASA's top-level strategic objectives is an important strength. The topics do not distinguish between science and human exploration but rather reflect the recognition that each objective offers the opportunity both to advance and to benefit from understanding of the universe in which we live, and each is a worthy endeavor in a robust space exploration program. The committee believes that exploration, in the broad sense defined in this report, is the proper goal for NASA.

**The committee recommends that, as planning roadmaps are developed to pursue NASA's objectives and as priorities are set among them, decisions be based on the potential for making the greatest impact and that the strategic roadmaps do the following:**

- **Emphasize the critical scientific or technical breakthroughs that are possible, and in some cases necessary, and**
- **Highlight how a vibrant space program can be achieved by selecting from an array of approaches to realizing potential breakthroughs across the full spectrum of goals embodied in NASA's mission statement.**

For many years priorities for space science research have been developed and recommended through decadal surveys conducted under the auspices of the National Research Council (NRC). These studies use a consensus process to identify the most important, potentially revolutionary science that should be undertaken within the span of a decade, and numerous mission and program concepts that do not meet this standard are not pursued. In that sense NASA's science program currently is and always has been planned with the intent to generate the paradigm-altering science that NASA should undertake.

The committee considered how NRC science strategies and other reports can contribute to NASA's strategic planning process, and it makes the following recommendations:

- The most recent NRC decadal surveys for the fields of astronomy and astrophysics, solar system exploration, solar and space physics, and the interface between fundamental physics and cosmology do provide appropriate guidance regarding the science that is critical for the next decade of space exploration. **The committee recommends that these reports—*Astronomy and Astrophysics in the New Millennium* (2000), *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2002), *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2002), and *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (2003)—be used as the primary scientific starting points to guide the development of NASA's strategic roadmaps that include these areas.**
- Other highly relevant, discipline-specific NRC studies provide guidance for prioritizing critically important biomedical and microgravity research that must be conducted to enable human space exploration. **The committee recommends that these reports—*A Strategy for Research in Space Biology and Medicine in the New Century* (1998), *Safe Passage: Astronaut Care for Exploration Missions* (2001), *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences* (2002), *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies* (2000), and *Assessment of***

***Directions in Microgravity and Physical Sciences Research at NASA* (2003)—be used as a starting point for setting priorities for research conducted on the International Space Station so that it directly supports future human exploration missions.**

- Science for enabling long-duration human spaceflight is inherently crosscutting, spans many of the agency's 13 new top-level objectives, and requires input from many fields of science and technology. Thus, no single decadal survey or combination of surveys necessarily can provide the totality of advice needed for the new programs that are anticipated under NASA's vision for exploration. Also, no single scientific or engineering discipline can provide the expertise and knowledge required for optimal solutions to the problems that will be encountered in human space exploration. Therefore, simply redoing the decadal surveys would not provide ideal guidance for defining the science that will enable human space exploration. Instead, the necessarily crosscutting advice should come from interdisciplinary groups of experts rather than from traditional committees that have a single scientific focus. **Therefore the committee recommends that NASA identify scientific and technical areas critical to enabling the human exploration program and that it move quickly to give those areas careful attention in a process that emphasizes crosscutting reviews to reflect their interdisciplinary scope, generates rigorous priority setting like that achieved in the decadal science surveys, and utilizes input from a broad range of expertise in the scientific and technical community.**
- NASA's robotic science program has enjoyed remarkable success, and it provides lessons that are worth applying to the human spaceflight program. **The committee recommends that successful aspects of the robotic science program—especially its emphasis on having a clear strategic plan that is executed so as to build on incremental successes to sustain momentum, use resources efficiently, enforce priorities, and enable future breakthroughs—should be applied in the human spaceflight program.**

New opportunities for research will arise as a result of human space exploration, and other research efforts will facilitate its success, but these two categories of science need to be treated differently. Science that is enabled by human exploration is properly competed directly with "decadal-survey" science[4] and then ranked and prioritized according to the same rigorous criteria. For science to enable human exploration, competitive choices will depend on the criticality of the problem the science addresses and the likelihood that it will resolve the problem. For the former kind of science, understanding is an end in itself. For the latter, understanding is a means to the goal of resolving an identified problem, and the degree of understanding needed depends on the problem at hand.

The presidential policy directive on exploration also provides the context for deciding on the future of the space shuttle and the mission of the International Space Station. NASA is directed to retire the shuttle as soon as the assembly of the ISS is complete, which is assumed to be by 2010, and to focus the use of the ISS on supporting the goals of long-duration, human space exploration. Doing this in the most cost-effective way possible is essential for achieving NASA's goals for robotic and human exploration.

[4] Decadal-survey science is the set of endeavors identified by the science community, via an NRC-organized process described in Chapter 3, as potentially yielding the most important, even revolutionary, science and thus recommended to NASA for emphasis over the coming decade.

# 1
# The Impetus to Explore

*In the winter of 1804-1805, a small band of Americans, two French-Canadian voyageurs, and a Shoshone woman and her baby faced the bitter cold in a camp on the upper Missouri River in what is now the state of North Dakota. They were on the way to the Pacific Ocean—sent on a journey of exploration by President Thomas Jefferson. The explorers survived the winter and pushed on to spectacular success, returning in 1806 with information that transformed the nation's view of itself.*

Although settlers had drifted across the Allegheny Mountains and down the Ohio River Valley after the Revolutionary War, the Lewis and Clark expedition was the first American scientific exploration of the Far West. The bounty of geographic and biological knowledge gathered by the Lewis and Clark expedition of 200 years ago initiated American migrations westward that have shaped the United States for two centuries, a transformative process that is continuing to this day.

Over the last few decades, humanity has used the vantage point of space and the power of robotics to dramatically advance the exploration of our planet, the solar system, and the universe beyond. This also has been a transformative era, because our understanding of every aspect of the cosmos has been profoundly altered. Robotic laboratories have produced evidence for water on Mars and have explored Saturn and its rings and moons in breathtaking detail. New space telescopes have revealed fluctuations in the primeval universe that show the influence of a mysterious form of dark energy; they have discovered that black holes are ubiquitous and have witnessed their birth via intense bursts of gamma rays; and they have begun to reveal the atmospheres of planets in other stellar systems. Other telescopes have revealed details about the surface and the interior of the Sun and have shown how the Sun's magnetic field explodes as solar flares. New robotic plasma physics laboratories have produced images that trace how high-energy particles interact with our magnetosphere and hit Earth. Other remote sensing instruments in space have documented an accelerating decline in arctic sea ice, mapped the circulation of the world's oceans, created quantitative three-dimensional data sets to improve the quality of hurricane forecasting, and created new tools to address a host of agricultural, coastal, and urban resource management problems.

