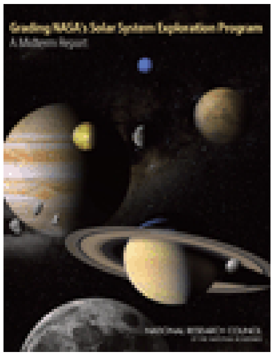

Grading NASA's Solar System Exploration Program: A Midterm Review

Committee on Assessing the Solar System Exploration Program, National Research Council

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Grading NASA's Solar System Exploration Program

A Midterm Report

Committee on Assessing the Solar System Exploration Program

Space Studies Board

Division on Engineering and Physical Sciences

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Preface

In Section 301(a) of the NASA Authorization Act of 2005, the Congress directed NASA to have "[t]he performance of each division in the Science directorate . . . reviewed and assessed by the National Academy of Sciences at 5-year intervals."[1] In late 2006, NASA asked the National Research Council (NRC) to conduct such an assessment for the agency's Planetary Science Division. The statement of task (see Appendix A) for the Committee on Assessing the Solar System Exploration Program was to review the alignment of NASA's Planetary Exploration Division program with previous NRC advice—primarily the reports *New Frontiers in the Solar System: An Integrated Exploration Strategy*[2] and several recent studies concerning Mars, such as *Assessment of Mars Science and Mission Priorities*.[3] *Assessment of Mars Science and Mission Priorities* was in effect a part of the decadal survey, and therefore including it was essentially redundant. However, the committee did include recommendations from *Assessment of NASA's Mars Architecture 2007-2016*, the most recent of three assessment reports on Mars plans and, in the committee's view, the most up-to-date NRC guidance to NASA with respect to these plans.[4] More specifically, the committee addressed the following:

1. The degree to which NASA's current solar system exploration program addresses the strategies, goals, and priorities outlined in Academy reports;
2. NASA progress toward realizing these strategies, goals and priorities; and
3. Any actions that could be taken to optimize the science value of the program in the context of current and forecasted resources available to it.

In the letter from NASA's Associate Administrator for the Science Mission Directorate, the committee was told that "the review should not revisit or alter the scientific priorities or mission recommendations provided in the

[1]The first of these assessments, prepared jointly by the National Research Council's Space Studies Board and Board on Physics and Astronomy, was delivered to NASA in February 2007; it is entitled *A Performance Assessment of NASA's Astrophysics Program* (The National Academies Press, Washington, D.C., 2007).

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

[3]National Research Council, *Assessment of Mars Science and Mission Priorities*, The National Academies Press, Washington, D.C., 2003.

[4]National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.

cited reports, but may provide guidance about implementing the recommended mission portfolio in preparation for the next decadal survey."[5]

The committee held three meetings, in February, March, and May 2007. Because this was a congressionally directed study, the committee also asked relevant congressional staff for input on what kind of report would be most relevant to their work. In addition, committee representatives visited the Johns Hopkins University Applied Physics Laboratory, the NASA Ames Research Center, the NASA Goddard Space Flight Center, and the Jet Propulsion Laboratory to hear from their directors and scientists on their perspectives on this subject.

During the course of the study, NASA revealed plans to make significant changes to the solar system exploration program. Although these will not be implemented until fiscal year 2009 and later, the committee requested additional information from NASA about the agency's planning, particularly with regard to Mars. Those plans are still preliminary, but they were reviewed by the committee.

[5] Colleen Hartman, for Mary Cleave, Associate Administrator for the Science Mission Directorate, to Lennard Fisk, Chair, Space Studies Board, October 31, 2007.

Acknowledgments

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:

Jim Bell, Cornell University,
George R. Carignan, University of Michigan,
Ted A. Maxwell, Smithsonian Institution National Air and Space Museum,
Alfred McEwen, University of Arizona,
Victoria Meadows, University of Washington,
George Pace, Jet Propulsion Laboratory (retired),
Norman H. Sleep, Stanford University,
Ellen Stofan, Proxemy Research,
Fred W. Taylor, University of Oxford,
Mark Thiemens, University of California, San Diego, and
Joseph F. Veverka, Cornell 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 Martha P. Haynes, Cornell University. Appointed by the National Research Council, she 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.

The committee also wishes to thank the directors and staff members of the NASA centers and the Johns Hopkins University Applied Physics Laboratory who met with the committee during several site visits.

Finally, the committee wishes to acknowledge the assistance of NASA Planetary Science Division Director James Green, who provided the committee with significant information required to make this assessment.

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FIGURE S.1 Artist's impression of the Mars Science Laboratory entering the atmosphere of Mars in 2010. SOURCE: Jet Propulsion Laboratory.

Summary

The Committee on Assessing the Solar System Exploration Program has reviewed NASA's progress to date in implementing the recommendations made in the National Research Council's (NRC's) solar system exploration decadal survey covering the period 2003-2013, *New Frontiers in the Solar System*,[1] and in its *Mars Architecture* report, *Assessment of NASA's Mars Architecture 2007-2016*.[2] The committee assessed NASA's progress with respect to each individual recommendation in these two reports, assigning an academic-style grade, explaining the rationale for the grade and trend, and offering recommendations for improvement. The committee generally sought to develop recommendations in cases where it determined that the grade, the trend, or both were worrisome and that the achievement of a decadal survey recommendation would require some kind of corrective action on NASA's part. This usually meant that the committee sought to offer a recommendation when the grade was a "C" or lower. However, the committee did offer recommendations in connection with some higher grades when it believed that minor corrective action was possible and desirable. More importantly, the committee did not offer recommendations for some of the activities given lower grades, particularly in the enabling technologies area (Chapter 6), because the committee determined that only the restoration of funding and the development of a strategic technology development program would solve these problems.

The general meanings of the assigned grades are as follows:

A—Achieved or exceeded the goal established in the decadal survey.
B—Partially achieved the decadal goal, or made significant progress.
C—Made some progress toward meeting the decadal goal, or achieved a supporting objective.
D—Made little progress toward meeting the decadal goal.
F—Regressed or made no progress toward meeting the decadal goal.
Withdrawn—Goal or objective dropped.
Incomplete—Unable to make an assessment due to lack of data, inconclusive decision process, or other factors.

[1]National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.
[2]National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.

In addition to a grade for progress to date, for each recommendation in the two NRC reports cited above, the committee assessed the direction of progress:

Trend: ↑ —Improving.
Trend: ↓ —Getting worse.
Trend: ➔ —No change.

The committee's results are organized in five major theme areas: (1) science goals and objectives; (2) flight missions; (3) Mars; (4) research and analysis (R&A), planetary astronomy, and mission data analysis programs; and (5) enabling technologies.

In making its assessments, the committee considered the recommendations of the two reports as essentially sacrosanct and made virtually no allowances for circumstances that might have led to a less than satisfactory grade, although the committee does acknowledge that the decadal survey in particular was limited in its ability to adequately predict the cost and complexity of some missions (such as Venus in situ measurements and comet sample return). The committee did consider, in remarking on the rationale for the grade and in recommending remedial measures, what these circumstances might have been. Because this is a "midterm" assessment of progress for the decade 2003-2013, NASA still has the ability to improve these grades significantly before the next decadal survey is produced. However, the committee also notes that the situation could get considerably worse, and the current overall trend (see the section below) is alarming.

Although this report mentions a number of proposed but not yet funded missions—some of which are currently under evaluation by NASA—the committee is not endorsing specific mission proposals, especially when those proposals are being made in the competitive evaluation process that NASA uses for its Discovery, Mars Scout, and New Frontiers programs.

In the formal letter from NASA to the NRC's Space Studies Board requesting this study, NASA asked for recommendations not only for NASA itself, but also for the next decadal survey starting in 2008 (and expected to last 2 years). The committee notes that during its own study, NASA undertook four studies of possible flagship missions: to Europa, Titan, the Jupiter system (focusing on Ganymede), and Saturn's moon Enceladus. Such studies are vital to the decadal survey process and help establish a baseline of mission options for future solar system exploration plans. The committee encourages NASA to conduct such future studies. The committee also encourages NASA to allow more time and to provide more resources in support of mission concept development and cost estimation for the next decadal survey. These surveys achieve their maximum utility when informed by credible cost estimates for all potential missions, not just those in the flagship category.

OVERALL SUMMARY FOR SOLAR SYSTEM EXPLORATION

The committee's overall assessment with respect to NASA's solar system exploration program is as follows:

Grade: B
Trend: ↓

Halfway into the 2003-2013 decade covered by the decadal survey *New Frontiers in the Solar System*, NASA has made significant progress toward implementing the recommendations of the NRC's decadal survey and *Mars Architecture* report. NASA's current planetary exploration program is highly productive, carrying out exciting missions and making fundamental discoveries.

However, the committee awarded a downward trend arrow to the overall planetary exploration program, concluding that current progress is unlikely to continue at the present rate and that *on its current course, NASA will not be able to fulfill the recommendations of the solar system exploration decadal survey*. The reasons for this conclusion include reduced investment in research, data analysis, technology development, and smaller mission programs, coupled with increasing mission costs, overruns on approved flight projects, and spiraling costs for launch vehicles. The committee weighted these areas more than others and notes that all of these are areas that are required for progress to continue. The trends in these individual areas mean that future progress toward fulfilling the recommendations of the decadal survey is unlikely. NASA has also made insufficient investments in vital infrastructure such as the Deep Space Network. The committee also notes that NASA has failed to start the Europa mission, which was the highest-priority mission recommended by the decadal survey. In addition, NASA has neglected work on the Mars Sample Return mission, particularly technology development. Although the agency indicates that this situation may change, the committee notes that only significant progress can erase skepticism about the prospects in this area.

Yesterday's investments have created a momentum that will carry the solar system exploration program for a few more years before the consequences of today's reductions become apparent. *The future of the nation's solar system exploration program as laid out in the decadal survey for 2003-2013 is in jeopardy unless NASA makes an effort to improve the situation.*

SUMMARY OF MAJOR THEME AREAS

Following is a summary of the committee's assessment of NASA's Planetary Science Division program's key programmatic elements as measured against recommendations made in the decadal survey and the *Mars Architecture* report.

Science Questions **OVERALL ASSESSMENT: Grade: B Trend: ➜**

In many respects, NASA has done a good job of meeting the science goals outlined in the decadal survey. The agency should be commended for this progress. However, there is one disturbing note in this area. Only in the Mars program has there been progress toward the survey recommendation of addressing whether life exists (or did exist) beyond Earth. The Mars program has an integrated strategy for addressing this science goal. However, the funding reductions for astrobiology research and technology development have had serious and very adverse impacts on addressing this goal throughout the solar system exploration program. The science goals in the decadal survey and the committee's assessment of NASA's progress in addressing them to date are summarized in Table S.1.

Flight Missions **OVERALL ASSESSMENT: Grade: B Trend: ↓**

There are some troubling indicators in the flight missions area. The launch rate for missions in all size categories is lower than envisioned in the decadal survey. This is especially true in the Discovery program. This low-cost, community-driven flight program is key to maintaining the pipeline of data returned from the solar system and is essential to the training of new mission scientists and students, ongoing efforts vital for a thriving solar system exploration community. If NASA approves the start of a Europa flagship mission and also approves two new Discovery missions and a New Frontiers mission, the committee believes that this trend will be reversed. However, the current lack of approval of a Europa flagship mission, plus the lack of new Discovery mission opportunities, has led the committee to assess the trend for flight missions as downward at this time. The committee is also concerned about various pressures on future missions, including the increasing costs of launch and the lack of technologies required to accomplish the other missions recommended in the decadal survey.

The committee recognizes that the shortage of funding is the primary reason—although by no means the only reason—that the launch rate in all mission categories is lower than envisioned in the decadal survey. Increasing the launch rate would require more money, which NASA is unlikely to receive. The agency will be forced to make hard choices in this area.[3]

The flight missions, including Mars missions (see the discussion below), recommended in the decadal survey and NASA's progress in implementing them to date are summarized in Table S.2.

[3]The committee notes that the flight rate was also affected by policy and management choices. For instance, the expenditure of significant amounts of money on the Jupiter Icy Moons Orbiter mission, which was canceled because of its high price tag, prevented the effective start of a flagship mission that would have met the recommendation of the decadal survey.

TABLE S.1 Committee Assessment of NASA's Progress over 5 Years (2003-2008) in Meeting Decadal Survey Science Goals

Crosscutting Themes and Key Questions from Decadal Survey[a]	Committee Assessment of Progress: Grade[b]	Trend[c]
The First Billion Years of Solar System History		
1. What processes marked the initial stages of planet and satellite formation?	**B**	↑
2. How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn?	**C**	↑
3. How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?	**B**	→
Volatiles and Organics: The Stuff of Life		
4. What is the history of volatile compounds, especially water, across the solar system?	**A**	↑
5. What is the nature of organic material in the solar system and how has this matter evolved?	**B**	↑
6. What global mechanisms affect the evolution of volatiles on planetary bodies?	**B**	→
The Origin and Evolution of Habitable Worlds		
7. What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in the solar system?	**A**	↓
8. Does (or did) life exist beyond Earth?	**C**	↓
9. Why have the terrestrial planets differed so dramatically in their evolutions?	**A**	↑
10. What hazards do solar system objects present to Earth's biosphere?	**B**	↑
Processes: How Planetary Systems Work		
11. How do the processes that shape the contemporary character of planetary bodies operate and interact?	**B**	↓
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?	**B**	→

[a]The crosscutting themes and key questions are reprinted from National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 3.
[b]Grades: A, Achieved or exceeded the goal established in the decadal survey; B, Partially achieved the decadal goal, or made significant progress; C, Made some progress toward meeting the decadal goal, or achieved a supporting objective; D, Made little progress toward meeting the decadal goal; F, Regressed or made no progress toward meeting the decadal goal; Withdrawn, Goal or objective dropped; Incomplete, Unable to make an assessment due to lack of data, inconclusive decision process, or other factors.
[c]Trends: ↑, Improving; ↓, Getting worse; →, No change.

Mars **OVERALL ASSESSMENT: Grade: A Trend: →**

NASA's Mars Exploration Program (MEP), which was redesigned in 2000, has been highly successful to date and appears on track through the end of the current decade. Both the Mars Science Laboratory (to be launched in 2009) and a 2011 Scout mission that will be selected soon meet the recommendations of the decadal survey. A key element of the success of this program is that it is not a series of isolated missions but rather a highly integrated set of strategically designed missions, each building on the discoveries and technology of the previous missions and fitting into long-term goals to expand the understanding of the planet: whether or not it ever had or does now have life, and how Mars fits into the origin and evolution of terrestrial planets. The strategic scientific thread thus far has been to "Follow the water" on Mars: its history, amount, form, and location. A new thread is emerging: "Follow the carbon," "Follow the organics," or "Find the life," which can only be accomplished if astrobiological instruments and capabilities become available. The committee assesses the Mars Exploration Program for the period 2000-2010 as meriting a grade of A.

However, the recommendations of the decadal survey and other NRC Mars reviews focus on the period out to 2017 and occasionally beyond. For those years, the program has suffered from a lack of technological progress

TABLE S.2 Committee Assessment of NASA's Progress over 5 Years (2003-2008) in the Area of Flight Missions and Implementation

			Committee Assessment of Progress	
Flight Missions	Recommendation[a]	Status	Grade[b]	Trend[c]
"Large" flagship missions				
"Large" flagship missions overall	One per decade	None yet to date.	**D**	→
Europa Explorer	Start Europa mission	Under extensive study, no new start to date.		
"Medium" New Frontiers missions				
"Medium" New Frontiers missions overall	3 or 4 per decade	One launched, one in development, new AO imminent.	**B**	→
Kuiper Belt/Pluto Explorer	Top priority	New Horizons mission launched.	**A**	→
Jupiter Polar Orbiter with Probes	Third priority	JUNO orbiter selected without probes.	**A**	→
South Pole-Aitken Basin Sample Return	Second priority	Option for next AO.	n.a.	n.a.
Comet Surface Sample Return	Fifth priority	Option for next AO.	n.a.	n.a.
Venus In Situ Explorer	Fourth priority	Option for next AO.	n.a.	n.a.
"Small" Discovery missions				
"Small" Discovery missions overall (Full missions and missions of opportunity both determined by competition.)	One launch every 18 months	No full mission selected in 5 years; two missions of opportunity selected.	**D**	→
Mars Exploration Program				
Mars Exploration Program overall			**A**	→
Mars Science Laboratory 2009	Conduct Mars Science Laboratory	In development for 2009.	**B**	→
Mars Science and Telecom Orbiter 2013	Conduct Mars Science Orbiter	Planned for 2013, science still under definition.	**A**	↑
Mars Astrobiology Field Laboratory	Option for 2016	Instrument development required.	**A**	→
Mars Mid-rovers	Option for 2016	Option for 2016.	**A**	→
Mars Long-lived Lander Network	Option for 2016	Option for 2016.	**A**	→
Mars Scouts	One launch every 52 months	Phoenix launch 2007, selection for 2011 imminent.	**A**	↑
Mars Sample Return	Start technology development for Mars Sample Return	Progress spotty on enabling technology and no recent systematic mission planning, but recent signs that this will change.	**C**	↓

NOTE: AO, Announcement of Opportunity; n.a., not applicable.

[a]Recommendations summarized from National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003; and National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.

[b]Grades: A, Achieved or exceeded the goal established in the decadal survey; B, Partially achieved the decadal goal, or made significant progress; C, Made some progress toward meeting the decadal goal, or achieved a supporting objective; D, Made little progress toward meeting the decadal goal; F, Regressed or made no progress toward meeting the decadal goal; Withdrawn, Goal or objective dropped; Incomplete, Unable to make an assessment due to lack of data, inconclusive decision process, or other factors.

[c]Trends: ↑, Improving; ↓, Getting worse; →, No change.

toward a sample return mission, lack of a commitment to a landed network mission, and indecision on the 2016 and 2018 launch opportunities.

As this report was being prepared, NASA presented to the committee new tentative Mars plans that the agency designated the "Ideal Mars Next Decade Campaign."[4] This new mission queue, described in detail in Chapter 4 of the present report, appears to address most of the issues raised in the NRC reports cited, except for the landed network. The "Ideal" plan commits the Mars Exploration Program to a sample return mission "anchored in 2020" (with actual samples being returned some years later) and using the Astrobiology Field Laboratory as the prime sample collection mission. The committee is cautiously optimistic about this approach, while emphasizing that it should be subjected to rigorous community review once it has been further investigated. Extensive community involvement is a major factor in the success of the Mars Exploration Program. The committee believes that major changes in the Mars Exploration Program should not be made if they contradict what is recommended in the decadal survey; such changes would effectively render the entire decadal survey process irrelevant.

The committee was also disappointed to learn that NASA was simultaneously suggesting that Mars missions after the 2011 Scout mission might be abandoned, with only the promise of a Mars Sample Return in 2020 but no clear investment or programmatic path to make it happen. At least some Mars missions during this period would have to be selected by way of the New Frontiers competition, thereby jeopardizing the strategic planning approach that has served the Mars Exploration Program and science community so well.

Research and Analysis, Planetary Astronomy, Flight Mission Data Analysis — **OVERALL ASSESSMENT: Grade: C Trend: ↓**

The committee is deeply concerned with both the grade of C and the downward trend in the area of research and analysis, planetary astronomy, and flight mission data analysis. The grade is driven by falling investment in fundamental science and two failing grades in planetary astronomy. Research and analysis funding is essentially the "seed corn" that helps to define future missions and to carry them out; serious cutbacks in this area have harmed NASA's ability to conduct future solar system exploration. Most importantly, the committee has serious concerns about the current and projected funding levels for the research and analysis program in the Planetary Science Division, with particular concern for astrobiology, resulting in the assessment of a downward trend. The problems in planetary astronomy reflect NASA's lack of participation in the Large Synoptic Survey Telescope and its inattention to the decadal survey recommendation regarding the ability of the James Webb Space Telescope to track moving objects in the solar system.

Enabling Technologies — **OVERALL ASSESSMENT: Grade: D Trend: ↓**

NASA's investment portfolio in technology development at the beginning of the decadal period appeared adequate and well structured to meet the needs projected by the decadal survey. However, severe reductions in funding since that time now pose a serious risk to enabling future flight missions. Of special concern is the lack of investment in aerocapture; optical communications; spacecraft autonomy; advanced avionics; instrument miniaturization; in situ sample gathering, handling, and analysis; autonomous mobility; and ascent vehicles. In reviewing missions under consideration, or even in the active planning stages for the next 5 years and beyond, it is clear that without a considerable, sustained investment in technology development, much of the technical risk of those missions cannot be reduced to levels that would instill confidence about mission success. In addition, NASA is encouraged to proceed to implementation with its plan for upgrading and revamping the Deep Space Network and to work aggressively to deal with the impending crisis in launch vehicles brought on by the planned retirement of the Delta II rocket, the spiraling costs of launch services, and uncertainty about the future availability of appropriately sized launch vehicles for smaller missions.

[4] Doug McCuistion, director, Mars Exploration Program, Planetary Science Division, Science Mission Directorate, NASA, "Mars Exploration Program Update," presentation to the committee, Washington, D.C., August 13, 2007.

RECOMMENDATIONS

NASA has made progress in science and flight missions, but there is a clear threat to meeting the goals outlined in the two NRC reports *New Frontiers in the Solar System* and *Mars Architecture* over the next 5 years. To repeat the committee's primary finding: **On its current course, NASA will not be able to fulfill the recommendations of the *New Frontiers in the Solar System* decadal survey.**

The committee offers the following recommendations toward redressing these problems.

The committee considers its findings to be represented in the grades, trends, and explanations for each subject area. The committee developed recommendations for those subjects that it believed were in particular need of corrective action (or, in some instances, where corrective action could be applied relatively easily). Following is the complete set of committee recommendations presented chapter by chapter. In the respective chapters, these recommendations appear in the context of the full discussion.

In Chapter 2, "Science"

Recommendation: The next solar system exploration decadal survey should address the objectives and merits of a Neptune/Triton mission.

Recommendation: NASA should return funding for the Astrobiology Science and Technology Instrument Development program and the Astrobiology Science and Technology for Exploring Planets program to at least their individual Planetary Instrument Definition and Development levels. However, this should not be accomplished to the detriment of the astrobiology research and analysis program, which has already suffered large cutbacks.

In Chapter 3, "Flight Missions"

Recommendation: To ensure that flagship mission costs do not negatively impact missions in other cost classes, NASA should apply sufficient resources to obtain good cost estimates in the earliest phases and rigorously review mission costs before selection.

Recommendation: NASA should continue studying possible flagship missions to both the inner and the outer planets as input to the next decadal study.

Recommendation: NASA should select a Europa mission concept and secure a new start for the project before 2011.

Recommendation: NASA should increase the rate of selection and launch of New Frontiers missions.

Recommendation: The New Frontiers missions should follow a two-stage development process, starting with (1) an opportunity to submit a proposal for funding for 1 or 2 years to develop mission concepts. This earlier stage would provide for some endorsement of the best ideas so that they can attract industry and NASA center support. Such support, in turn, would (2) allow more concepts to reach a level of maturity required for considering full-scale proposal development.

Recommendation: NASA should select two of the three Discovery missions currently in Phase A studies (if two are sufficiently meritorious to be selectable) and should seek to achieve an 18-month period between selections for the rest of the decade. These steps can help to restore vitality to this important program.

Recommendation: NASA should return to conducting Senior Reviews once every 2 years to improve efficiency.

In Chapter 4, "Mars"

Recommendation: NASA should begin actively planning for Mars Sample Return, including precursor missions that identify and cache well-characterized samples of both geological and biological interest.

Recommendation: NASA should begin consulting various groups such as the Mars Exploration Program Analysis Group and the astrobiology/exobiology research community to assess the current state of the art in laboratory analysis instruments, identify where further development would be beneficial for Mars sample analysis and biosignature detection, and verify that the needed instruments, laboratory facilities, and new researcher training will be made available as part of the sample-handling facility as soon as samples are returned.

Recommendation: NASA should begin robust technology investment aimed at reducing the risk associated with the four major engineering challenges of a successful Mars Sample Return, that is, the definition, design, and development of the following:

1. A Mars sample-receiving facility that can serve to certify the samples as safe for distribution;
2. A sample return vehicle that can provide a high probability of successful sample return to Earth consistent with the guidelines from the NASA planetary protection officer and the Committee on Space Research (COSPAR);
3. Autonomous on-orbit rendezvous and docking capability at Mars for sample transfer and return; and
4. A Mars ascent vehicle that is capable of being transported to Mars, landing, and returning cached samples to Mars orbit.

Recommendation: NASA should take all of the scientific, programmatic, and technical information available and make a decision on a mission queue that includes the 2016 and 2018 Mars launch opportunities.

Recommendation: NASA should seek community review to carefully scrutinize the new Mars architecture and its budget implications in order to ensure that the value of the sample returned is worth the cost to the Mars Exploration Program.

In Chapter 5, "Research and Analysis, Planetary Astronomy, and Flight Mission Data Analysis"

Recommendation: NASA should restore an adequate funding level for astrobiology research, based on consultation with the scientific community, that will lead to the achievement of the goals of the *New Frontiers in the Solar System* decadal survey. NASA should provide a stable and sustainable funding environment that is adequate to ensure the vitality and continued scientific productivity of all its research and analysis programs.

Recommendation: NASA should continue to work to integrate astrobiology more completely into all solar system science disciplines.

Recommendation: NASA should improve the visibility of its Fellowships for Early Career Researchers program and advertise it as a postdoctoral program. NASA should also expand the participating research program areas to include origins of solar systems, as well as all appropriate space mission data analysis programs.

Recommendation: NASA should establish formal contacts with the Large Synoptic Survey Telescope project.

Recommendation: NASA should incorporate into the James Webb Space Telescope as quickly as possible the capability to track moving solar system objects.

Recommendation: NASA Announcements of Opportunity should require each space mission proposal to estimate and budget explicitly for archiving activities.

Recommendation: NASA should consider encouraging principal investigators to offer archival data sets in their initial proposals so that the review panels can assess the desirability of the data sets.

In Chapter 6, "Enabling Technologies"

Recommendation: NASA should develop a strategic plan for technology development and infusion independent of flight programs. In addition, NASA should restore funding to its New Millennium program.

Recommendation: NASA should conduct a study of the trade-offs of the cost versus risk of developing a Ka-band array system to handle the required transmissions (uplink and downlink) and determine whether optical communications are required for data delivery during the 2013-2023 time frame. Prior to the next decadal survey, NASA should present the results of such a study to the science community.

Recommendation: NASA should make an assessment of which technologies will be required for Mars Sample Return and conduct an independent assessment of the analogous technology needs for the Moon, Venus, asteroids, and other targets.

Recommendation: NASA should fund the Small Aperture Receive Array for the Deep Space Network and plan to replace the 70-meter antennas with arrays of small-diameter antennas by 2015.

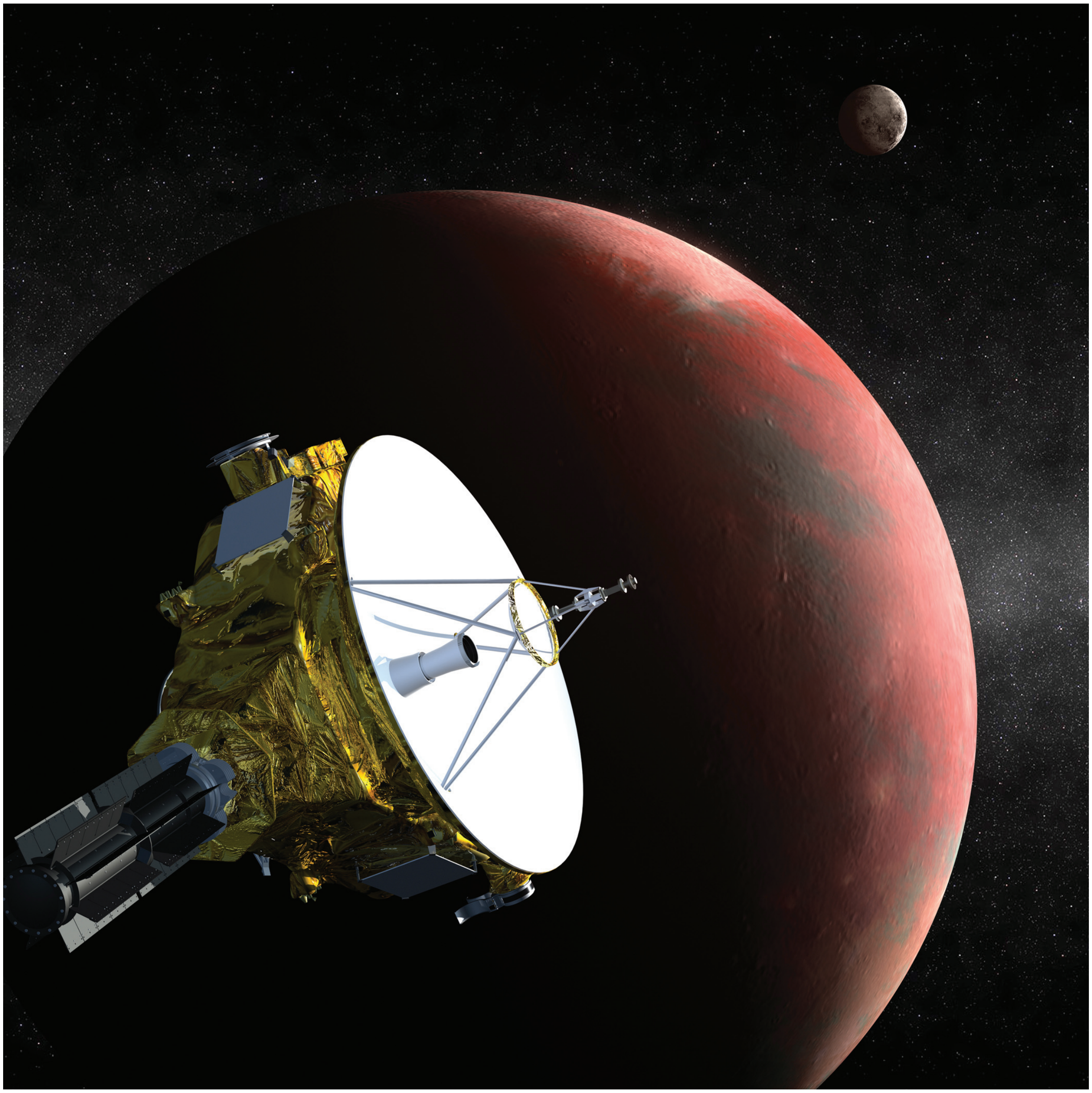

FIGURE 1.1 NASA's New Horizons spacecraft will fly past the outermost planet in the solar system, Pluto, in 2015. SOURCE: NASA.

1

Introduction

The exploration of our solar system using Earth-based tools, robotic spacecraft, and, at times, people has been a human endeavor for hundreds of years. From Galileo's first observations of Jupiter through an early telescope to the Galileo flight mission to Jupiter, solar system exploration has been a rich scientific field encompassing biology, chemistry, geology, physics, meteorology, and many other disciplines.

The solar system exploration community and its principal supporter, NASA's Science Mission Directorate (SMD), have worked together over the years to determine the direction and scientific rationale and goals for both a space-based and a ground-based program of exploration. They have then worked to develop a set of missions to achieve these goals.

In 1994, the National Research Council (NRC) through the Space Studies Board produced a 15-year strategy for solar system exploration, *An Integrated Strategy for the Planetary Sciences: 1995-2010*.[1] Since that report was issued, a number of important developments and changes in circumstances for the program necessitated a new strategy. Adopting the model of decadal surveys used successfully by the astronomy and astrophysics community since the 1960s, NASA requested a decadal survey encompassing all of the elements of solar system exploration, including the major scientific questions to be addressed and recommendations for flight missions and ground-based activities. The result of this effort was the 2003 report *New Frontiers in the Solar System*, generally referred to as the solar system exploration decadal survey.[2] The committee notes that whereas the astronomy and astrophysics community has a long and successful history of decadal surveys, the solar system exploration community is still relatively new to this process and not all community members fully recognize or acknowledge the importance of the decadal survey. The committee stresses that *the solar system decadal survey is the primary process for establishing scientific priorities for the exploration of the solar system*. Only the decadal survey process involves broad-scale community involvement and input and a careful vetting process.

Five years into the decade covered by the survey (2003-2013) and in preparation for the next survey effort, Congress asked NASA to engage the community through the NRC's Space Studies Board in assessing progress toward the scientific and mission goals recommended in the decadal survey and in a similar NRC report on the

[1]National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994.

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

Mars Exploration Program, *Assessment of NASA's Mars Architecture 2007-2016*.[3] This midterm progress report follows a similar assessment completed in early 2007 of the astronomy and astrophysics decadal survey and will be followed by similar efforts in heliophysics and Earth science.[4]

The committee recognizes that the decadal survey represents the first time that the solar system science community has done such a broad community survey to produce a strategic path forward for solar system exploration. It is a positive and welcome development that the committee enthusiastically supports as a way of operating in the future. The committee also recognizes that these "midterm grades" represent an assessment of work in progress. It has endeavored to accumulate evidence and information to back up its performance assessment as well as to provide guidance for future activities in the context of the current decadal survey and in preparation for the next decadal survey, scheduled to start in late 2008.