Despite the breadth and magnitude of these revolutionary advances, many fundamental questions remain just beyond our grasp. For the first time in human history, we may be nearing a time when the answers to fundamental questions about life—such as, Are we alone? Where did we come from? What is our destiny?—may be within our reach. So also may be the answers to such equally fundamental cosmological questions as, Where did the universe come from? What is its destiny? Is there only one universe?

## ELEMENTS IN A VIBRANT APPROACH TO EXPLORATION

What approach to exploration will now serve the nation well? The issue of how to proceed in space exploration following the Columbia accident was the subject of an NRC workshop on national space policy held in November 2003.[1] In contrast to the dramatic strides in understanding made in recent decades as a result of the robotic science program, progress in human space exploration has been limited, with astronauts confined to low Earth orbit, circling Earth without a clear long-range direction for further exploration. The principal theme of the workshop was that the human spaceflight program needed clearly

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

articulated long-range goals for human exploration and a step-by-step program to meet such goals. It emphasized that it was essential to recognize the importance of humans in exploration and to break the bounds of low-Earth orbit and once again have humans venture forth into the solar system.

**In agreement with views expressed at the workshop, the committee believes that aspects of the robotic science program's planning and execution are applicable to the human spaceflight program, and the committee recommends that successful aspects of the robotic science program—especially its emphasis on having a clear strategic plan that is executed so as to build on incremental successes to sustain momentum, use resources efficiently, enforce priorities, and enable future breakthroughs—should be applied in the human spaceflight program.**

Workshop participants also argued that human space exploration conducted synergistically with robotic exploration would produce the best possible overall space program. There also was recognition that success in this new type of venture would require a cultural change in the organization and management of NASA itself.

In discussing the rationale for sending humans into space, the NRC workshop participants noted that the old issues tied to Cold War competition with the Soviet Union have been superseded by more complex dimensions of global technological competition, and today the reasons emerge from an innate human desire to know—to learn, to extend our grasp with technology, to move civilization forward. We do so by exploring, and we choose the means that are most appropriate. In some cases, we can achieve our exploration goals through robotic missions that conduct in situ sampling or telescopic observations. In other cases, the human presence and human expertise and experience are necessary.

On January 14, 2004, NASA received specific instructions from President George W. Bush to undertake a space exploration program with a clear set of goals, including "[implementation of] a sustained and affordable human and robotic program to explore the solar system and beyond" and "[extension of] the human presence across the solar system, starting with a human return to the Moon in preparation for human exploration of Mars and other destinations."[2] Thus the president's new vision for space exploration shares many of the characteristics defined independently in the November 2003 NRC space policy workshop. A statement in the president's speech accompanying his announcement particularly resonates with the views of workshop participants: "This is a journey, not a race." That principle recognizes that reorienting the human spaceflight program toward exploration goals is a pivotal step in the inevitable march of humankind into space.[3] It also emphasizes the risk and inefficiency of artificial deadlines, and it supports the "go as you pay" principle enunciated in the 2003 workshop.

## EXPLORATION AND SCIENCE

In considering the various opportunities available in the context of a reinvigorated human exploration program, the committee concluded that expansion of the frontiers of human spaceflight and the robotic study of the broader universe can be complementary approaches to a larger goal. The robotic exploration of space has led to and will continue to provide paradigm-altering discoveries: Understanding the dark energy that powers the universe as well as the Sun's role in influencing Earth's climate, for

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[2] *A Renewed Spirit of Discovery, the President's Vision for U.S. Space Exploration*, The White House, January 2004.

[3] Analyzing roles for humans in space exploration was not part of the committee's charge, but the value of human exploration is a premise that the committee accepts. That subject has been addressed in the NRC report *Scientific Opportunities in the Human Exploration of Space* (National Academy Press, Washington, D.C., 1994). Specific examples of past benefits from astronauts' flexibility and capacity to evaluate complex situations and adapt to unexpected situations are documented in *Where No Man Has Gone Before, A History of the Apollo Lunar Exploration Missions* (by William David Compton, The NASA History Series, NASA SP-4214, NASA, Washington, D.C., 1989) and in *Assessment of Options for Extending the Lifetime of the Hubble Space Telescope* (National Academies Press, Washington, D.C., 2004).

example, will expand the horizons of our knowledge in profound ways. Human spaceflight also presents a clear opportunity to change our sense of our place in the universe. It surely will be a transformative event to place humans on Mars.

The science conducted through the robotic exploration of space and human spaceflight to the Moon and Mars are synergistic enterprises. Both are worthy of inclusion in a robust space program that serves the aspirations of our civilization, and both enhance U.S. leadership in science and technology. Indeed, human exploration and science are united in their purpose to understand the universe in which we live as well as to improve life here on Earth.

The committee also recognized that major advances in understanding will be required to send humans forth on long-duration spaceflight beyond Earth. For example, we do not know with confidence today how to sustain humans in microgravity and how to protect them from the effects of space radiation for long periods. Nor do we know how sound the scientific basis is for the systems needed to support long-duration human spaceflight and remote operations to reliably put humans into space. The behavior of fluids in microgravity will require special attention; the reliability and predictability of materials exposed for long periods to the conditions of space must be investigated; both the medical and the psychological issues related to humans engaging in long-duration spaceflight need to be better understood; and countermeasures for the effects of exposure to radiation and reduced gravity will have to be developed. These essential tasks pose new engineering and science challenges that require fundamental discoveries through basic research across multiple traditional disciplines.

*The appropriate science in a vibrant space program is, therefore, nothing less than that science that will transform our understanding of the universe around us, and will in time transform us into a space-faring civilization that extends the human presence across the solar system.*

This viewpoint is captured well in NASA's mission statement as articulated in its 2003 strategic plan:[4]

> "To understand and protect our home planet,
> To explore the universe and search for life,
> To inspire the next generation of explorers,
> . . . as only NASA can."

NASA's mission has its foundation in the Space Act that created NASA, and in other more recent national policy directives.

The committee believes that this is a bold and appropriate agenda. The opportunities for discovery are vast. They encompass the Earth on which we dwell, the Moon and Mars and other places in the solar system where humans might be able to visit, the broader solar system including the Sun that we probe with robotic spacecraft missions, and the vast universe beyond that is reachable only via telescopes. Indeed, there is an extraordinary richness to the opportunities, although not all can be actively pursued given the resources available.