NASA'S SOLAR SYSTEM EXPLORATION PROGRAM

NASA's Planetary Science Division (PSD) is one of five divisions that make up NASA's Science Mission Directorate. In fiscal year (FY) 2007, SMD had a total budget of $5.251 billion, of which $1.391 billion was allocated to the PSD. Within the $1.391 billion, $626 million, or 45 percent of the budget, was used for Mars exploration. The remaining 55 percent was split among the Discovery ($177 million) and New Frontiers ($156 million) programs, technology development ($72 million), and planetary science research ($275 million).[5] See Figure 1.2 for details on how this money is divided by projects in the FY 2008 budget.

The Planetary Science Division is currently overseeing more than a dozen space-based missions (Table 1.1). These missions are studying the solar system from the inner-most planet Mercury outward to beyond Pluto and the edge of the Kuiper Belt, and almost everywhere in between (see Figures 1.1 and 1.3). The operations are conducted by a fleet of sophisticated robots that orbit, land on, drive over, and even collect samples from planetary bodies.

Mars, unlike the other potential solar system targets, has been treated as a special case and is managed as a "program" in its own right, with a set of high-level science goals that individual missions are expected to address. Each new mission to Mars builds on the science and technology resulting from past missions and is expected to operate in concert with the other spacecraft already at Mars to produce a better understanding of that planet as a *system*. Planetary scientists consider Mars to be the planet in our solar system most similar to Earth and the planet other than Earth that is most likely to have developed life in the past. It is, therefore, a high-priority target.

Only one of the current missions in flight—the initial flight in the New Frontiers program, the New Horizons mission to Pluto and the Kuiper Belt—is the result of a decadal survey recommendation. A second New Frontiers mission, the Juno mission to Jupiter, has been selected for launch in 2011. One mainline Mars mission, the Mars Science Laboratory rover, has been approved, and a down-selection is imminent between two Mars Scout missions, the Great Escape mission and the Mars Atmosphere and Volatile Evolution (MAVEN) mission—both Mars aeronomy (atmosphere science) missions. No new Discovery missions have been selected for flight in the past 5 years, although two small "missions of opportunity" have been approved, EPOXI and Stardust New Exploration of Tempel 1 (NExT), which use spacecraft already in flight that have accomplished their primary missions.[6] The recommended flagship mission, a Europa orbiter, has not been started. All of these current and approved missions address key scientific questions in the decadal survey.

[3]National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.

[4]The first of these assessments, *A Performance Assessment of NASA's Astrophysics Program* (The National Academies Press, Washington, D.C., 2007), prepared jointly by the National Research Council's Space Studies Board and Board on Physics and Astronomy, was delivered to NASA in February 2007.

[5]See http://www.aaas.org/spp/rd/nasa08p.htm#tb.

[6]The acronym EPOXI combines Extrasolar Planet Observations and Characterization (EPOCh) and Deep Impact eXtended Investigation (DIXI). Note added in proof: A new Discovery mission, GRAIL, was selected after this report was completed.

TABLE 1.1 Current (2007) Planetary Science Missions

Mission	Type	Date Launched	Milestones
Cassini	Flagship	October 15, 1997	Saturn arrival: July 1, 2004
Dawn	Discovery	September 27, 2007	Vesta arrival: 2011; Ceres arrival: 2015
Deep Impact	Discovery	January 12, 2005	Tempel 1 impact: July 4, 2005
Mars Exploration Rovers	Mars Scout Mars Scout	June 10, 2003—Spirit July 7, 2003—Opportunity	Land on Mars: January 4, 2004; Land on Mars: January 25, 2004
Mars Express—ASPERA instrument	Mars Scout	June 2, 2003	Mars arrival: December 26, 2003
Mars Odyssey	Mars Scout	April 7, 2001	Mars arrival: October 24, 2001
Mars Reconnaissance Orbiter	Mars Scout	August 12, 2005	Mars arrival: March 2006
Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER)	Discovery	August 3, 2004	Mercury orbital arrival: 2011
New Horizons	New Frontiers	January 19, 2006	Pluto arrival: July 2015
Phoenix	Discovery	August 4, 2007	Mars arrival: May 25, 2008
Stardust	Discovery	February 7, 1999	Sample return: January 15, 2006
Voyager	Flagship	Summer 1977	

NOTE: There are also NASA instruments on the European Space Agency's Venus Express and Japan's Hyabusa spacecraft. ASPERA, Analyzer of Space Plasma and Energetic Atoms.

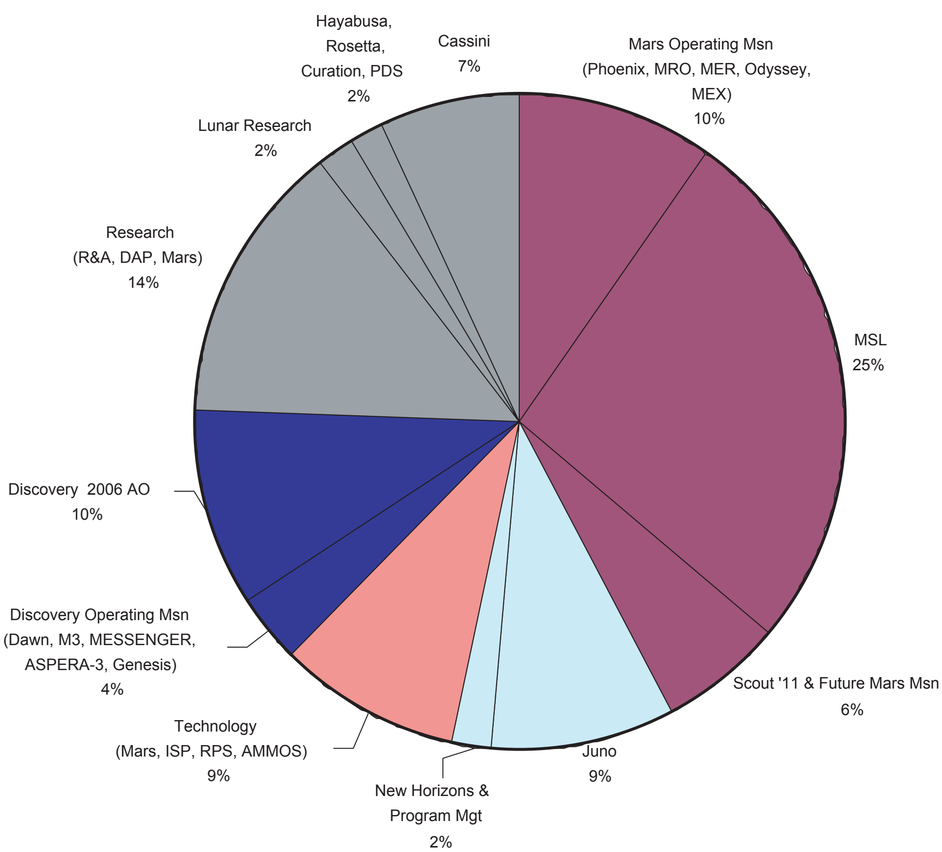

FIGURE 1.2 Breakdown of the NASA Planetary Science Division budget for fiscal year 2008. NOTE: Acronyms are spelled out in Appendix E. SOURCE: Jim Green, director, NASA Planetary Science Division, briefing to the committee, Washington, D.C., February 22, 2007.

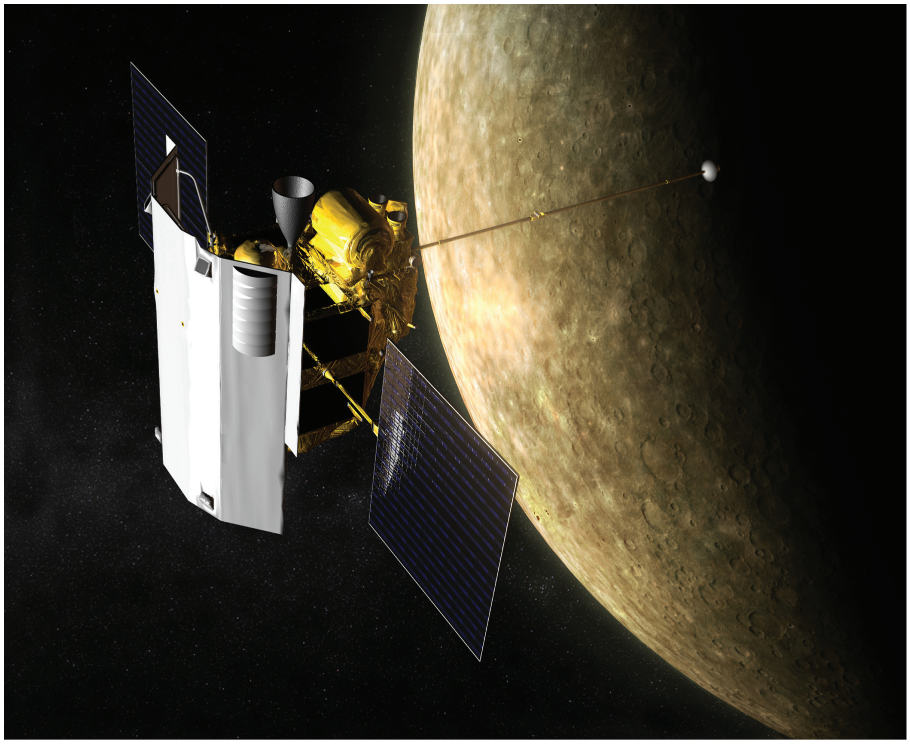

FIGURE 1.3 NASA's MESSENGER spacecraft is due to arrive at Mercury in 2011. SOURCE: NASA.

THE MIDTERM REPORT

To assess the current state of solar system science and exploration, the Committee on Assessing the Solar System Exploration Program examined each of the recommendations in the decadal survey and the *Mars Architecture* report and assigned both a grade and a trend arrow to the NASA effort associated with each. The general meanings of these grades and trend arrows are as follows:

A—Achieved or exceeded the goal established in the decadal survey.
B—Partially achieved the decadal goal, or made significant progress.
C—Made some progress toward meeting the decadal goal, or achieved a supporting objective.
D—Made little progress toward meeting the decadal goal.
F—Regressed or made no progress toward meeting the decadal goal.
Withdrawn—Goal or objective dropped.
Incomplete—Unable to make an assessment due to lack of data, inconclusive decision process, or other factors.

Trend: ↑ —Improving.
Trend: ↓ —Getting worse.
Trend: ➜ —No change.

The recommendations are grouped in five major theme areas: (1) science goals and objectives; (2) flight missions; (3) Mars; (4) research and analysis, planetary astronomy, and flight mission data analysis; and (5) enabling technologies. Each of those areas was given an overall rating and trend arrow (see the section entitled "Summary of Major Theme Areas" in the Summary). In addition, the committee looked at the major scientific questions in the decadal survey and assigned a grade and a trend to the progress made in addressing these questions. All of the results are summarized in Tables S.1 and S.2 in the Summary.

For the most part, NASA has done a very good job so far in implementing the recommendations of the decadal survey and *Mars Architecture* report, but the committee is concerned that further progress will be significantly hampered by several factors, particularly a lack of attention to technology development and research and analysis. Without further investment in technology development in particular, it will not be possible for NASA to achieve many of the goals in the decadal survey.

The more detailed assessments that led to the results in Tables S.1 and S.2 are given in Chapters 2 through 6. The committee also offers recommendations for improvements that NASA can make in order to realize as many of the decadal survey and *Mars Architecture* report recommendations as possible in the remaining time frame addressed in the two reports. In addition, the committee identified four major obstacles (listed below) that stand in the way of the fulfillment of all of the recommendations of the decadal survey by 2013 and of the *Mars Architecture* report by 2016.

MAJOR OBSTACLES TO FULFILLMENT

The major obstacles to fulfillment of the recommendations of the decadal survey by 2013 and of the *Mars Architecture* report by 2016 are these:

1. *The uncertain funding situation and reduced expectations for the next several years.* The overall NASA budget is projected to grow at about 3 percent per year for the next 4 years. However, within that total, the budget for the Science Mission Directorate (within which solar system exploration funding resides) is projected to grow at only 1 percent per year over that same period (a rate that is below inflation and thus equivalent to a greater than 10 percent reduction).[7] Projections are not destiny, but the federal budget picture for the foreseeable future is subject to many compelling competing demands; thus, the potential for even modest increases in space science funding as a whole is unknown. Without a significant addition of funds, the activities envisioned in the decadal survey are probably unachievable.

2. *Larger liens on the overall solar system exploration program caused by the increased mortgages (cost growth) of missions previously approved and initiated.*[8] This cost growth has had the effect of necessitating reduced investments in research and data analysis and in technology development—both of which help to characterize and reduce (or "retire," in agency parlance) risk for future missions as well as bolster the future vitality and productivity of the solar system scientific community.

3. *The underestimated costs for missions proposed in the decadal survey.* This first-ever solar system decadal survey was conducted within a compressed schedule, with insufficient resources invested in mission concept studies and cost estimates. The New Frontiers missions proposed in the report cannot achieve all of the recommended science objectives for the costs estimated. In addition, NASA did not dispute the costs, highlighting the necessity of an iterative process whereby the agency does not simply accept decadal survey recommendations that it later declares unrealistic. It is hoped that this deficiency will be rectified for the next decadal survey.

4. *The increased infrastructure cost to enable the achievement and/or the success of solar system exploration.* The lack of a robust fleet of launch vehicles that is also reasonably affordable has the potential to bring much of the program as currently planned to a halt or to force a radical restructuring both of specific missions and of their scientific goals. The committee could not see a resolution for this issue. The aging and fragile telecommunications infrastructure for deep-space missions needs immediate attention and investment. Taken together, these issues represent a very significant risk to the solar system exploration program's performance in the future.

[7]NASA, *NASA FY 2008 Budget*, Washington, D.C., 2007.

[8]The committee notes that there are unfortunately numerous examples of this, including—but by no means limited to—the Mars Science Laboratory, Juno, and other missions. Although the reasons for this cost growth vary by mission, the end result is the same: insufficient money for new missions and disruptions to the overall program.

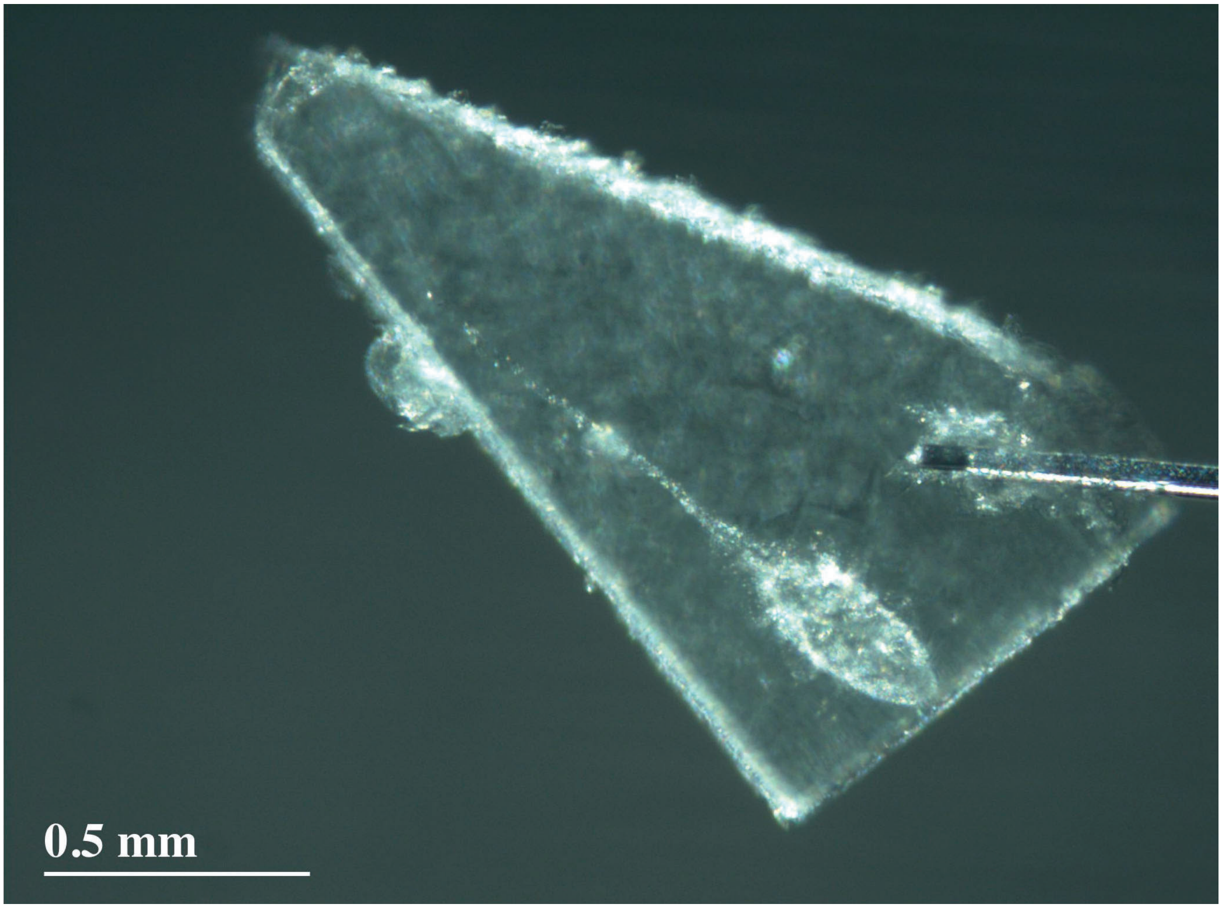

FIGURE 2.1 Analysis of a particle from the Stardust mission. SOURCE: NASA.

2

Science

The National Research Council's (NRC's) decadal survey *New Frontiers in the Solar System* established an ambitious and comprehensive set of science objectives for solar system exploration.[1] In the present midterm review, the Committee on Assessing the Solar System Exploration Program evaluates the progress being made in addressing these objectives, assessing NASA's mission portfolio, concept studies, research and analysis programs, Earth-based observing programs, and supported laboratory science, and the degree to which each has addressed the decadal science objectives. For each science objective, the committee provides a grade based on current progress toward the science objective, along with an indication of the trend in progress foreseen over the remaining 5 years of the period (2003-2013) covered by the decadal survey. (The grades and trends are defined in Chapter 1.)

Science Questions **OVERALL ASSESSMENT: Grade: B Trend: ➜**

Overall, NASA is making impressive progress toward many of the decadal survey science goals, with continued gains foreseen over the next 5 years. NASA's Mars program in particular has been highly successful, with a comprehensive and detailed plan of investigations aimed at high-priority science objectives. Also, tremendous progress has been made in understanding the primitive, nonplanetary bodies in the solar system. The committee gives this area a grade of B.

Despite its evident importance, however, NASA has not significantly addressed the primary goal of astrobiology (life detection), and progress toward other objectives has been slowed by the steep reduction in astrobiology research and analysis funding. Also, although it is beyond the horizon of the decadal survey, the committee notes that there is a large and growing gap between missions to the giant planets once the Juno mission (currently scheduled for launch in 2011) is completed. Because of these reductions, the committee debated assessing the area of meeting the science goals of the decadal survey as having a downward trend, but concluded that "No change" is more appropriate for now.

As presented in Summary Table S.1, the crosscutting themes of the decadal survey form the titles of the sections below, and each key question is shown together with the grade and trend for activity in that arrea as assessed by the committee.

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

THE FIRST BILLION YEARS OF SOLAR SYSTEM HISTORY

***New Frontiers:* Key Question No. 1**	**Results of Midterm Review**	
"What processes marked the initial stages of planet and satellite formation?" (p. 3)	**Grade: B**	**Trend: ↑**

NASA has made significant progress toward answering this question through a series of Discovery missions to comets; the missions include Stardust and Deep Impact (another Discovery mission, CONTOUR, or Comet Nucleus Tour, was lost in 2002). Missions such as Dawn and mission concepts to asteroids will extend the understanding of the parts of the solar system that did not go through the planetary formation process. The Discovery mission of opportunity (MoO) EPOXI and Stardust New Exploration of Tempel 1 (NExT) will extend the utility of existing assets (Deep Impact and Stardust) to provide additional investigations into other small bodies or into surface processes on a recently impacted comet.[2]

Laboratory study of meteoritic material and Earth-based observations of primitive bodies in the solar system and of extrasolar planets and circumstellar nebulae provide constraints on the evolution of solids in the early solar system. The New Frontiers mission line will address this question of the processes marking the initial stages of planet and satellite formation through support of operations of the New Horizons spacecraft on its way to study the composition and dynamics of Pluto (arrival in 2015), and through the Juno mission to study the interior of Jupiter (launch in 2011). Upcoming MESSENGER flybys of Mercury will also add to the understanding of the planet by imaging areas of Mercury that have not yet been seen. Two of the future New Frontiers mission concepts, South Pole-Aitken Basin Sample Return from the Moon and Comet Surface Sample Return (CSSR), would both make major contributions to this objective. Finally, the Lunar Reconnaissance Orbiter (LRO) and Moon Mineralogy Mapper (M3, a Discovery MoO) would make significant observations of the structure and composition of the Moon's surface. NASA's mix of current and future missions has made significant progress toward achieving the goal outlined in the decadal survey and may meet or exceed the objective by the end of the decade (2013).

***New Frontiers:* Key Question No. 2**	**Results of Midterm Review**	
"How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn?" (p. 3)	**Grade: C**	**Trend: ↑**

This is a giant-planet-specific objective requiring missions to these bodies. The ongoing Cassini-Huygens flagship mission has contributed significantly toward the understanding of giant planets, and the approved 2-year extension (while shorter than requested by the decadal survey) will further the understanding of the composition and dynamics of Saturn. The Juno mission will take another important step by investigating the deep interior of Jupiter. The committee notes that all of the flagship missions currently under study are to the giant planets, and it encourages NASA to include characterization of the giant planets themselves in these studies, along with investigation of the satellite targets. Some progress has been made toward understanding Saturn in particular, and Juno will enable a significant advance in the scientific understanding of Jupiter. But the relationship of the gas giants to the ice giants Uranus and Neptune has been left unexplored. The decadal survey identified a Neptune/Triton mission as being of great interest in the next decade, and the committee recommends that the next decadal survey address this mission concept. The flagship mission studies that NASA sponsored in 2006-2007 are highly encouraging, but any such mission is still at least a decade from launch, resulting in a significant (and growing) gap in time after the completion of the Juno mission before the next giant-planet mission can arrive.

Recommendation: The next solar system exploration decadal survey should address the objectives and merits of a Neptune/Triton mission.

[2]The acronym EPOXI combines Extrasolar Planet Observations and Characterization (EPOCh) and Deep Impact eXtended Investigation (DIXI).

New Frontiers: **Key Question No. 3**	**Results of Midterm Review**	
"How did the impactor flux decay during the solar system's youth, and in what way(s) did this decline influence the timing of life's emergence on Earth?" (p. 3)	**Grade: B**	**Trend: →**

NASA is undertaking or studying many missions that will investigate the heavily cratered surfaces of Mercury (MESSENGER), the Moon (M3, LRO), asteroids (Dawn), and certain inactive bodies in the outer solar system (Cassini-Huygens, New Horizons, flagship mission studies) that reveal to varying degrees the early history of the impactor flux across the solar system. Lunar sample return (South Pole-Aitken Basin) will help improve understanding of the history of large impacts on the Moon and the impact process itself; the Moon also constrains the impact history on Earth. Visits to comets (Stardust, Deep Impact, EPOXI, Stardust NExT) and asteroids (Dawn) help characterize surviving members of the impactor population. Earth-based observations of near-Earth objects (NEOs) constrain the present population and provide constraints for theoretical studies of the dynamics and evolution of such populations. The effects of the impact processes on the origin and evolution of life have been investigated through the astrobiology research and analysis program. The mix of present and future missions has resulted in significant progress in characterizing the past and current impactor flux, with much more to be learned in the near future. But progress in understanding the effects of the impactor flux on life is threatened by cuts to astrobiology research and analysis funding. Continued research efforts in astrobiology will be needed to fully understand how impact processes would have influenced the origin of life on Earth.

VOLATILES AND ORGANICS: THE STUFF OF LIFE

New Frontiers: **Key Question No. 4**	**Results of Midterm Review**	
"What is the history of volatile compounds, especially water, across the solar system?" (p. 3)	**Grade: A**	**Trend: ↑**

This objective is addressed very strongly by NASA's mission portfolio for 2003-2013. The Mars program's "Follow the water" strategy has led to a series of ongoing and planned missions (Odyssey, Express, Reconnaissance Orbiter, Exploration Rovers, Mars Science Laboratory, the Phoenix Scout mission, the Analyzer of Space Plasma and Energetic Atoms [ASPERA]-3 Discovery MoO, and studies of the Astrobiology Field Laboratory, Mars Science Orbiter, and Mars Sample Return) investigating the processes that affect water. Missions to comets (Stardust, Deep Impact, EPOXI, NExT), asteroids (Dawn), and primitive bodies (New Horizons) constrain the original distribution of water and other volatiles through the solar system. Investigation of the outer planets and their icy satellites by Juno, Cassini-Huygens, and the flagship missions constrain the evolution of water and other volatiles during giant-planet and satellite formation. Missions to characterize the Venus atmosphere and surface, although currently only under study and not yet funded, can search for the signature of past water on Earth's sister planet. The MESSENGER mission will seek evidence of ice at Mercury's poles, while closer to home, planned lunar missions (M3, LRO) will address the presence of ice at the lunar poles. Earth-based observations of comets and Kuiper Belt objects provide constraints for theoretical models of the distribution and evolution of volatiles in the solar system. NASA has "followed the water" all over the solar system. The result has been a tremendous increase in the understanding of the distribution and evolution of water and other volatiles.

New Frontiers: **Key Question No. 5**	**Results of Midterm Review**	
"What is the nature of organic material in the solar system and how has this matter evolved?" (p. 3)	**Grade: B**	**Trend: ↑**

The NASA mission portfolio is well composed to address this objective. Significant contributions to the understanding of the nature, distribution, and evolution of organic material in the solar system have been and will continue to be made by missions to comets (Stardust, Deep Impact, EPOXI, NExT), asteroids (Dawn), and primitive bodies (New Horizons). Cassini-Huygens has provided valuable new data on the composition and dynamics of Saturn, Titan, and the other Saturnian satellites including active Enceladus. The outer-planet flagship mission studies would also contribute to the understanding of organics in the outer solar system. A Mars mission has possibly detected methane in the martian atmosphere, and future in situ measurements (Mars Science Laboratory and Phoenix) will be made of this and more complex organic compounds. Excellent progress has already been made, and NASA seems poised to make great strides toward and beyond this goal in the near future. However, the committee gives progress toward this recommendation a grade of B because neither Mars's methane nor Titan's organics have been well studied.

***New Frontiers:* Key Question No. 6**	**Results of Midterm Review**	
"What global mechanisms affect the evolution of volatiles on planetary bodies?" (p. 3)	**Grade: B**	**Trend: ➜**

This is a broad goal that seeks to understand the processes that drive the evolution of volatiles on planetary bodies. Past, current, and planned missions are relevant to answering this question. Several missions have visited comets, providing constraints on the sources of planetary volatiles, while Dawn will be visiting an ice-rich asteroid (Ceres). Significant progress has been made in understanding the climate and hydrology of Mars, and the ASPERA-3 instrument and the next Mars Scout selection (Mars Atmosphere and Volatile Evolution [MAVEN] mission or Great Escape) will study the processes of volatile evolution in the martian upper atmosphere. Cassini-Huygens has made great progress in contributing to understanding of the evolution of volatiles on icy satellites, including the astounding discovery of water geysers erupting from Enceladus (see Figure 2.2). MESSENGER will also add to knowledge about volatiles on Mercury. Not yet approved or funded, a mission to study the Venus atmosphere would extend knowledge of processes affecting the evolution of volatiles on terrestrial planets.

THE ORIGIN AND EVOLUTION OF HABITABLE WORLDS

***New Frontiers:* Key Question No. 7**	**Results of Midterm Review**	
"What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in the solar system?" (p. 3)	**Grade: A**	**Trend: ↓**

The Mars program has contributed substantially to answering this question with a comprehensive strategy of orbital, atmospheric, and in situ investigations. Expanding current understanding of the locations of habitable zones requires the study of other parts of the solar system. Cassini-Huygens is making progress toward this objective among the icy satellites of the giant planets. In particular, the Cassini-Huygens exploration of Titan and Enceladus has had an important impact on this question. The exploration of comets (Stardust, Deep Impact, EPOXI, NExT), asteroids (Dawn), and primitive bodies (New Horizons) increases the understanding of the building blocks from which Earth was constructed.

NASA is currently conducting studies of flagship missions to the outer planets that could also contribute to addressing this question if a flagship mission is funded. The study of Venus would provide a compelling contrast to the generation of the habitable planet Earth. Astrobiology research and analysis is also a critical component of this objective, and recent cuts to that program threaten progress. The broad range of current and potential, but not yet approved, future missions addressing this objective meets the goals of the decadal survey for this decade and should continue into the next.

FIGURE 2.2 Saturn's moon Enceladus as viewed by the Cassini spacecraft. Barely visible in this image is the plume of ice particles jetting from the tiny moon's south pole. SOURCE: NASA.

***New Frontiers:* Key Question No. 8**	**Results of Midterm Review**	
"Does (or did) life exist beyond Earth?" (p. 3)	**Grade: C**	**Trend: ↓**

This objective is separated from the habitability objective and is narrowly focused on life and biosignature detection.[3] Of all the missions within the decade 2003-2013, only the Mars Science Lander will attempt to measure biosignatures elsewhere in the solar system, although the Phoenix mission will also address this question through a search for complex organics. Mission studies of two future Mars missions (Astrobiology Field Laboratory and Mars Sample Return) will contribute to addressing this question in the next decade. No measurements elsewhere in the solar system are under study, and the lack of a Europa mission has also had a negative impact on the ability to answer this question. Instrument development for such measurements is essential, but the astrobiology instrument development programs (Astrobiology Science and Technology Instrument Development, or ASTID, and Astrobiology Science and Technology for Exploring Planets, or ASTEP) have experienced decreased funding, with no new selections since 2004. Some development of life and biosignature detection instrumentation has been funded through the Planetary Instrument Definition and Development Program (PIDDP) since then. But decreased funding for ASTID and ASTEP will negatively impact future mission planning and delay progress in the next decade. Although the Mars program has an integrated strategy for achieving this objective at Mars in this decade and the next, there is need for a comprehensive strategy to address this question throughout the solar system.

Recommendation: NASA should return funding for the Astrobiology Science and Technology Instrument Development program and the Astrobiology Science and Technology for Exploring Planets program to at least their individual Planetary Instrument Definition and Development levels. However, this should not be accomplished to the detriment of the astrobiology research and analysis program, which has already suffered large cutbacks.

***New Frontiers:* Key Question No. 9**	**Results of Midterm Review**	
"Why have the terrestrial planets differed so dramatically in their evolutions?" (p. 3)	**Grade: A**	**Trend: ↑**

The Mars program has significantly improved the understanding of that terrestrial planet, and MESSENGER is on its way to greatly increasing our knowledge of the smallest terrestrial planet, leaving Venus as the remaining terrestrial body to be investigated. The strong Mars program and the MESSENGER study of Mercury are the basis for the grade of A and the assessment of an upward trend. There is one Venus mission under study at present; if selected, it will close a gap in the knowledge of the terrestrial planets. A Venus mission is also a possible candidate for the next New Frontiers Announcement of Opportunity. The ASPERA instrument is currently carried on the European Space Agency's Venus Express. If the NASA Venus missions are not funded, it would negatively affect the current trend in the ability to answer this question.

Missions to the Moon (LRO) and the largest asteroids (Dawn) also inform us about processes that were important in the early history of the terrestrial planets. The Mars Long-Lived Lander Network (ML3N) study will address interior processes on that planet in a future decade. Significant progress has been made across the terrestrial planets by current missions, and a number of future missions to address this question are under study. The limited data on Venus must be augmented in order to allow an understanding of the origin and evolution of the terrestrial planets. If one of several Venus missions under study at present is selected, the program would significantly advance such studies.

[3]The terms "biosignatures" and "biomarkers" are used interchangeably throughout this report to refer to evidence of biological activity, past or present.

***New Frontiers:* Key Question No. 10**	**Results of Midterm Review**	
"What hazards do solar system objects present to Earth's biosphere?" (p. 3)	**Grade: B**	**Trend: ↑**

The present hazards posed to Earth's biosphere by solar system objects have been partially characterized by the ongoing NASA Near Earth Object Observing Program (Spaceguard). Additionally, investigations into recent lunar impacts by planned lunar missions (Moon Mineralogy Mapper, LRO) will constrain the impact flux in Earth's neighborhood over the recent past. Many of the missions that address the early history of the impactor flux (the third in this series of science questions) contribute to this objective. Investigation of the effect of impacts on the biosphere has been slowed by the reduced funding for astrobiology research and analysis. But significant progress has been made, and Spaceguard and the planned lunar missions should allow NASA to meet the objective outlined in the decadal survey. This progress is the basis for the committee's assessment of an upward trend.