The issue then is not what to pursue ultimately, but rather what to pursue first, and then how to prioritize what follows. The standard for deciding what science to select can be set by recalling the motivation for pursuing space exploration. We do so to ensure that we will continue to advance our intellectual understanding of the cosmos, including our place in it, and will continue our development as a civilization for which human spaceflight becomes routine and inevitable. The array of choices can include plans for missions and enabling science that will not be achieved for decades or longer, but it also needs to include programs from which major achievements can be expected in the nearer term. What is selected must include the essential enabling science that not only will make long-duration human space exploration possible but also will provide the basis and rationale for future space exploration. The results

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[4] NASA, *National Aeronautics and Space Administration 2003 Strategic Plan*, NP-2003-01-298-HQ, NASA, Washington, D.C., 2003.

of such enabling science must be available and current so as to support timely engineering and programmatic decisions that will allow humans to go into space with the greatest assurance of success at the minimum possible risk.

# 2
# Planning at NASA

## NASA'S CURRENT SCIENCE PROGRAM

NASA's current space and Earth science programs are the result of a strategic planning process that has been honed over many years. Scientific and programmatic priorities are developed by expert committees convened under the auspices of the National Research Council (NRC), reported on in NRC studies, and then translated by NASA's roadmapping teams into integrated implementation plans supportive of the agency's mission. In their most comprehensive form, these NRC studies have strived to identify the potentially most revolutionary science activities in a specific scientific discipline that should be undertaken within a decade.[1] Through this process explicit priorities are set, and numerous mission and program concepts assessed as not meeting the standard for producing potentially transformational science are eliminated. In that sense, NASA's current science program does provide and has always existed to provide the paradigm-altering science consonant with NASA's purpose, as it pursues the opportunities to explore and in doing so to transform our understanding of the cosmos.

The committee welcomes the addition of appropriate strategic goals for human spaceflight. These goals for human exploration build upon and expand the strategic goals that have determined NASA's Earth and space science program to date. The adoption of new human spaceflight goals for the exploration of space beyond low Earth orbit now requires that near-term efforts be expanded to emphasize the research that is necessary to make long-term human spaceflight a reality. The current NASA mission statement covers all of the appropriate goals—to understand and protect our home planet and to explore the universe. Clarifying the role that humans will play in this enterprise, as stated by President Bush, adds an exciting dimension to the undertaking. The reinvigoration of the human space exploration program makes NASA complete, in that all of its primary space activities, including the synergistic use of robotic spacecraft and human explorers, will contribute to an integrated whole devoted to increasing our understanding of Earth and the universe and to building the foundation for further exploration.

## NASA'S NEW MAJOR OBJECTIVES

To implement its new exploration goals, NASA has embarked on a strategic planning activity organized around the following 13 top-level agency objectives:[2]

1. *Robotic and Human Lunar Exploration*. Robotic and human exploration of the Moon to further science and to enable sustained human and robotic exploration of Mars and other destinations.*
2. *Robotic and Human Exploration of Mars*. Exploration of Mars, including 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; human expeditions to Mars after acquiring adequate knowledge about the planet using these robotic missions and after successfully demonstrating sustained human exploration missions to the Moon.*

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[1] These studies, often referred to as decadal strategy surveys, are described in more detail in Chapter 3, and the science activities recommended in them are listed in Appendix A.

[2] Available at <http://www.hq.nasa.gov/office/apio/roadmap_committees.htm>.

3. *Solar System Exploration*. Robotic exploration across the solar system to search for evidence of life, to understand the history of the solar system, to search for resources, and to support human exploration.*

4. *Search for Earth-Like Planets*. Search for Earth-like planets and habitable environments around other stars using advanced telescopes.*

5. *Exploration Transportation System.* Develop a new launch system and crew exploration vehicle to provide transportation to and beyond low Earth orbit.

6. *International Space Station*. Complete assembly of the International Space Station and focus research to support space exploration goals, with emphasis on understanding how the space environment affects human health and capabilities, and developing countermeasures.*

7. *Space Shuttle*. Return the space shuttle to flight, complete assembly of the International Space Station, and safely transition from the space shuttle to a new exploration transportation system.*

8. *Universe Exploration*. Explore the universe to understand its origin, structure, evolution, and destiny.*

9. *Earth Science and Applications from Space*. Research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems.*

10. *Sun-Solar System Connection*. Explore the Sun-Earth system to understand the Sun and its effects on the Earth, the solar system, and the space environmental conditions that will be experienced by human explorers.

11. *Aeronautical Technologies*. Advance aeronautical technologies to meet the challenges of next-generation systems in aviation, for civilian and scientific purposes, in our atmosphere and in the atmospheres of other worlds.

12. *Education*. Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the nation's scientific and technological capabilities.

13. *Nuclear Systems*. Utilize nuclear systems for the advancement of space science and exploration.

Eight of these objectives have a scientific component and are so noted (*). NASA officials have indicated that strategic roadmaps will be developed that will outline the agency's plans for accomplishing each of these objectives.

The committee reviewed the 13 NASA strategic objectives, particularly those relating to science, and finds them to be comprehensive and appropriate. They have the potential to cover all of the scientific goals identified by the science community that should be pursued under NASA's broad mission statement, which in turn is supported by the recent policy directives governing NASA. However, the committee recognized that the real challenge will be to develop an appropriate mechanism to integrate these different efforts and, where appropriate, to develop interdisciplinary programs in support of a sustainable and affordable space exploration endeavor.

## PLANNING FOR SCIENCE SELECTION

The breadth of NASA's strategic objectives is an important strength. The topics do not distinguish between science and human exploration. Rather, they recognize that each topic offers the opportunity to advance, and to benefit from, understanding of the universe in which we live, and each is a worthy endeavor in a strong space exploration program. **Therefore the committee recommends that, as**

**planning roadmaps are developed to pursue NASA's objectives and as priorities are set among them, decisions be based on the potential for making the greatest impact and that the strategic roadmaps do the following:**

- **Emphasize the critical scientific or technical breakthroughs that are possible, and in some cases necessary, and**
- **Highlight how a vibrant space program can be achieved by selecting from an array of approaches to realizing potential breakthroughs across the full spectrum of goals embodied in NASA's mission statement.**

As programs are developed to fulfill the objectives and generate results, NASA will have to periodically ask whether they are

- Altering our basic understanding of the cosmos,
- Changing our perceptions of our place in the universe, and/or
- Advancing our future as a space-faring civilization.

There are many examples of significant breakthroughs in the history of NASA. Surely, the Apollo program's landing of a human on the Moon was revolutionary and transformational. So was the Voyager mission to the outer planets, which revealed new and unanticipated worlds; the Hubble Space Telescope, which observes the wonders of the distant universe; and the Earth Observing System missions, which reveal the fantastic complexity of global-scale environmental connectivities on our home planet. Lesser-known programs have also made dramatic advances, such as the collection of missions that have revealed the complexity of Earth's magnetosphere or the dynamic behavior of the Sun, the results of which are crucial to successful human habitation of space beyond low Earth orbit.

For both human and robotic programs, the basic standard of achievement and impact is whether a program will lead to a fundamentally different understanding or perspective. For future missions or programs it is imperative to prioritize based on which will provide the greatest return. If a new mission or program is to proceed it must demonstrate the potential for, and likelihood of, a transformative outcome, through a more comprehensive approach, increased measurement resolution and sensitivity, or the opportunity to visit or observe some unique new location. The argument needs to be realistic and compelling because available resources always will limit the number of programs that can be supported.

There will be some science programs that *enable* human exploration and its transformative results and others that in themselves will *transform* our understanding of the cosmos. These programs will compete with each other for resources, and it will be difficult to select among them. In this competition it is important to insist that "enabling" science must be truly enabling—that is, necessary to solve a critical problem in the exploration program. Such problem-focused research must be subjected to regular reviews that are as open, rigorous, and selective as those conducted to assess proposals for transformative science (e.g., the decadal surveys). In most cases enabling science is broadly multidisciplinary, which calls for review by groups with expertise in diverse specializations—a requirement necessary not only to ensure an appropriate review but also to guard against the possibility that purely disciplinary reviews will have an inappropriately narrow focus on critical problems. To ensure that the research and the reviews stay focused on the problems that need to be solved, it will be important for representatives of organizations that identified the operational requirements and/or that will have to deliver operational systems to participate in the reviews.

Based on the preceding discussions, the committee recommends the following *guiding principles*:[3]

[3] These principles share much in common with those recommended in the National Research Council report *Science Management in the Human Exploration of Space* (National Academy Press, Washington, D.C., 1997).

- Exploration is a key step in the search for fundamental and systematic understanding of the universe around us. Exploration done properly is a form of science.
- Both robotic spacecraft and human spaceflight should be used to fulfill scientific roles in NASA's mission to explore. When, where, and how they are used should depend on what best serves to advance intellectual understanding of the cosmos and our place in it and to lay the technical and cultural foundations for a space-faring civilization. Robotic exploration of space has produced and will continue to provide paradigm-altering discoveries; human spaceflight now presents a clear opportunity to change our sense of our place in the universe.
- The targets for exploration should include the Earth where we live, the objects of the solar system where humans may be able to visit, the broader solar system including the Sun, and the vast universe beyond.
- The targets should be those that have the greatest opportunity to advance our understanding of how the universe works, who we are, where we came from, and what is our ultimate destiny.
- Preparation for long-duration human exploration missions should include research to resolve fundamental engineering and science challenges. More than simply development problems, those challenges are multifaceted and will require fundamental discoveries enabled by crosscutting research that spans traditional discipline boundaries.

## INTERNATIONAL COLLABORATION

An important aspect of the roadmapping process for fulfilling NASA's new major objectives will involve international activities. Many of the roadmaps will be more effective if they are developed in collaboration with the parallel similar efforts being conducted by space programs throughout the world. There exists already a rich history of successful international collaborations—a foundation worth strengthening, expanding, and building upon. In the committee's view, it is the whole of humankind that pushes out the boundaries of the known universe, and it is therefore essential to encourage international collaborators.

## SPACE SHUTTLE AND THE INTERNATIONAL SPACE STATION

One of the important ideas at the 2003 NRC space policy workshop[4] was the need for an exit strategy for the space shuttle and the International Space Station (ISS), including the need for a focused mission for the ISS. The workshop recognized that human exploration could provide the context for deciding on the future of the shuttle and the mission of the ISS.[5] In the January 2004 presidential policy directive on exploration, NASA is told to retire the shuttle as soon as the assembly of the ISS is complete, which is assumed to be by 2010,[6] and to focus the research conducted on the ISS on supporting the space exploration goals. Indeed, in the FY2005 presidential budget request for NASA, it was argued that the

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

[5] Several NRC reports have addressed the implications of focusing ISS research on support of space exploration. For example, see *A Strategy for Research in Space Biology and Medicine into the Next Century* (1998), *Review of NASA's Biomedical Research Program* (2000), *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences* (2002), and *Assessment of Directions in Microgravity and Physical Sciences Research at NASA* (2003), all NRC reports published by the National Academies Press, Washington, D.C.

[6] The policy guidance is ambiguous with respect to what should happen if ISS assembly is not completed by 2010. There exists a range of options on the matter that must ultimately be decided before exploration beyond low Earth orbit can reasonably commence.

human exploration program is affordable because the shuttle will be retired and the operations of the ISS will be refocused on identifying and solving problems associated with long-duration human spaceflight missions.

The importance of retiring the shuttle and focusing ISS research in the most cost-effective way cannot be overemphasized. Concerns with costs underscore the need for a compelling plan for the science that can be accomplished only with the ISS. NASA's goals to continue exploration of the universe through its robotic science missions, and now to move forward with human exploration, will require expanded resources. It is difficult to imagine a budget for NASA that will allow it both to accommodate its past and to pursue its future. The committee believes that the burdens of NASA's past that do not support the future should be eliminated as soon as possible.

# 3
# Relevance of the Decadal Strategies and Related Reports

In 1960, astronomers in the United States first undertook the task of developing consensus strategies that spanned the full range of interests of the discipline and that recommended explicit programmatic priorities for the field.[1] That community has revisited the effort every decade thereafter, with its most recent work reported in *Astronomy and Astrophysics in the New Millennium* (NRC, 2000). Each of these efforts has surveyed the status of the field and has taken a long-term look at the most compelling directions for the field over the coming decade. This thorough planning process, now commonly known as the preparation of decadal surveys, has been applied recently to the field of solar system exploration and to solar and space physics as well, with the results presented in *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC, 2002) and *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (NRC, 2002), respectively.[2] A decadal survey for Earth science and applications from space, now being conducted by an NRC committee to develop long-range goals and priorities for the field, is expected to be published in 2006. In addition to the decadal surveys noted above, the recent report *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (NRC, 2003) assesses long-range scientific directions for research at the interface between fundamental physics and astrophysics.[3]

Several attributes of the decadal-survey process are important for this discussion:

1. The decadal-survey process is inclusive, engaging many members of the relevant science community in open discussions and thereby building a broad consensus across that community. The scientists engaged in these discussions will be the users of data generated in research programs selected for future implementation.
2. The decadal-survey process defines a short list of critical scientific questions or goals that should guide research and that, if addressed successfully, would have major impacts on progress in the field. That is, the surveys have identified the most notable opportunities for achieving transformational or paradigm-altering advances—opportunities that therefore should be considered in setting priorities for future research.
3. The decadal-survey process develops priorities for future investments in research facilities, space missions, and/or supporting programs. These consensus priorities are explicit, and the surveys rank competing opportunities and ideas, clearly indicate which ones are of higher or lower priority in terms of the timing, risk, and cost of their implementation, and make the difficult adverse decisions about other meritorious ideas that cannot be accommodated within realistically available resources.