PROCESSES: HOW PLANETARY SYSTEMS WORK

***New Frontiers:* Key Question No. 11**	**Results of Midterm Review**	
"How do the processes that shape the contemporary character of planetary bodies operate and interact?" (p. 3)	**Grade: B**	**Trend: ↓**

This is an extremely broad science question that extends across the solar system in time and space. NASA's overall mission portfolio, extending from Mercury to Pluto to extrasolar planets and from the solar wind to primitive bodies to giant planets, is well constructed to address this question. The current missions have made significant progress, and the second half of the decade promises many more advances. Nonetheless, the part of this objective related to how processes interact requires comprehensive investigations with multiple mission architectures (for example, orbiters, landers, rovers) building on one another at multiple destinations. The Mars program provides an excellent example for this type of comprehensive investigation, but a solar-system-wide strategy, so vital for such a broad objective, is lacking. NASA's broad array of research and analysis programs is well constructed to address such a broad question, but recent across-the-board funding cuts have affected progress.

***New Frontiers:* Key Question No. 12**	**Results of Midterm Review**	
"What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?" (p. 3)	**Grade: B**	**Trend: →**

The observational campaigns for detecting and characterizing exoplanets have provided a wealth of information and have made great progress toward this objective. Studies of extrasolar planetary systems have determined the distributions of giant-planet masses, orbital periods, and eccentricities. Theoretical analysis of these data is now illuminating the physical processes responsible for these observed distributions of system characteristics. Application of these physical processes to our own solar system is significantly improving the understanding of the early phases of solar system exploration. The collaboration between NASA and the National Science Foundation in this area is encouraging, but the committee notes the absence of a specific research and analysis program for extrasolar planet research. The Kepler Discovery-class mission scheduled for launch in 2008 will directly address this question by studying transiting extrasolar planets; this mission offers great hope for progress in the future. Scientists are making slower progress toward understanding our own planetary system, particularly the giant planets that are most like those which scientists detect around other stars. The committee is also concerned about the future, after the conclusion of the Juno mission in the second half of the next decade. The essential cancellation of the Stellar Interferometry Mission and the indefinite postponement of the Terrestrial Planet Finder are events that prevent the committee from declaring an upward trend in this area.

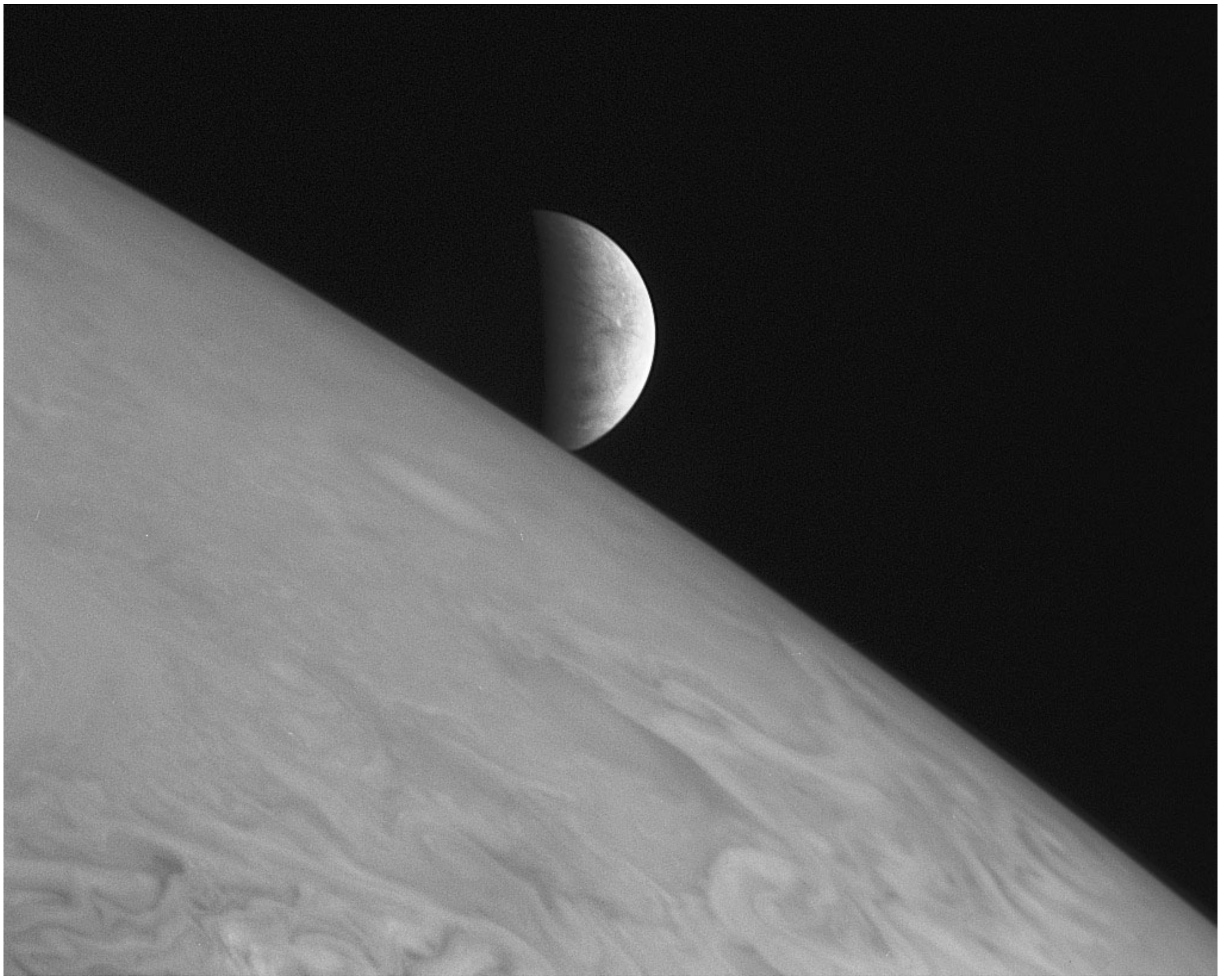

FIGURE 3.1 Europa above the clouds of Jupiter, as imaged by the New Horizons spacecraft. Europa was the top-priority flagship mission for the decadal survey. SOURCE: Jet Propulsion Laboratory.

3

Flight Missions

Some of the major recommendations of the decadal survey *New Frontiers in the Solar System* concern how to select and fly space missions to the planets.[1] The decadal survey makes recommendations for mission classes of different sizes and proposes a list of targets for the largest mission in the flagship and New Frontiers classes.

Flagship missions are the largest, having a cost that was defined in *New Frontiers in the Solar System* as greater than $650 million, but in reality costing more than a billion dollars. The decadal survey recommends a flagship mission to Jupiter's moon Europa as the highest priority. This committee reiterates that recommendation, and commends NASA for studies of other future possible flagship missions now under way. To meet the recommendation in the decadal survey, NASA should start the Europa flagship mission in this decade.

NASA has succeeded in initiating a New Frontiers program of principal-investigator-led, moderate-cost missions. In order to fulfill the decadal survey recommendations, NASA should increase the rate of selection and launch of New Frontiers missions.

The Discovery missions are smaller still, and also competitively selected. Although the flight rate of Discovery missions is less than expected in the decadal survey, these missions provide a valuable contribution to the program of planetary exploration. However, to ensure that the Discovery program continues with appealing, low-cost, and low-risk planetary missions, the next decadal survey should examine closely the rationale, achievements, and direction of the program.

Flight Missions	**OVERALL ASSESSMENT:**	**Grade: B**	**Trend: ↓**

The lack of the start of the Europa flagship mission and new Discovery missions has led the committee to give the flight missions area a grade of B. The committee assessed this area with a downward trend because of the lack of new Discovery opportunities.

The flagship flight missions recommended by the decadal survey for 2003-2013 are listed in Table 3.1.

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

TABLE 3.1 Mission Concepts for 2003-2013 Proposed by the *New Frontiers* Decadal Survey Panels

Mission[a]		Status at Midterm Review
Large, Flagship Missions		
1	Venus Sample Return	No detailed study or study plans
2	Mercury Sample Return	No detailed study or study plans
3	Comet Cryogenic Sample Return	No detailed study or study plans
4	Neptune Orbiter with Probes	Two funded "Vision Mission" studies; no future study plans
5	Saturn Ring Observer	No detailed study or study plans
6	Uranus Orbiter with Probes	No detailed study or study plans
7	Europa Geophysical Explorer	Now undergoing detailed study
8	Europa Lander	Studied as part of Jupiter Icy Moons Orbiter and Europa studies
9	Titan Explorer	Two funded "Vision Mission" studies; now undergoing detailed study in parallel with Europa Geophysical Explorer
10	Neptune Orbiter/Triton Explorer	See (4) above
11	Mars Sample Return	Now entering early study
Medium Missions		
12	Venus In Situ Explorer	In last New Frontiers Announcement of Opportunity
13	South Pole-Aitken Basin Sample Return	In last New Frontiers Announcement of Opportunity
14	Kuiper Belt-Pluto Explorer	Implemented as New Horizons (launched January 2006)
15	Comet Surface Sample Return	In last New Frontiers Announcement of Opportunity
16	Trojan/Centaur Reconnaissance Flyby	No known current studies or plans
17	Asteroid Rover/Sample Return	No known current studies or plans
18	Jupiter Polar Orbiter with Probes	In last New Frontiers Announcement of Opportunity; implemented without probes as Juno (planned launch 2011)
19	Io Observer	No known current studies or plans
20	Ganymede Orbiter	Now undergoing detailed study with (7) and (9) on flagship list (above)

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

In the recommendations quoted below from *New Frontiers in the Solar System*,[2] the Solar System Exploration Survey (SSE Survey) referred to is called simply the decadal survey in the present report. The grade and trend assigned by the Committee on Assessing the Solar System Exploration Program in its midterm review of efforts to address the recommendations appear to the right of the quoted recommendations.

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

***New Frontiers* Recommendations**	**Results of Midterm Review**
"The SSE Survey recommends that flagship (>$650 million) missions be developed and flown at a rate of about one per decade. In addition, for large missions of such inclusive scientific breadth, a broad cross section of the community should be involved in the early planning stages." (pp. 2, 193) "Rather than compete large-class missions with missions in other cost classes, the SSE Survey recommends flying large-class missions at an appropriate frequency (i.e., roughly one per decade), independent of the issues facing new starts in other cost classes." (p. 196)	**Grade: D Trend: ➜**

NASA has not initiated a new flagship mission this decade, resulting in the low grade of D. The agency has tasked four science definition teams to study future flagship mission concepts. The reports of these teams were finished in August 2007 but not publicly released until later. Until NASA actually funds a new flagship mission, the committee cannot assess an upward trend.

In NASA planning, flagship missions are considered separately from missions in lower cost categories, as suggested by the decadal survey. However, budgetary concerns and the long lead time between approval and launch of a flagship mission make it difficult for NASA to support launches once per decade. (The last flagship mission, Cassini, was launched in 1997.) Overruns of large mission budgets inevitably would limit the launch rate and could cause budgetary problems for other parts of the NASA science program.

Recommendation: To ensure that flagship mission costs do not negatively impact missions in other cost classes, NASA should apply sufficient resources to obtain good cost estimates in the earliest phases and rigorously review mission costs before selection.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey recommends that NASA conduct a series of advanced studies of Flagship mission concepts with broad community participation over each 10-year period prior to decadal surveys." (p. 193)	**Grade: B Trend: ➜**

The Outer Planets Analysis Group (OPAG) is providing ongoing community input to NASA planning for future missions. The four science definition team flagship studies conducted from 2006 to 2007 responded to this recommendation.

NASA also needs to consult with the Mars Exploration Program Analysis Group (MEPAG) and the Venus Exploration Analysis Group (VEXAG) on future flagship missions. The current flagship mission studies can be advocated to only 4 of the 10 proposed targets listed in the decadal survey. New missions to Venus and Mercury, listed in the decadal survey, are not being studied at this time, but NASA consultation with appropriate advisory groups is under way, and the committee hopes that this effort proceeds to formal studies.

Recommendation: NASA should continue studying possible flagship missions to both the inner and the outer planets as input to the next decadal study.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey endorses the current recommendations for a mission to orbit Europa. However, given the high cost of the Europa Geophysical Explorer mission, the Survey considers it essential that the mission address both the Group 1 and Group 2 science objectives described by the Europa Orbiter Science Definition Team." (p. 196)	**Grade: D Trend: ➜**

The 2006 Europa Explorer study addresses Group 1 and 2 science objectives articulated in the decadal survey. Although no flagship mission selection has yet been made, the committee believes that after several false starts NASA is now moving forward responsibly toward such a flagship mission selection.

NASA has taken seriously the advice in the decadal survey to develop a flagship mission to Europa. (See Figure 3.1.) For several years, studies of a nuclear-powered spacecraft (Jupiter Icy Moons Orbiter, JIMO) were conducted, but they were ultimately terminated as it became clear that technical problems would be extremely costly to solve. For missions requiring standard propulsion, technological problems are also significant, particularly those arising from the intense radiation environment in which this mission will have to operate. If a lander is required as part of the exploration, significant mass must be provided for propulsion. All of these issues are being investigated by a science definition team (SDT) at this time. Another SDT is examining what can be learned about Europa from flybys and remote sensing using a spacecraft orbiting Jupiter but not Europa. The actions taken by NASA to this point have been very responsive, but the committee notes that the decadal survey recommended *beginning* a flagship mission to Europa, and studies of such a mission are not by themselves responsive.

Recommendation: NASA should select a Europa mission concept and secure a new start for the project before 2011.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey recommends that NASA establish a procedure for reevaluating the candidate list of large-class missions for the decade 2013-2023. Two possible mechanisms for this procedure include (1) the appointment of a Science Definition Team every 3 years to define candidate missions or (2) a periodic competition for funds to support initial definition studies of mission concepts." (p. 196)	**Grade: A** **Trend: ➜**

NASA has tasked four science definition teams to consider some candidate flagship missions. There were 10 "large" missions (in addition to a Mars Sample Return mission) listed in the decadal survey (see Table 3.1). The studies under way cover some of the concepts proposed and some that were not suggested. Such studies are vital to the health of the decadal survey process.

Because of both cost growth and a better understanding of actual mission costs, some of the "medium-class" missions in the decadal survey may now be above the medium cap and thus really of the flagship class. For example, the Mars Science Laboratory was originally a medium-class mission, but NASA now considers it to be a flagship-class mission. See Table 3.1 for a list of medium-class missions proposed by the decadal survey.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey recommends that NASA engage prospective international partners in the planning and implementation of the Europa Geophysical Explorer." (p. 196)	**Grade: C** **Trend: ➜**

NASA conducted a bilateral discussion with the European Space Agency (ESA) in the fall of 2007, which demonstrated good progress toward meeting this objective.

NASA maintains good communication with ESA on planning for outer planet missions. U.S. investigators are being encouraged to participate in proposing a Europa mission for ESA's Cosmic Vision selection. A working group established to consider a joint NASA-ESA mission to Europa concluded that collaboration would be very desirable but that separate U.S. and European spacecraft would be required (because of International Traffic in Arms Regulations [ITAR] restrictions). The bilateral meeting mentioned above shows NASA's continued interest in pursuing international partners.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey recommends that NASA encourage and continue to pursue cooperative programs with other nations." (pp. 2, 156)	**Grade: A Trend: ➜**

NASA has made use of international partners for the Stardust, Cassini, Rosetta, Mars Exploration Rovers (Spirit and Opportunity), Mars Reconnaissance Orbiter, Mars Odyssey, Dawn, Juno, Phoenix, Mars Science Lander, and the ESA's Mars Express, Venus Express, and planned Exo-Mars missions. The committee notes that this cooperation has had significant impact. For instance, the direct sharing of data and knowledge between the European Mars Express mission and the U.S. Mars Reconnaissance Orbiter has helped to identify areas on the martian surface of high scientific interest.

Despite ITAR's chilling effect, NASA maintains a good level of international collaboration in planetary exploration and should be commended. Current trends will lead to maintaining this satisfactory level of support.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey strongly endorses the New Frontiers initiative. These spacecraft should be competitively procured and should have flights every 2 or 3 years, with the total cost capped at approximately twice that of a Discovery mission. Target selection should be guided by the list in this report." (pp. 2, 190)	**Grade: B Trend: ➜**

NASA succeeded in initiating a New Frontiers program, and the committee praises the agency for undertaking this effort. The New Horizons mission to Pluto was the first New Frontiers mission. It was selected in 2001 before the writing of the decadal survey (2002). Juno was selected for flight in 2005. Despite these achievements, the rate is half that recommended. NASA is planning to release an announcement for the next selection in FY 2009.

Recommendation: NASA should increase the rate of selection and launch of New Frontiers missions.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey recommends an early study to find ways to avoid the potentially adverse consequences of conflicts of interest relating to, for example, access to unique expertise and infrastructure at NASA centers." (p. 191)	**Grade: Incomplete**

The decadal survey did not give clear advice about how to underwrite proposal competition, and NASA has not introduced any such process in its selections. The committee is concerned about how this could be implemented and suggests that a better solution would be to focus on the pre-proposal phase.