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[1] Their work was reported in *Ground-based Astronomy: A Ten-Year Program* (NRC, 1964). All of the National Research Council reports cited in this chapter were published by the National Academy (later Academies) Press, Washington, D.C., in the year indicated.

[2] The surveys for the decades of the 1970s, 1980s, and 1990s were *Astronomy and Astrophysics for the 1970's* (1972), *Astronomy and Astrophysics for the 1980's. Volume I: Report of the Astronomy Survey Committee* (1982), and *The Decade of Discovery in Astronomy and Astrophysics* (1991), respectively.

[3] This report, which complements the astronomy and astrophysics decadal survey, differs from a full decadal survey in the eyes of the scientific community in that it stops short of recommending specific mission and ground-based research facilities, but its treatment of science priorities is at the same level as in the other surveys.

## DECADAL AND OTHER STRATEGIES

To illustrate the role of the decadal surveys in identifying the top-priority scientific questions for the future,[4] the committee points out that *Astronomy and Astrophysics for the New Millennium* lists a set of five major scientific objectives to be addressed in the first decade of the 21st century. These include, "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," and "understand the formation and evolution of black holes of all sizes" (p. 3). *New Frontiers in the Solar System* presents 12 key scientific questions that fit within four crosscutting themes. The questions include, How did the impactor flux decay in the early solar system, and how did this affect the timing of life's emergence on Earth? What planetary processes generate and sustain habitable worlds, and where are the habitable zones in the solar system?, and, What hazards do solar system objects present to Earth's biosphere? (p. 3).

In a similar manner, the priorities presented in the solar and space physics survey, *The Sun to the Earth—and Beyond*, were narrowed to eight scientific questions, including, "What is the nature of the interstellar medium, and how does the heliosphere interact with it?" and "How does Earth's global space environment respond to solar variations?" (p. 2). Likewise, *Connecting Quarks with the Cosmos* posed 11 fundamental questions, including, "What is dark matter? What is the nature of dark energy?" and, "How did the universe begin?" (p. 2).

In setting priorities among an array of recommended missions, the capacity to address these kinds of questions was an explicit criterion. For example, the judgments on the scientific merit of competing mission concepts reflected in *New Frontiers in the Solar System* were made on the basis of how missions could provide new knowledge as measured by application of the following criteria:

- Will answering the scientific question create or change an existing scientific paradigm?
- Might the new knowledge gained strongly direct future research?
- Will the new knowledge gained substantially strengthen understanding?

Consequently, the committee concludes that the most recent NRC decadal surveys for the fields of astronomy and astrophysics, solar system exploration, solar and space physics, and the interface between fundamental physics and cosmology remain valid in the context of NASA's new exploration vision because they do identify the critical science questions to be addressed in the next decade of space exploration. **The committee recommends that these reports—*Astronomy and Astrophysics in the New Millennium* (2000), *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2002), *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2002), and *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (2003)—be used as the primary scientific starting points to guide the development of NASA's strategic roadmaps that include these areas.**

In addition, the first-of-its-kind decadal survey-style study for Earth sciences and applications from space mentioned above represents a fresh opportunity to look forward as the era of the Earth Observing System program comes to an end and to consider the implications of NASA's exploration vision for NASA's Earth science program. Prior to the completion of that study there will also be an opportunity to apply the criteria listed above as NASA prepares its roadmap for research to understand the Earth system.

Several other reports are particularly relevant for the critical scientific goals and priorities for research that must be conducted to enable human exploration. In the life sciences, the conclusions and

[4] The complete sets of major scientific questions posed in the surveys are presented in Appendix A.

recommendations presented in *A Strategy for Research in Space Biology and Medicine in the New Century* (NRC, 1998)[5] remain valid today. That report surveyed the current state of research on the physiological and psychosocial responses of humans to spaceflight and identified the highest-priority questions that require attention to improve the feasibility of extended-duration human spaceflight missions. Priority areas included "research aimed at understanding and ameliorating problems that may limit astronauts' ability to survive and/or function during prolonged spaceflight" (p. 2) and crosscutting research on musculoskeletal and vestibular physiology, radiation hazards, psychological and social issues, and plant and animal sensitivity to gravity.

Finally, but equally importantly, two key studies are available that provide timely guidance about the major research issues for physical science research in reduced gravity. *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies* (NRC, 2000) addresses critical aspects of research to enable development of technologies that will be needed for the human exploration of space. This topic was also a key element of the study *Assessment of Directions in Microgravity and Physical Sciences Research at NASA* (NRC, 2003), which prioritized areas of microgravity research in terms of their strategic importance with respect to NASA's long-term capability to pursue human space exploration. Both reports cited the need for enabling research in areas such as combustion and fire safety, multiphase flow and heat transfer, interfacial phenomena, and indirect effects of reduced gravity.

Consequently, the committee concludes that already-published National Research Council studies provide highly relevant discipline-specific guidance for prioritizing critically important research that must be conducted to enable the human exploration of space. **The committee recommends that these reports—*A Strategy for Research in Space Biology and Medicine in the New Century* (1998), *Safe Passage: Astronaut Care for Exploration Missions* (2001), *Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences* (2002), *Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies* (2000), and *Assessment of Directions in Microgravity and Physical Sciences Research at NASA* (2003)—be used as a starting point for setting priorities for research conducted on the International Space Station so that it directly supports future human exploration missions.**

## PRIORITY SETTING IN THE CONTEXT OF HUMAN EXPLORATION

In NASA's new exploration vision, the relevance of the studies cited above must be judged in the light of the presence of humans in space. The studies for astronomy and astrophysics, fundamental physics and cosmology, solar system exploration, and solar and space physics were prepared before the vision for space exploration appeared and were conducted without regard to scientific opportunities provided by human exploration beyond low Earth orbit. For example, they do not address what scientific research is required before sending explorers far from Earth, nor do they consider either the new opportunities for research made possible by human exploration or the potential incompatibilities of already-identified research with human missions. Given these new perspectives, some individual research discipline communities have begun to consider whether current priorities should be reexamined. The answers to questions about potential reassessments of priorities are likely to vary from discipline to discipline. For example, the committee does not find any compelling arguments for changing the priorities for the period 2000-2010 set forth in *Astronomy and Astrophysics in the New Millennium*; a forthcoming report of the NRC is expected to address the question in more detail.[6]

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[5] See also National Research Council, *Review of NASA's Biomedical Research Program* (NRC, 2000) and *Safe Passage: Astronaut Care for Exploration Missions* (NRC, 2001).

[6] "Progress in Astronomy and Astrophysics Toward the Decadal Vision," letter report, in preparation.