Recommendation: The New Frontiers missions should follow a two-stage development process, starting with (1) an opportunity to submit a proposal for funding for 1 or 2 years to develop mission concepts. This earlier stage would provide for some endorsement of the best ideas so that they can attract industry and NASA center support. Such support, in turn, would (2) allow more concepts to reach a level of maturity required for considering full-scale proposal development.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"In order to confirm the readiness of any New Frontier mission concept prior to the issuance of an Announcement of Opportunity and to certify the mission concept's qualification for this program, the SSE Survey recommends that after the first selection, an independent group conduct a certification review of the mission concept to be solicited, prior to the issuance of any Announcement of Opportunity." (p. 191)	**Grade: A Trend: ➜**

NASA is planning to review input from the National Research Council (NRC) before announcing new targets for the next New Frontiers Announcement of Opportunity. NASA reviewed the decadal survey concepts before announcing the 2003 New Frontiers opportunity. The NRC currently has a study effort under way—Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity—that is considering whether the next New Frontiers Announcement of Opportunity should be open to all proposals or should instead include a candidate list of science goals and/or missions.

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends that the National Research Council's Committee on Planetary and Lunar Exploration conduct a review to confirm or modify decadal survey recommendations and priorities for the New Frontiers flight program." (p. 192)	**Grade: A**	**Trend: ➜**

An NRC study is currently under way as a result of NASA's request, which was based on the decadal survey recommendation quoted above.[3] The committee gives NASA high marks for implementing a logical process toward the next New Frontiers program selection.

***New Frontiers* Recommendations**	**Results of Midterm Review**	
"Given Discovery's highly successful start, the SSE Survey endorses the continuation of this program, which relies on principal-investigator leadership and competition to obtain the greatest science return within a cost cap. A flight rate of no less than one launch every 18 months is recommended." (pp. 2, 192) "Recognizing the Discovery program's success, the SSE Survey recommends that adequate resources be provided to sustain an average flight rate of no less than one launch every 18 months." (p. 192)	**Grade: D**	**Trend: ➜**

No Discovery missions have been selected since 2001. A low grade was assigned because so little progress has been made toward meeting the recommended launch interval of 18 months. The committee notes that the previously selected Dawn and Kepler missions are scheduled for launch in this decade, but this still does not mitigate the fact that none has been selected in the past 6 years. Allowing for the launch of the two already-selected missions and the typical 3-year development time before launch, it would take five mission selections in the next 4 years to satisfy the decadal survey recommendations.[4]

Recommendation: NASA should select two of the three Discovery missions currently in Phase A studies (if two are sufficiently meritorious to be selectable) and should seek to achieve an 18-month period between selections for the rest of the decade. These steps can help to restore vitality to this important program.

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"The SSE Survey supports NASA's current Senior Review process for deciding the scientific merits of a proposed mission extension and recommends that early planning be done to provide adequate funding of mission extensions, particularly Flagship missions and missions with international partners." (pp. 4, 192)	**Grade: A**	**Trend: ➜**↓

NASA has a regular process for reviewing proposals for mission extensions, and funding was provided to Cassini for planning mission extensions. The committee assessed the trend as downward, however, because the frequency of Senior Reviews has increased for the Mars program from every 2 years to annual reviews. The

[3]Note added in proof: The report of the study, *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity*, was approved for public release in early March 2008.
[4]Note added in proof: NASA selected the GRAIL lunar gravity Discovery mission soon after this report was completed.

committee concluded that the change from biennial to annual reviews has little or no added value. The time and resources spent on preparing for such reviews every year, on the part of both reviewers and investigators, seems out of proportion to the benefits to mission planning or implementation. The committee also notes that NASA can re-examine the assumptions from the biennial review at any time should major changes occur (e.g., loss of spacecraft capability or an exciting new discovery).

Recommendation: NASA should return to conducting Senior Reviews once every 2 years to improve efficiency.

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"[A] top-level programmatic priorit[y]: Continue approved missions, such as the Cassini-Huygens mission to Saturn and Titan. . . ." (pp. 189-190)	**Grade: A**	**Trend: ➜**

NASA has taken steps toward approving a 2-year extension of the Cassini mission. The committee agrees with this choice and believes that it is a sound decision consistent with the intent of the decadal survey and the realities of operating the Cassini spacecraft.

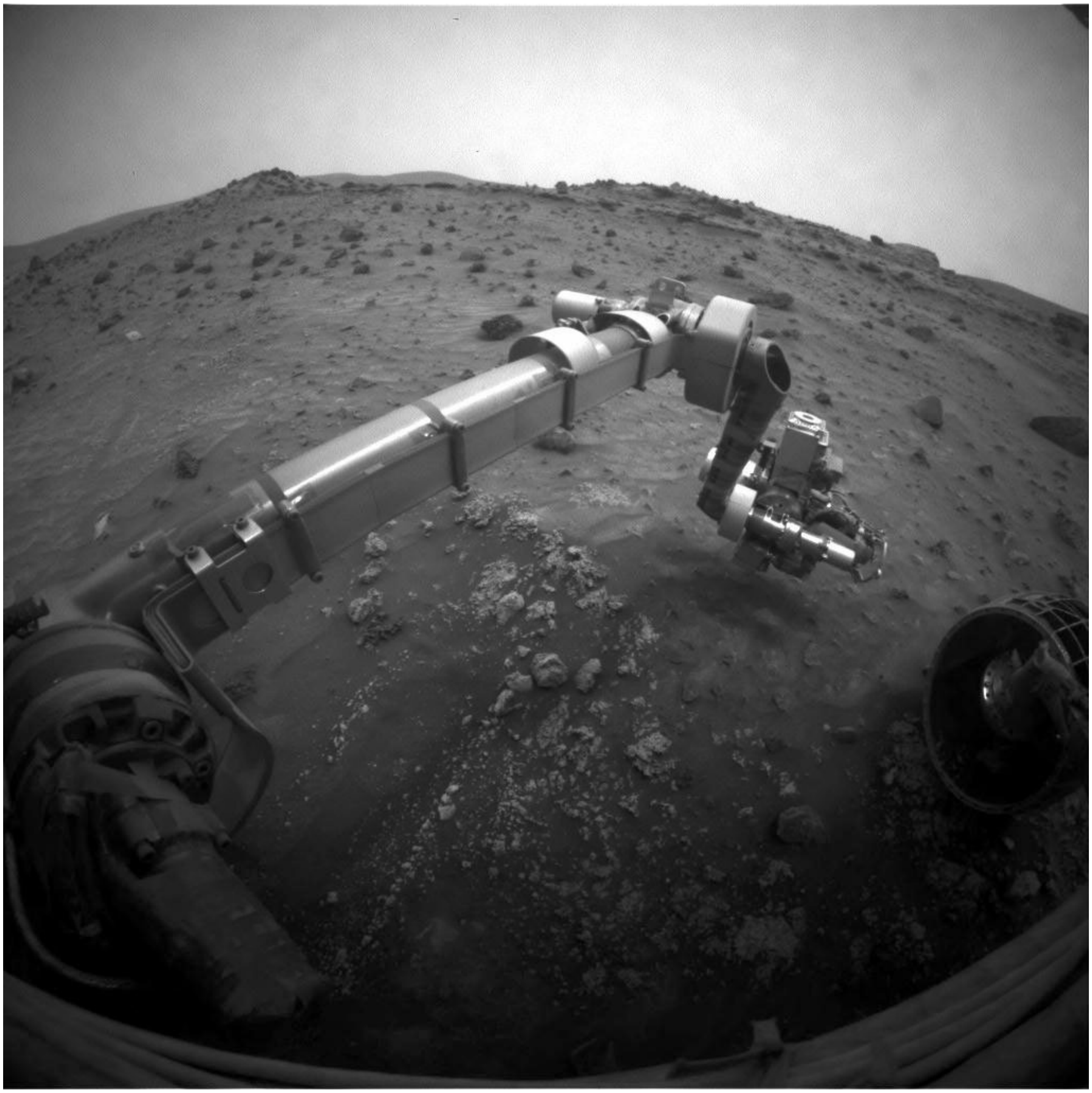

FIGURE 4.1 Spirit rover's robotic arm. SOURCE: NASA.

4

Mars

Mars	**OVERALL ASSESSMENT:**	**Grade: A**	**Trend: ➜**

NASA's exploration of Mars has been an outstanding example of a successful solar system exploration program, and for this reason the Committee on Assessing the Solar System Exploration Program assessed it with a grade of A with a steady trend, although the committee notes that NASA is currently considering making substantial changes to the Mars program that will require careful evaluation by the scientific community.

The Mars Exploration Program (MEP) was restructured in 2000 after the failures of the Mars Climate Orbiter and Mars Polar Lander. Key in the restructuring was the recognition that to understand Mars as a *system* requires a set of interrelated missions in a coupled program.[1] Such a program also requires supporting infrastructure, particularly communications, so that the high-data-rate, high-bandwidth data from current and future missions can be successfully returned. Finally, a long-term technology investment is needed to develop the systems and subsystems for future missions of ever-increasing complexity.

Another principle in the restructuring was to alternate orbital missions providing global context with landed "ground truth" projects to gradually reduce the number of potential sites for a sample return to a few high-interest scientific locations. This strategy has proven sound as the "Follow the water" theme combined the results of Mars Global Surveyor, Odyssey, and the Spirit and Opportunity rovers into solid scientific understanding of the history of ancient water.

The committee identified two scientific threads in the MEP that support future missions. One thread addresses the long-deferred understanding of Mars's atmosphere and the solid planet geophysics through aeronomy, climatology, and seismology. The other thread is a well-defined scientific and engineering path to obtain and return a well-characterized sample of Mars rock and soil. By "well-characterized" sample, the committee means that the sample should be of both geological and biological interest and must have preserved or recorded the context from which the sample was taken.[2] The committee believes that NASA will need to engage relevant members of the Mars science community in the Mars Sample Return (MSR) planning process to ensure that a consistent definition of a "well-characterized" sample is employed by the program.

[1]G. Scott Hubbard, Firouz M. Naderi, and James B. Garvin, "Following the Water, the New Program for Mars Exploration," *Acta Astronautica* 51(1-9):337-350, 2002.

[2]For further reference to current thinking about the sample return sites and locations, see National Research Council, *An Astrobiology Strategy for the Exploration of Mars*, The National Academies Press, Washington, D.C., 2007.

The past or present biological potential of Mars will ultimately best be examined by many science teams using the full arsenal of laboratory instrumentation on a properly selected returned sample. The committee strongly encourages NASA to begin the investment and planning necessary to make an MSR mission a reality.

After the committee had begun writing its report, it was informed of NASA plans to significantly alter the Mars Exploration Program with the primary goal of achieving a Mars Sample Return mission starting around 2020 (meaning returning the actual sample to Earth several years after that date). The committee addresses this subject at the end of this chapter and notes that in this report it only assessed NASA's Mars performance to date and not the incomplete and preliminary plans for the Mars program that NASA is currently developing, even if they may substantially alter NASA's progress in meeting the goals of the decadal survey.

ASSESSMENT OF PROGRESS TOWARD MEETING MARS-SPECIFIC RECOMMENDATIONS MADE IN THE SOLAR SYSTEM EXPLORATION DECADAL REPORT

***New Frontiers*[3] Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends that the Mars Scout program be managed as is the Discovery program, with principal-investigator leadership and competitive selection of missions." (p. 200)	**Grade: A**	**Trend: ↑**

NASA currently has one Mars Scout mission (Phoenix) under way to Mars and two missions (the Great Escape mission and the Mars Atmosphere and Volatile Evolution, or MAVEN, mission) in formulation competing for the second Scout opportunity in 2011. All three are principal-investigator (PI)-led and were selected through a competitive process. NASA has been doing an excellent job in initiating and implementing the Mars Scout program.

***New Frontiers* Recommendations**	**Results of Midterm Review**	
"The SSE Survey strongly recommends that the Mars Exploration Program commit equally as strongly to the Scout program as to sample return." (p. 200) "The SSE Survey recommends that a Mars Scout mission be flown at every other launch opportunity." (p. 200)	**Grade: A**	**Trend: ↑**

The Phoenix mission is already flying in the first Mars Scout launch opportunity in 2007 and will be followed by either the MAVEN mission or the Great Escape aeronomy mission in the second launch opportunity in 2011 (subsequently delayed until 2013). The committee endorses the current plan that would ensure that Scout missions fly at every other launch opportunity and that NASA should continue to plan for an Announcement of Opportunity for a 2016 competed Scout mission.

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends that while carrying out its science mission, the Mars Science Laboratory mission should test and validate technology required for sample return (e.g., sample handling and storage in preparation for sample return and feed-forward lander design, consistent with the future use of a Mars Ascent Vehicle)." (p. 200)	**Grade: B**	**Trend: →**

A number of technologies that can and will be applied to missions in the next decade have been integrated into the Mars Science Laboratory (MSL) mission. In particular, the Skycrane and the MSL entry, descent, and landing system will provide technologies to the Astrobiology Field Laboratory (AFL), to a Mars Sample Return mission, and possibly to systems related to the human exploration of Mars (in which the risk of contamination of

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

samples is significantly greater than the risk from exploration by robots). Thus, the committee applauds NASA's effort on entry, descent, and landing design; testing; and implementation for the MSL mission. Preparations for the MSL mission have also led to some advancements in surface sample handling. The MSL mission's work on in situ sample handling has been productive and has demonstrated the challenges in obtaining, processing, and caching samples that meet scientific and planetary protection objectives. The committee encourages the Mars Exploration Program to use this experience to guide future technology development for the Astrobiology Field Laboratory and Mars Sample Return.

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends that NASA begin its planning for Mars Sample Return missions so that their implementation can occur early in the decade 2013-2023." (pp. 7, 198)	**Grade: C**	**Trend: ↓**

Mars Sample Return has long been a high priority for the planetary science community, as was reflected in the decadal survey. Some early preparations for MSR have been facilitated by the MSL mission (advancements in entry, descent, and landing and in surface sample acquisition and sample handling). Additional preparations will likely be facilitated by the AFL mission (sample caching and handling, sterilization, and precision landing). Nevertheless, the committee found that MSR-specific planning and preparation activities are not occurring and that an MSR mission has been pushed beyond the time frame specified in the decadal survey. Over the next year (2007-2008), the Mars Exploration Program plans to, and should, charter a technology assessment group to prioritize the technology developments needed in the next 10 to 15 years to enable a sample return mission. Technology advancements required for MSR, and indeed other upcoming Mars missions, have been seriously eroded by recent reductions in research and technology programs. The specific programs under stress are the Planetary Instrument Definition and Development Program (PIDDP), the Mars Instrument Development Project (MIDP), Astrobiology Science and Technology Instrument Development (ASTID), Astrobiology Science and Technology for Exploring Planets (ASTEP), and the Mars Technology Project (MTP).

While NASA has shown strong leadership in the long-term implementation of Mars Sample Return, no single individual currently has oversight of a future MSR mission as his or her primary responsibility. MSR will contain several tightly coupled major projects (orbital rendezvous spacecraft, Mars Ascent Vehicle, Sample Return Vehicle, and others). The committee expresses serious concern that sample return will not be possible in the next decade under the current investment environment. MSR planning and preparation will need significant attention in the next solar system exploration decadal survey.

Recommendation: NASA should begin actively planning for Mars Sample Return, including precursor missions that identify and cache well-characterized samples of both geological and biological interest.

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends that NASA engage prospective international partners in the planning and implementation of Mars Sample Return at an early stage in order for this complex mission to benefit fully from the capabilities and resources offered by the international community." (p. 201)	**Grade: B**	**Trend: ↑**

The committee notes that international participation has proven beneficial for recent Mars missions and encourages the Mars Exploration Program to continue to pursue opportunities for international participation for future missions. Notably, the MEP should continue to actively pursue partnering with the European Space Agency's (ESA's) Aurora Program, which has a Mars sample return element planned for late in the next decade. The MEP should also continue to work through the International Mars Exploration Working Group (IMEWG) to begin broader international MSR studies. The committee emphasizes the need for the IMEWG and NASA to obtain a consensus in time for the preparation of future budgets to allow the MSR mission to proceed expeditiously. Considering the complex nature of a sample return mission, international partners may be necessary in order to make this mission affordable under current program budget out-year expectations. The committee also believes that an analysis of the interface issues and a realistic cost and risk assessment should precede any formal international agreements regarding an MSR mission.

***New Frontiers* Mars-Specific Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends that well before cosmic materials are returned from planetary missions, NASA should establish a sample-analysis program to support instrument development, laboratory facilities, and the training of researchers." (p. 9)	**Grade: C**	**Trend: ↓**

The committee found little progress toward establishing a sample analysis program that supports instrument development, analytical facilities, and researcher training as preparation for MSR, and yet cosmic materials have already been returned in the Stardust and Genesis missions. Past progress on a sample-handling/sample-receiving facility for the quarantine, characterization, curation, and distribution of returned Mars samples has stalled. In preparation for Mars Sample Return, NASA should work with the Mars Exploration Program Analysis Group (MEPAG) and the broader astrobiology/exobiology research community to assess the current state of the art in laboratory analysis instruments, identify where further development would be beneficial for Mars sample analysis and biosignature detection, and verify that the needed instruments and laboratory facilities will be made available as part of the sample-handling facility as soon as samples are returned. As the state of the art advances, these assessments should be periodically reevaluated.