In the case of solar and space physics there is now an expanded rationale for using the tools and knowledge from that discipline to understand, predict, and mitigate the exposure of human explorers to harmful space radiation. Aspects of the fundamental science needed to understand the problem of space radiation were addressed in a special report that concluded that the priorities recommended in *The Sun to the Earth—and Beyond* (NRC, 2002) remained timely and appropriate and that there was no reason to change the recommended near-term mission sequence.[7] However, a specific mission set required to develop the capability to predict the space radiation environment through which humans will fly will have to be dealt with as an aspect of crosscutting studies of enabling science called for below.

It is instructive to ask how scientific priorities for exploration of the Moon and Mars might change in view of the plans to send humans to these bodies in the next few decades. Whereas scientific activities enabled directly by the presence of astronauts on the Moon or Mars are not an immediate consideration in terms of the current solar system exploration decadal planning horizon (2013), an active human exploration program will have an indirect but important impact. For example, technologies developed to support a human return to the Moon in 2020 (e.g., heavy-lift launch vehicles or nuclear power sources) could make it possible to conduct desired robotic exploration that in the most recent decadal survey was deferred beyond 2020 because the relevant technology was not available. Similarly, scientific activities undertaken by astronauts on the Moon (e.g., resolution of issues surrounding the terminal phase of accretion of material left over from the formation of the solar system) might bring into focus new scientific questions to be addressed by robotic activities conducted on Mars long before humans first set foot on the Red Planet. Finally, it is conceivable that attention to human exploration will create an imperative for additional studies of terrestrial analogs of lunar or martian environments. Thus, the likely impact of a human exploration program on solar system exploration priorities will be complex and multifaceted. In the short term there is a need to conduct a crosscutting study to define the necessary enabling activities for, and to scope the likely impacts of, the human exploration program on the scientific priorities for the robotic exploration of the Moon, Mars, and Earth, and possibly even Venus.

Although efforts will have to be made to seek out new areas of research that are specifically enabled by human space exploration, or that can facilitate its success, these two categories of science will need to be treated differently. Science that is enabled by human exploration is properly competed directly with "decadal-survey" science and evaluated and prioritized according to the same rigorous criteria. Science to enable human exploration must compete on the basis of the criticality of the problem it addresses (not necessarily a science issue) and the likelihood that it will resolve the problem. Put another way, for the former kind of science, greater understanding is an end in itself, and science that seeks to contribute to such understanding must compete in this metric with decadal-survey science. For the latter science, understanding is a means to the end of resolving a particular problem, and the degree of understanding needed depends on the problem. For example, in the life sciences area, past NRC studies have recognized the need to precisely define the specific risks faced by astronauts exposed to radiation hazards and microgravity. Additional fundamental research on basic cellular and physiological mechanisms is required; the knowledge needed will not be gained in a focused engineering and development program alone. Development of clinical countermeasures to protect human explorers is currently constrained by the lack of access to critical astronaut data, as well as a paucity of data due to the small numbers of humans who have flown for extended periods in space. All of these problems will require much greater focus in the future if long-duration human spaceflight is to become a reality.

Another essential consideration is that science to enable human exploration is inherently crosscutting, involving insights from many fields of science and technology. All of the decadal surveys and other studies cited above were, by design, discipline-based. That is, they provide scientific strategies for a particular field or set of related disciplines. This approach to setting scientific goals for breakthroughs in individual fields is effective, and the current reports remain timely and relevant today in their respective areas. However, NASA's new vision for exploration opens up novel and previously

[7] *Solar and Space Physics and Its Role in Space Exploration* (NRC, 2004).

unexplored issues whose nature can best be illustrated by the question, How, and by whom, is the decision to be made that we have acquired the necessary relevant medical, scientific, and technological knowledge needed before we actually send humans to Mars? No single decadal survey or combination of surveys provides the type of advice needed for the new programs that are anticipated under the new vision for exploration. Also, no single scientific or engineering discipline can provide the expertise and knowledge necessary to optimally solve these problems. Therefore, a reexamination of the decadal surveys would not provide ideal guidance for enabling science. Instead, crosscutting advice needs to come from cross-disciplinary groups of experts representing diverse scientific fields rather than from the traditional single-discipline survey committees.

Such crosscutting studies will identify fundamental, problem-oriented research in a number of key areas of enabling science. For example, understanding and mitigating the deleterious effects of space radiation on both astronauts and operational systems is a complex, multifaceted problem. Progress in countering the harmful effects of different space radiation environments will have to draw on advances in solar and space physics, radiation monitoring, risk assessment, materials science, biomedical science, medical systems engineering, space systems design, and more; it also may be facilitated by the use of robotic "guinea pigs" rather than human subjects. A piecemeal approach to planning research and setting priorities under the guidance of individual scientific disciplines is unlikely to produce robust, reliable solutions.

Other examples of crosscutting problems for which interdisciplinary planning will be appropriate are the assessment of measures needed to counter the physiological effects of partial gravity on humans in spaceflight, techniques for life detection on planetary bodies, approaches to prevent and/or control the cross-contamination of Mars by human missions, and the design of self-sustained habitats. This list is not meant to be definitive or all-inclusive, but rather to illustrate the point. Importantly, these interdisciplinary challenges, by definition, encompass more than one of NASA's new 13 roadmap areas (see Chapter 2), and so NASA will have to take special care to foster and advance these efforts.

Finally, all enabling science, regardless of whether the topics fall within a particular disciplinary area or are broadly crosscutting, should be evaluated and planned with the same scientific rigor, openness, and thoughtful prioritization that have characterized the decadal surveys, and should be executed according to a process that provides for incremental successes to sustain momentum, use resources efficiently, enforce priorities, and enable future breakthroughs. In many cases, paralleling the decadal-survey approach in which the users of information participate in setting priorities for obtaining it, it would be appropriate to have representatives of organizations that put forward operational requirements and/or will have to deliver operational systems participate in the evaluation of enabling science.

**Therefore the committee recommends that NASA identify scientific and technical areas critical to enabling the human exploration program and that it move quickly to give those areas careful attention in a process that emphasizes crosscutting reviews to reflect their interdisciplinary scope, generates rigorous priority setting like that achieved in the decadal science surveys, and utilizes input from a broad range of expertise in the scientific and technical community.**

# Appendixes

# A
# Major Scientific Questions Defined by the Decadal Survey Reports

## ASTRONOMY AND ASTROPHYSICS[1]

*Defining questions for astronomy and astrophysics:*

How were the universe and its constituent galaxies, stars, and planets formed?
How did they evolve?
What will their destiny be?