Lastly, the establishment of a vigorous scientific community and the development of advanced skills needed to analyze Mars samples will require the training of young researchers in the decades before MSR. The severe budget reductions in astrobiology/exobiology have stalled research activities and have had a profoundly negative effect on early-career scientists who will be the leaders in future Mars missions. The committee believes that astrobiology/exobiology will likely play heightened and critical roles in the development of advanced instrumentation in future landed Mars missions.

Recommendation: NASA should begin consulting various groups such as MEPAG and the astrobiology/exobiology research community to assess the current state of the art in laboratory analysis instruments, identify where further development would be beneficial for Mars sample analysis and biosignature detection, and verify that the needed instruments. laboratory facilities, and new researcher training will be made available as part of the sample-handling facility as soon as samples are returned.

PROGRESS TOWARD MEETING RECOMMENDATIONS MADE IN *ASSESSMENT OF NASA'S MARS ARCHITECTURE 2007-2016*

***Mars Architecture*[4] Recommendation**	**Results of Midterm Review**	
"In addition, planetary protection requirements for missions to worlds of biological interest will require investments, as will life-detection techniques, sample quarantine facilities, and sterilization technologies." (p. 45)	**Grade: B**	**Trend: ↓**

Planetary protection is critical for the preparation and successful implementation of landed Mars missions, including the MSL and the proposed AFL and Mars Sample Return missions. As future landed missions become more capable and focus on the search for biosignatures, planetary protection measures will become even more important. The committee applauds past NASA investments in planetary protection research and analysis (R&A) that have led to current capabilities in the rapid quantification of spore counts on spacecraft materials. As emphasized in the NASA Research Announcement entitled "Research Opportunities in Space and Earth Sciences (ROSES)

[4]National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.

2006," planetary protection should incorporate sophisticated molecular biological approaches (for example with lab-on-a-chip and genomics technologies—i.e., the ability to detect the fingerprints of life, or the presence of biological signatures that are carried in the genetic material of all living things) to significantly improve capabilities. The committee finds, however, that the current funding level for R&A with respect to planetary protection is inadequate to make these important, and costly, advancements.

A sophisticated search for biosignatures on Mars will require significant advancements in the knowledge of biomarkers in cultured and uncultured microorganisms, in extreme environments, and in Earth's geologic record. Indeed, early-Earth materials may provide some of the best Earth analogues for testing and refining biosignature detection capabilities for Mars missions. Such efforts in basic research will require significant investments in R&A, in laboratory equipment, in instrument development, and in the training of young researchers.

At the same time, the committee found that budget reductions in ASTID, ASTEP, PIDDP, and MIDP have significantly curtailed the ability to develop new analytical approaches and instruments for biosignature detection on upcoming Mars missions. The committee is seriously concerned that progress in U.S. capabilities for spacecraft bioload characterization, biosignature detection, and analytical instrumentation will stall.

A comprehensive study, which involved three independent industry groups, on a sample-handling/sample-receiving facility for the quarantine, characterization, curation, and distribution of returned Mars samples has been completed under the direction of the Mars Exploration Program. However, the committee found that progress on this facility was stalled once NASA made the decision to delay MSR until the third decade (beyond 2023). In the Mars Sample Return-Mars Returned Sample Handling Facility science roadmap provided to the committee, it is clear that up to 12 years of funding and preparation are necessary before a sample is returned to Earth. In order to proceed effectively with a Mars Sample Return program, NASA will need to resume progress on developing this facility as soon as possible.

Mars Architecture **Recommendation**	**Results of Midterm Review**	
"Include the Mars Long-Lived Lander Network in the mix of options for the 2016 launch opportunity." (p. 2)	**Grade: B**	**Trend: ↓**

The committee notes that the long-recommended landed network mission has been included as an option for a 2016 launch, and NASA therefore has complied with the recommendation qoted above. Furthermore, the 2016-2018 Science Analysis Group (SAG) was initiated in July 2007 to address questions about the Long-Lived Lander Network. The committee encourages the ongoing engagement of community-based SAGs for mission analysis and definition. However, the committee is concerned that the continued study of options may not result in a decision and also notes that certain technologies required for networks have not yet been developed; therefore, it cannot award this subject the highest grade, but awards it a grade of B. The committee believes that innovative thinking such as carrying long-lived landed science packages on the proposed 2013 Mars Science Orbiter is a way to reach a second-decade mission queue that maximizes scientific return while also providing much-needed communications infrastructure.

However, late in its deliberative process, the committee received information from NASA implying that the Mars Long-Lived Lander Network may be removed from the Mars Exploration Program entirely. The committee assesses a downward trend because of this information.

Mars Architecture **Recommendation**	**Results of Midterm Review**	
"Consider delaying the launch of the Astrobiology Field Laboratory until 2018 to permit an informed decision of its merits and the selection of an appropriate instrument complement in the context of a mature consideration of the results from the Mars Science Laboratory and other prior missions." (p. 2)	**Grade: A**	**Trend: →**

As with the lander network mission, NASA is considering delaying the Astrobiology Field Laboratory mission, thus meeting the letter of the decadal recommendation. However, the committee is concerned that if the only activity is a study by a SAG, this will not lead NASA to a definitive conclusion regarding AFL delay. The committee notes that a decision on when to proceed with the AFL mission will require a program-level analysis that includes multiple considerations: (1) the science will focus on a scientific hot spot with a high probability of examining a habitable zone, (2) the technology and instruments are ready for biosignature detection, and (3) the mission can provide a good start on MSR, possibly even caching samples for MSR. The prime consideration will be to balance these maturity considerations with the need for in situ biological characterization prior to MSR and to maintain the momentum supplied by Spirit and Opportunity, Mars Science Laboratory, and the ESA's Exo-Mars spacecraft.

Mars Architecture **Recommendation**	**Results of Midterm Review**	
"Establish science and technology definition teams for the Astrobiology Field Laboratory, the Mars Science and Telecommunications Orbiter [name now changed to Mars Science Orbiter], the Mid Rovers, and the Mars Long-Lived Lander Network as soon as possible to optimize science and mission design in concert with each other." (p. 2)	**Grade: A**	**Trend: ➜**

The committee again applauds the Mars Exploration Program for its use of science definition teams (SDTs) and SAGs. This process is very useful in obtaining the sense of the community and establishing a range of options. The committee's understanding is that a SAG will look at the 2016-2018 period and its results will feed into a more focused SDT to set the scope of the missions for Announcement of Opportunity competition in an appropriate time frame.

Mars Architecture **Recommendation**	**Results of Midterm Review**	
"Devise a strategy to implement the Mars Sample Return mission, and ensure that a program is started at the earliest possible opportunity to develop the technology necessary to enable this mission." (p. 2)	**Grade: C**	**Trend: ↓**

The committee notes that despite lacking a strategy to implement the Mars Sample Return mission, NASA has made some progress in developing some of the necessary technologies. For example, the committee lauds the close interaction between NASA and the Defense Advanced Research Projects Agency (DARPA) Orbital Express experiment that may provide technology for the autonomous rendezvous system. However, the committee is concerned that while some individual components of an MSR mission are being addressed, the overall strategy is not apparent. NASA's lack of visible resources dedicated to the project is the basis for the committee's downward trend assessment.

The committee notes that reaching the best sites on Mars may be challenging. The ultimate benefit of a well-selected and well-characterized sample return justifies the development of long-lead-time technologies and the implementation of the mission either through international collaboration or through changes in NASA funding priority. The committee is encouraged to learn that NASA will assess compartmentalizing Mars Sample Return into manageable components to spread the risks and cost over several launch opportunities and permit substantive and separable contributions from international partners of the United States.

NASA is making progress in the technology areas of medium and deep drilling, soil scoops, and coring, and in the entry, descent, and landing of the Skycrane. Previous efforts yielded good initial designs for the sample return capsule. However, the committee has learned that little recent progress has been made on the Mars Autonomous Vehicle or the quarantine facility. The lack of applied resources and dedicated effort to MSL science and technology development bodes poorly for reaching the goal of a mission in the next decade.

Recommendation: NASA should begin robust technology investment aimed at reducing the risk associated with the four major engineering challenges of a successful Mars Sample Return, that is, the definition, design, and development of the following:

1. **A Mars sample-receiving facility that can serve to certify the samples as safe for distribution;**
2. **A sample return vehicle that can provide a high probability of successful sample return to Earth**

consistent with the guidelines from the NASA planetary protection officer and the Committee on Space Research (COSPAR);

3. Autonomous on-orbit rendezvous and docking capability at Mars for sample transfer and return; and

4. A Mars ascent vehicle that is capable of being transported to Mars, landing, and returning cached samples to Mars orbit.

SCIENCE RETURN FROM CURRENT ARCHITECTURE

***Mars Architecture* Recommendation**	**Results of Midterm Review**	
"Develop and articulate criteria for distinguishing between the three options for missions to launch in 2016. Similarly, define a strategy that addresses the short lead time between science results obtained from the Mars Science Laboratory and selection of the mission to fly in 2016." (p. 2)	**Grade: C**	**Trend: ➜**

The committee applauds the diligence with which NASA is employing community-based information through the 2016-2018 Science Analysis Group process. However, consistent with the decadal survey recommendations, the committee strongly encourages NASA to make near-term decisions and to adopt a mission queue for the 2010-2020 decade that leads to an MSR mission early in the 2020-2030 decade. The lack of a clear-cut decision thus far and the uncertainty of an unambiguous outcome place this item on an uncertain trend. It is worth noting that the trend and the grade of C are only a midterm assessment and may be improved greatly over the coming months.

Given the average of 8 years for development from scientific measurement concept to Mars mission implementation, the 2008 budget needs to address the project selection for the next decade.

Recommendation: NASA should take all of the scientific, programmatic, and technical information available and make a decision on a mission queue that includes the 2016 and 2018 Mars launch opportunities.

***Mars Architecture* Recommendation**	**Results of Midterm Review**	
"Clarify how trade-offs involving mission costs versus science were made for the various launch opportunities to justify the rationale behind the proposed sequence of specific missions and the exclusion of others." (p. 2)	**Grade: B**	**Trend: ➜**

While reviewing the progress thus far in planning, defining, and executing missions that cover the time period from 2003 to 2023, the committee found mixed results. NASA has made good progress for missions from 2003 to 2011. However, NASA's progress in clearly defining the mission set beyond a Scout mission in 2011 is less encouraging. The committee is concerned about the uncertainty of future planning and outcomes and assigns a trend assessment that, although stable, is uncertain.

***Mars Architecture* Recommendation**	**Results of Midterm Review**	
"Maintain the Mars Scouts as entities distinct from the core missions of the Mars Exploration Program. Scout missions should not be restricted by the planning for core missions, and the core missions should not depend on selecting particular types of Scout missions." (p. 2)	**Grade: A**	**Trend: ↑**

The committee applauds the consistency of the Mars Exploration Program in maintaining Scout missions as distinct entities, now and in the future. Scouts remain an important element in Mars exploration and will continue to bring innovative ideas for exploration at modest cost. The committee hopes that NASA will maintain cognizance of the goals and objectives of both future core missions and selected or solicited Scout missions so as to encourage that they are complementary and avoid duplication.

Mars Architecture **Recommendation**	**Results of Midterm Review**
"Immediately initiate appropriate technology development activities to support all of the missions considered for the period 2013-2016 and to support the Mars Sample Return mission as soon as possible thereafter." (p. 2)	**Grade: B Trend: ➜**

The committee has noted that a defining characteristic of a highly coupled program such as the Mars program is the necessity of investing continually in the development of technologies that enable future missions in an interdependent queue. The committee is pleased to see that the Mars Exploration Program plans to charter a technology assessment group (TAG), which will include broad science-and-technology community involvement, to prioritize the technology developments needed for the next 10 to 15 years. The committee's assessment reflects NASA's good work and intentions to get the technology program back on track. However, the committee also notes that study alone is not sufficient.

BALANCE IN CURRENT ARCHITECTURE

Mars Architecture **Recommendation**	**Results of Midterm Review**
"If the Mars Long-Lived Lander Network cannot be implemented in the period [2007-2016] under consideration, provide for an effort to make some of the highest-priority measurements on the landed missions that are included in the proposed Mars architecture." (p. 3)	**Grade: A Trend: ➜**

As stated above, the committee finds that the long-recommended lander network mission has been included as an option for a 2016 launch, and thus a grade of A is justified. Furthermore, the 2016-2018 Science Analysis Group was initiated in July 2007 to address these questions. The committee hopes that NASA continues to use the community-based SAGs for mission analysis and definition. As always, such information is most useful when timed to match the federal budget cycle and agency planning.

Mars Architecture **Recommendation**	**Results of Midterm Review**
"Ensure that the primary role of the Mars Science and Telecommunications Orbiter [name now changed to Mars Science Orbiter] is to address science questions, and not simply to serve as a telecommunications relay. This distinction is particularly important with respect to the required orbital parameters that are adopted." (p. 3)	**Grade: A Trend: ↓**

Following the loss of two spacecraft late in the last decade, the Mars Exploration Program was restructured to emphasize tightly coupled, science-driven strategic missions with supporting infrastructure, along with community based PI-led Scout projects. Given this basic strategic approach and the high data rates generated by current and proposed instruments, ongoing high-bandwidth telecommunications via a relay orbiter is a very high priority and therefore an integral part of the 2013 mission. For example, the committee learned that the Spirit and Opportunity rovers are capable of returning far more data than have been obtained thus far. An enhanced communications relay capability would greatly improve data return from future missions.

Further, high-resolution imaging afforded by the Mars Reconnaissance Orbiter has proved invaluable in defining a safe landing site for the Phoenix mission. (See Figure 4.2 for an illustration of the Phoenix lander.) Given the critical upcoming landed missions such as Astrobiology Field Laboratory and Mars Sample Return, NASA will have to make an assessment of the likely lifetime and surface coverage of the Mars Reconnaissance Orbiter. The results can then be used to determine whether high-resolution imaging is required for the Mars Science Orbiter.

The committee notes that NASA has reoriented the goals of the Mars Science and Telecommunications Orbiter and renamed it the Mars Science Orbiter (MSO). NASA clearly intends for this mission to have a science goal,

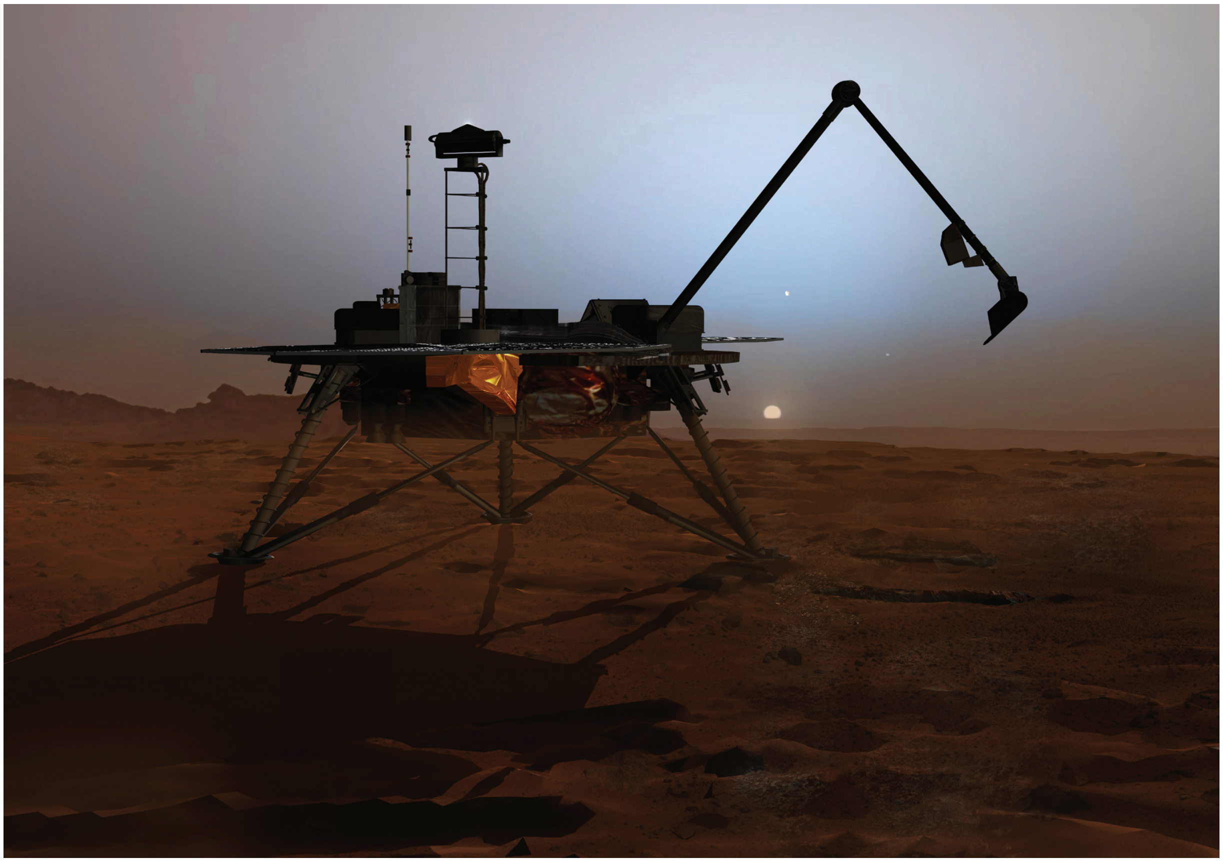

FIGURE 4.2 The Phoenix Scout mission landing site was selected using high-resolution imagery from the Mars Reconnaissance Orbiter, demonstrating the tight coupling of spacecraft in NASA's Mars Exploration Program. Future landers will also require such imagery to select safe landing sites. SOURCE: Jet Propulsion Laboratory.

and the committee applauds this decision. However, the committee is concerned about how committed the agency is to funding this mission, considering plans to reorient the Mars program.