*Strategy to achieve that goal:*

Survey the universe and its constituents (galaxies and their evolution, stars in formation stage, interstellar and intergalactic matter, dark matter and dark energy).
Use the universe as a unique laboratory for understanding physics.
Search for life beyond Earth and, if it is found, determine its nature and distribution.
Develop a conceptual framework accounting for all observations made.

*Key problems ripe for advance in this decade:*

Determine large-scale properties of the universe: its age, the nature (amount and distribution) of the matter and energy that make it up, 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 and planetary systems, and the birth and evolution of giant and terrestrial planets.
Understand how the astronomical environment affects Earth.

## THE UNIVERSE AND THE NATURE OF MATTER, SPACE, AND TIME[2]

1. What is the dark matter?
2. What is the nature of the dark energy?
3. How did the universe begin?
4. Did Einstein have the last word on gravity?
5. What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
6. How do cosmic accelerators work and what are they accelerating?
7. Are protons unstable?
8. Are there new states of matter at exceedingly high density and temperature?
9. Are there additional space-time dimensions?
10. How were the elements from iron to uranium made?
11. Is a new theory of matter and light needed at the highest energies?

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[1] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2000.

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

## SOLAR SYSTEM EXPLORATION[3]

*First Billion Years of Solar System History (planet formation/emergence of life)*

What processes marked the initial stages of planet and satellite formation?
What was the nature of Jupiter's formation, and how different was it from that of Neptune, Uranus, and Saturn?
How did the impactor flux decay in the early solar system, and how did this affect the timing of the emergence of life on Earth?

*Volatiles and Organics: The Stuff of Life (organic materials, water, etc.)*

What is the history of volatile compounds, especially water, in the solar system?
What is the nature of organic material in the solar system and how has it evolved?
What global mechanisms affect the evolution of volatiles on planets?

*The Origin and Evolution of Habitable Worlds*

What planetary processes generate and sustain habitable worlds, and where are the habitable zones in the solar system?
Does (or did) life exist beyond Earth?
Why have the terrestrial planets differed so dramatically in their evolution?
What hazards do solar system objects present to Earth's biosphere?

*Processes: How Planets Work*

How do processes that shape the character of planets operate and interact?
What does the solar system tell us about the development of extrasolar planetary systems, and vice versa?

## SOLAR AND SPACE PHYSICS[4]

1. *Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona.* Why does solar activity vary in a regular 11-year cycle? Why is the solar corona several thousand times hotter than its underlying visible surface, and how is the supersonic solar wind produced?

2. *Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium.* What is the nature of the interstellar medium, and how does the heliosphere interact with it? How do energetic solar events propagate through the heliosphere?

3. *Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.* How does Earth's global space environment respond to solar variations? What are the roles of planetary ionospheres, planetary rotation, and internal

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[3] National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, National Academy Press, Washington, D.C., 2002.

[4] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, National Academy Press, Washington, D.C., 2002.

plasma sources in the transfer of energy among planetary ionospheres and magnetospheres and the solar wind?

4. *Understanding the basic physical principles manifest in processes observed in solar and space plasmas.* How is magnetic field energy converted to heat and particle kinetic energy in magnetic reconnection events?

5. *Developing near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere.* What is the probability of occurrence of specific types of space weather phenomena over periods from hours to days?

# B
# Committee Member and Staff Biographies

## COMMITTEE MEMBERS

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 is an active researcher in both theoretical and experimental studies of the solar atmosphere and its expansion into space to form the heliosphere. 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 professor of physics and vice president for research and financial affairs at the University of New Hampshire. He is a member of the National Academy of Sciences and is chair of the National Research Council's (NRC) Space Studies Board (SSB).

DANIEL N. BAKER is director of the Laboratory for Atmospheric and Space Physics and a professor of astrophysical and planetary sciences at the University of Colorado. His primary research interest is the study of plasma physical and energetic particle phenomena in the planetary magnetospheres and in Earth's magnetosphere. He was a member of the staff at Los Alamos National Laboratory and leader of its Space Plasma Physics Group, and he was chief of the Laboratory for Extraterrestrial Physics at the NASA Goddard Space Flight Center. He is a current member of the SSB and chair of its Committee on Solar and Space Physics, and he is a former member of the NRC Committee on Solar and Space Physics: A Community Assessment and Strategy for the Future.

ANA P. BARROS is a professor of civil and environmental engineering at Duke University.  Her primary research interests are in hydrology and environmental fluid dynamics with a focus on water-cycle processes in the coupled land-atmosphere-biosphere environment and the study of multiscale interface phenomena in complex systems across the Earth sciences.  She is a member of the SSB.

RETA F. BEEBE is a research professor in the Astronomy Department at New Mexico State University, Las Cruces.  Her research activities involve the study of the atmospheres of Jupiter and Saturn, and in particular, studies of cloud motions and evolution in Jupiter's atmosphere.  She is the author of several books and articles concerning telescopic observations of the giant planets, including *Jupiter: The Giant Planet*.  She serves on the SSB and chairs its Committee on Planetary and Lunar Exploration. She chaired the Solar System Exploration Survey Panel on Giant Planets.

ROGER D. BLANDFORD is the 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 participated in the last two astronomy and astrophysics decadal surveys and was a member of the Committee on the Physics of the Universe, which produced the NRC report *Connecting Quarks with the Cosmos*.  He currently co-chairs the NRC Committee on Astronomy and Astrophysics and serves on the SSB.  He is a fellow of both the Royal Astronomical Society and the Royal Society and is a member of the American Academy of Arts and Sciences.

RADFORD BYERLY, JR., is a senior fellow in the Center for Science and Technology Policy Research, University of Colorado.  Formerly he worked at the National Institute of Standards and Technology (then the National Bureau of Standards) in the environmental measurement and fire research programs, 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 currently a member of the SSB. He served as rapporteur for the NRC workshop report on space policy that was published in early 2004.

DONALD E. INGBER is the Judah Folkman Professor of Vascular Biology in the Department of Pathology at Harvard Medical School and the Departments of Pathology and Surgery at 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. Although trained in cell biology and medicine, he has integrated approaches from molecular biology, engineering, chemistry, microfabrication, nanotechnology, and computer science to define how cells sense and respond to mechanical forces. He is a member of the SSB.

RALPH H. JACOBSON, a retired USAF Major General, is President Emeritus, the Charles Stark Draper Laboratory. General Jacobson is a distinguished military officer who has served in many capacities in the USAF. He worked in the Office of the Deputy Chief of Staff for Research, Development and Acquisition at Air Force headquarters, initially as assistant deputy chief of staff for space shuttle development and operations. Subsequently, he was named director of space systems and command, control, and communications. He later served as assistant vice commander of the Space Division, Los Angeles Air Force Station, California. After retiring from the USAF, General Jacobson became president of Draper Labs.

TAMARA E. JERNIGAN is principal deputy associate director of the Physics and Advanced Technologies Directorate at Lawrence Livermore National Laboratory. She is a veteran of five space shuttle missions, having supervised the pre-flight planning and in-flight execution of critical activities aboard five shuttle flights, including serving as mission specialist on the first dedicated life sciences mission, STS-40, and as payload commander of STS-67. Formerly she served as deputy chief of the astronaut office and as deputy to the chief of the Astronaut Office for the Space Station.

MARGARET G. KIVELSON is Distinguished Professor of Space Physics in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics at UCLA. Her principal scientific interests are the magnetospheric plasma physics of Earth and Jupiter and the interaction of flowing plasmas with planets and moons. She is a member of the National Academy of Sciences, the American Academy of Arts and Sciences, and the SSB. She was a participant in the first decadal survey in solar and space physics, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, and is a former member of the Committee on Solar and Space Physics and of the NRC Commission on Physical Sciences, Mathematics, and Applications.

LAURIE LESHIN is the Dee and John Whiteman Dean's Distinguished Professor of Geological Sciences and director of the Center for Meteorite Studies at Arizona State University. She is a cosmochemist whose research focuses on understanding the formation and evolution of Earth's solar system and its planets. She studies the water content of meteorites in an effort to understand the occurrence of water on Earth and how water on Mars could affect the possibility of life there. She was a member of the 2004 President's Commission on Implementation of United States Space Exploration Policy.

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. She is an active investigator in the laboratory, as well as in the clinical setting, and directs a large basic and clinical research group in vascular biology and hypertension. She is a member of the Institute of Medicine and is a current member of the SSB. She has served as president of the American Federation of Clinical Research and the American Heart Association.

GEORGE A. PAULIKAS retired after 37 years at The Aerospace Corporation, having joined Aerospace in 1961 as a member of the technical staff and later becoming department head, laboratory director, vice president, senior vice president, and executive vice president. He has been at the forefront of advances in space science and space systems, making many technical contributions to the development of national security space systems. He is a current member of the SSB and serves as its vice-chair.

RONALD F. PROBSTEIN is Ford Professor of Engineering, Emeritus, at the Massachusetts Institute of Technology. His research has centered on applications of fluid mechanics, both theoretical and experimental, to numerous areas of technical, scientific, economic, or societal importance, including hypersonic flows, rarefied gas dynamics, reentry physics, dust comets, desalination, physicochemical hydrodynamics, synthetic fuels, electrokinetic soil remediation, and slurry rheology. He is a member of the National Academy of Engineering, the National Academy of Sciences, and the American Academy of Arts and Sciences. He is a current member of the SSB, and he previously served on the NRC Committee on Microgravity Research.

DENNIS W. READEY is the Herman F. Coors Distinguished Professor of Ceramic Engineering and director of the Colorado Center for Advanced Ceramics at the Colorado Center for Advanced Ceramics. His current research interests include the properties of ceramics, processing and properties of ceramic-metal composites, combustion synthesis in reactive atmospheres, and the effect of gravity on gas/solid reactions. He has held research positions at Argonne National Laboratory, Raytheon Company, the U.S. Energy Research and Development Administration, and Ohio State University. He is a current member of the SSB.

EDWARD C. STONE is the David Morrisroe Professor of Physics at the California Institute of Technology and former director of the Jet Propulsion Laboratory (1991-2001). Since 1972, he has been the project scientist for the Voyager mission, coordinating the scientific study of Jupiter, Saturn, Uranus, and Neptune and Voyager's continuing exploration of the outer heliosphere and search for the edge of interstellar space. His research has focused on studying galactic cosmic rays, solar energetic particles, and planetary magnetospheres. He is president of the International Academy of Astronautics and is a vice president of COSPAR. He is a member of the National Academy of Sciences, and he formerly served on the NRC Commission on Physical Sciences, Mathematics, and Resources and on the Space Studies Board.

HARVEY D. TANANBAUM is director of the Smithsonian Astrophysical Observatory's Chandra X-ray Center, where he is responsible for overseeing of the operation of the Chandra X-ray Observatory and providing support to the scientific users of the observatory. In 1981 he became associate director for high energy astrophysics at the Harvard-Smithsonian Center for Astrophysics, a position he held for 12 years. He is a current member of the SSB, and he previously served on the NRC Committee on the Physics of the Universe.

J. CRAIG WHEELER is the Samuel T. and Fern Yanagisawa Regents Professor of Astronomy at the University of Texas at Austin and past chair of the department. His research interests include supernovae, black holes, and astrobiology. He has published more than 300 scientific papers, a recent popular book on supernovae and gamma-ray bursts, and a novel, and he has edited five books. He has served as chair of the High-Energy Astrophysics Division of the American Astronomical Society and vice-president of the AAS. He is currently a member of the SSB and co-chair of its Committee on the Origins and Evolution of Life.

A. THOMAS YOUNG is retired executive vice president of Lockheed Martin. He previously was president and chief operating officer 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. He is a former member of the NASA Advisory Council and chaired its International Space Station Management and Cost Evaluation Task Force. He is a member of the National Academy of Engineering, a current member of the SSB, and a former member of the NRC Committee on a New Science Strategy for Solar System Exploration.

## STAFF

JOSEPH K. ALEXANDER is director of the Space Studies Board. He served previously as deputy assistant administrator for science in the Environmental Protection Agency'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. Mr. Alexander's own research work has been in radio astronomy and space physics. He received his B.S. and M.A. degrees in physics from the College of William and Mary.

DAVID H. SMITH joined the staff of the Space Studies Board in 1991. He is the senior staff officer and study director for a variety of NRC activities, including the Committee on Planetary and Lunar Exploration and the Committee on the Origins and Evolution of Life. He received a B.Sc. in mathematical physics from the University of Liverpool in 1976 and a D.Phil. in theoretical astrophysics from Sussex University in 1981. Following a postdoctoral fellowship at Queen Mary College, University (1980-1982) he held the position of associate editor and, later, technical editor of *Sky and Telescope*. Immediately prior to joining the staff of the Space Studies Board, Dr. Smith was a Knight Science Journalism Fellow at the Massachusetts Institute of Technology (1990-1991).

CLAUDETTE K. BAYLOR-FLEMING has worked as a senior program assistant with the NRC's Space Studies Board since 1995, primarily as the program assistant to the director and administrative officer. She came to the NRC in 1988, first serving as senior secretary for the Institute of Medicine's Division of Health Sciences Policy, and then working for 7 years as the administrative/financial assistant for the NRC's Board on Global Change. In 2003, Ms. Baylor-Fleming completed two certificate programs, one at the Catholic University of America in Web technologies and the other at Trinity College of Washington in information technology applications. She is currently pursuing a B.A. in graphic design from American University.

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