Finally, as described earlier, a long-deferred goal, a lander network for seismology, meteorology, and other geophysical measurements, might be achieved by incorporating landers on the Mars Science Orbiter. The committee notes that, in general, orbital science and telecommunications orbits are incompatible, and thus mission orbital mechanics design must be carefully defined. The committee observes that the intention of the Mars Exploration Program is clearly to keep scientific objectives uppermost, as reflected in the name change to Mars Science Orbiter. However, without sufficient maintenance of the Deep Space Network, increased data rates from Mars are inconsequential.

ADDENDUM: NASA'S NEW MARS DIRECTION

The committee's charter calls for a midterm review of NASA's progress in relation to the National Research Council's (NRC's) decadal survey *New Frontiers in the Solar System*[5] and supporting documents such as *Assess-*

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

ment of NASA's Mars Architecture 2007-2016.[6] Since the time of the study initiation, several relevant NRC documents have been published, including *An Astrobiology Strategy for the Exploration of Mars*,[7] *The Limits of Organic Life in Planetary Systems*,[8] and *Exploring Organic Environments in the Solar System*.[9] In addition, as the present report of the committee was in its near-final draft, NASA presented the committee with new information on both the Mars Science Laboratory mission and the agency's strategic planning for the decade 2010-2020. The set of options under consideration for the decade 2010-2020 potentially represents a dramatic change from what has been recommended in previous NRC documents and thus stimulated this addendum entitled "NASA's New Mars Direction" to the "Mars" chapter of this report. In addition, the committee perceived very mixed messages about the actual budgetary commitment to a new Mars exploration strategy. The committee urges the community to conduct a more thorough review of the new Mars exploration strategy when the executive branch budget process under way at the time of this writing has been completed and the NASA 2009 budget is publicly available.

Mars Science Laboratory Mission

The Mars Science Laboratory mission had just had its Critical Design Review (CDR) completed as the present report was being prepared. CDR is the last point at which hardware changes can be made prior to actual spacecraft construction without having significant, and often expensive and time-consuming, effects on the project.[10] Thus, the committee was quite surprised to hear that a new requirement had been added by NASA *after the CDR:* namely, a sample caching mechanism. This mechanism, intended to demonstrate a method of sequestering rock samples for a possible future Mars Sample Return, is now being developed for inclusion on the MSL project. The committee has been informed that the sample caching hardware is only intended to collect a "contingency sample," not a "primary sample," and this will not drive the scientific operations or development of the MSL project. The committee notes that this contingency sample will not be a "well-characterized" sample according to current commonly accepted definitions of the term; for example, it will not include samples of high biological interest.

The committee sees value in beginning the preparations for Mars Sample Return in such a concrete way, much as the small rover on Mars Pathfinder set the stage for the much more capable rovers Spirit and Opportunity. However, the committee strongly cautions NASA that there are inherent technical, scientific, and programmatic risks in including such a dramatically different requirement after CDR. While NASA personnel provided a plausible sketch of the safeguards put in place to prevent this caching requirement from driving or undermining the balance of the mission, the committee believes that very rigorous reviews will have to be implemented to ensure overall MSL mission success.

The "Ideal Mars Next Decade Campaign"

Throughout most of this report, the committee has generally applauded NASA's Mars Exploration Program as an impressive and well-managed program achieving substantial scientific results and greatly increasing our knowledge of the red planet. A major exception is the lack of progress toward a Mars Sample Return mission. NRC documents have for many years emphasized the importance of the MSR mission, though often tempering this emphasis with the realization that to justify the significant expense, the sample must be well characterized and

[6]National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006.

[7]National Research Council, *An Astrobiology Strategy for the Exploration of Mars*, The National Academies Press, Washington, D.C., 2007.

[8]National Research Council, *The Limits of Organic Life in Planetary Systems*, The National Academies Press, Washington, D.C., 2007.

[9]National Research Council, *Exploring Organic Environments in the Solar System*, The National Academies Press, Washington, D.C., 2007.

[10]"The CDR demonstrates that the maturity of the program's design is appropriate to support proceeding [with] full-scale fabrication, assembly, integration, and test and that the technical effort is on track to complete the flight and ground system development and mission operations in order to meet overall performance requirements within the identified cost and schedule constraints. Progress against management plans, budget, and schedule, as well as risk assessment, are presented." NASA Procedural Requirement 7120.5D, March 6, 2007. See http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7120_005D_.

well selected. In addition, there are a number of technologies unique to MSR that require major advance funding to ensure mission success. Funding for those technologies has been sporadic at best.

The committee notes that with the release of the NRC reports on possible forms of life elsewhere in the solar system—*The Limits of Organic Life in Planetary Systems*, *An Astrobiology Strategy for the Exploration of Mars*, and *Exploring Organic Environments in the Solar System*—the NRC has solidly endorsed the "life thread" as a driving goal for the Mars Exploration Program. By continuing the "Follow the water" approach, perhaps augmented by a "Follow the carbon," "Follow the organics," or "Find the life" set of scientific objectives, a properly designed Mars Sample Return mission could add an enormous storehouse of scientific information to our knowledge of the universe.

The new strategic approach presented in outline form to the committee and described by NASA as the "Ideal Mars Next Decade Campaign" (hereafter referred to as the "Ideal" plan)[11] seems to address many of the concerns contained in the balance of this report. The new strategic approach is founded on the stated goal of "anchoring" a Mars Sample Return mission in the launch year of 2020, with actual samples returned sometime later. This goal requires some further explanation, since the launch year for a single segment of what is likely to be a multiple-launch mission could lead to confusion and misunderstanding. Given below are the committee's comments on the key elements of the "Ideal" plan.

Mars Scout in 2011

The 2011 Mars Scout project was characterized by NASA as being "on track" for a down-selection from two mission concepts to one in January 2008. Both concepts address the long-neglected aeronomy science area, and thus either project will benefit the overall Mars Exploration Program. However, during the committee's most recent discussions with NASA on future budgets, liens, and threats, it became apparent that funding may not be possible for another Scout Announcement of Opportunity for many years. Given the importance of portfolio balance among flagship, medium, and small missions, the committee finds it inconsistent with recommendations in the decadal survey that the 2011 Scout mission may be the last.

Mars Science Orbiter 2013

As noted elsewhere in this report, the architecture of the Mars Exploration Program embraces interdependent missions that provide both scientific context and supporting infrastructure. In the current Mars architecture, the 2013 orbiter provides technology for future missions as well as science that will be solicited by an Announcement of Opportunity in early 2008. Given the likely demise of the Mars Reconnaissance Orbiter spacecraft (currently in orbit around Mars) well before the putative Mars Sample Return launch in 2020, and given the need for landing site selection as well as telecommunications, the committee concludes that there must be some type of science and telecommunications orbiter preceding the MSR mission. The committee is pleased that this critical component is included in the "Ideal" plan, although, based on NASA statements that the 2013 mission could be deleted from the budget, the committee is strongly concerned that this mission could vanish entirely.

Mars Sample Return General Information

NASA told the committee that an MSR mission will be "anchored" in 2020 with a number of associated conditions and objectives:

- Extensive international collaboration, perhaps as much as 50 percent;
- Alignment with the European Space Agency's Aurora Program and Exo-Mars in particular; and
- Initiation of a first phase of study by the International Mars Exploration Working Group.

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[11]Doug McCuistion, director, Mars Exploration Program, Planetary Science Division, Science Mission Directorate, NASA, "Mars Exploration Program Update," presentation to the committee, Washington, D.C., August 13, 2007.

The committee is very pleased to learn of this new international effort, which corresponds so closely with previous NRC recommendations.

Astrobiology Field Laboratory (AFL) 2016

The new "Ideal" plan's mission queue presented by NASA to the committee now specifies the Astrobiology Field Laboratory as the first step in the MSR effort. AFL would identify, collect, and cache the prime set of samples for return on a subsequent mission. The committee applauds this step in definition of the mission queue, although the committee also wishes to emphasize that appropriate instrumentation must be developed in order for the AFL to realize its astrobiological promise.[12] A returned sample that contains organics would add immeasurably to the knowledge of the biological potential of Mars. This mission as now defined is also consistent with the NRC report *An Astrobiology Strategy for the Exploration of Mars*.

Mars Sample Return Missions 2020 and 2022

As has been noted previously, a sample return mission is very costly; it would be expected to consume all of the resources of the Mars Exploration Program over at least three launch opportunities; it will also require stable funding and high reliability. Thus, it was not surprising that NASA's plan to anchor an MSR mission in 2020 would necessitate skipping the 2018 launch opportunity. The committee was also informed that a 2024 mission might also be deleted to meet the budgetary requirements of the MSR mission. Such economies are clearly necessary for such an ambitious project.

NASA described the MSR mission as comprising three separate projects and three separate launches. The 2016 Astrobiology Field Laboratory would identify and cache the sample. In 2020, the orbiter that will contain the sample return vehicle and Earth entry system will be launched. Finally, in 2022, the landed system with a sample retrieval rover and the Mars ascent vehicle will be launched. Thus, an actual sample of Mars will not return to Earth until perhaps 2025.

The committee was delighted to see a clear sequence of missions that will lead to a Mars sample return in the first half of the 2020-2030 decade. As noted elsewhere in this report, such planning has been suggested by a number of previous NRC reports. However, as also noted in those earlier reports, an MSR mission will not and cannot occur without a significant technology investment, whether by NASA alone or through a shared international effort. In addition, the committee wishes to emphasize that *the primary scientific goal should be to obtain a well-selected sample that advances scientific understanding of the biological potential as well as geological history of Mars*. Subsequent NRC reviews will undoubtedly evaluate whether the budgetary investment and scientific emphasis continue to advance the MSR mission.

Additional Possibilities for Next-Decade Tradeoffs

During NASA's presentation of the well-reasoned and seemingly achievable description of the "Ideal" plan's mission queue,[13] the committee was surprised by the addition of several other options also now being considered by NASA:

- Possible cancellation of the 2013 Mars Science Orbiter;
- Potential conversion of the 2016 Astrobiology Field Laboratory to an orbiter;
- Starting a Mars Sample Return mission in 2018; and
- Opening the New Frontiers program to Mars missions.

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[12]The committee notes that the decadal survey recommended slipping the Astrobiology Field Laboratory to 2018, whereas the NRC *Mars Architecture* report considered it as an option for 2016. The committee believes that keeping the AFL in 2016 and giving the mission a role in the important Mars Sample Return mission is a reasonable decision.

[13]Doug McCuistion, director, Mars Exploration Program, Planetary Science Division, Science Mission Directorate, NASA, "Mars Exploration Program Update," presentation to the committee, Washington, D.C., August 13, 2007.

The committee finds this set of options, taken together, to represent nothing less than the dismantling of a strategically planned Mars program in return for a promised Mars Sample Return mission well beyond the current budgetary horizon. Some more-specific deductions can be made for each possible tradeoff:

- *Possible cancellation of the 2013 MSO.* Without orbital telecommunications support and with the highly probable loss of both the Odyssey and MRO spacecraft by 2011, the carefully constructed Mars scientific and programmatic infrastructure will cease to exist, possibly stranding the 2009 Mars Science Laboratory without high-data-rate capability. In addition, the possible MSO option to include a small number of landers to conduct network science would clearly be eliminated.
- *Potential conversion of the 2016 AFL to an orbiter.* The committee can only conclude that such a move would signal the termination of the astrobiology and the "life thread" of Mars investigations endorsed in numerous NRC and community reports. The "contingency sample" cache by the MSL would presumably then become the prime sample—one selected primarily for its geological interest. Conversion to an orbiter does acknowledge that the subsequent MSR mission would need both site selection and telecommunications support.
- *Starting MSR in 2018.* Given the current liens and budgetary requirements of an MSR mission as described by NASA, the committee does not believe that this is a realistic option.
- *Opening the New Frontiers program to Mars missions.* The impact of such a move could be to abandon a strategically planned Mars Exploration Program in favor of a competitive process that is already oversubscribed. The New Frontiers program is currently open to the full range of solar system missions outside of Mars. The success of the Mars Exploration Program has been to combine the strategic exploration of Mars as a system with competition for investigations and instruments meeting those community-based strategic goals. Competition at the small-mission level was met by the creation of the Scout program.

The committee notes that the decadal survey placed as much emphasis on the Scout missions as on Mars Sample Return. Any decision to cancel the Scout program completely in favor of MSR would run counter to the decadal survey and will have to be revisited by the Mars community.

In summary, the committee finds much to recommend and applaud in the proposed "Ideal Mars Next Decade Campaign." The sequence of missions, assuming adequate technology investment, addresses nearly all of the concerns expressed elsewhere in this report except for a landed network mission and the demise of the Mars Scout line. *The committee is therefore concerned to hear also of a set of options in this "Ideal" plan that would effectively negate nearly everything recommended in many previous NRC studies.* Opening the New Frontiers and Discovery lines to Mars missions is no replacement for the current Mars Exploration Program. There is a real risk in this new "Ideal" plan's architecture that future implementation and budget issues could result in the substitution of an "engineering spectacular" for a scientifically sound Mars Exploration Program.

Recommendation: NASA should seek community review to carefully scrutinize the new Mars architecture and its budget implications in order to ensure that the value of the sample returned is worth the cost to the Mars Exploration Program.

FIGURE 5.1 Scientists begin analysis of the cometary particles returned to Earth from the Stardust mission. SOURCE: NASA.

5

Research and Analysis, Planetary Astronomy, and Flight Mission Data Analysis

RESEARCH AND ANALYSIS

The NASA research and analysis (R&A) program and the various data analysis programs (DAPs) help to ensure maximum scientific return from the operating missions and help prepare the science foundation for future NASA missions. Many of the current missions are based on the results of individual R&A or DAP grants from the past. For example, the New Horizons mission, now on its way to Pluto and the Kuiper Belt, was based on two decades of ground-based observations and detailed theoretical analysis and modeling, which were funded primarily by several NASA R&A programs. The Stardust mission, which had been started as a NASA-funded R&A program to study interplanetary dust particles in the laboratory, greatly extended the scope of analysis of extraterrestrial materials.

Research and Analysis, Planetary Astronomy, Flight Mission Data Analysis	OVERALL ASSESSMENT:	Grade: C	Trend: ↓

A vigorous and healthy R&A grants program is essential for the continued overall vitality and productivity of NASA science in the coming decades. Thus, the committee concluded that the first New Frontiers *decadal survey recommendation below pertaining to overall research and analysis funding is of far more importance than any of the other R&A-related recommendations;*[1] *the grade for progress toward this one recommendation therefore heavily affects the committee's overall assessment of NASA's response to the decadal survey recommendations pertaining to research and analysis. The committee awarded NASA a grade of C with a downward trend primarily on the basis of its R&A grants program; only a significant improvement in this area will reverse the overall trend.*

The committee notes that NASA could substantially improve several low grades with relatively little effort and expenditure. For instance, it would be easy for the agency to improve the visibility of its fellowships program and to establish formal contacts with the Large Synoptic Survey Telescope (LSST). The committee was also informed that it should be relatively easy for the James Webb Space Telescope (JWST) to be adapted to provide at least some capability to track solar system objects. The committee also offers several recommendations for minor improvements to otherwise healthy efforts in data archiving.

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

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey recommends an increase over the decade in the funding for fundamental research and analysis programs at a rate above inflation that parallels the increase in the number of missions, amount of data, and diversity of objects studied." (p. 9)	**Grade: C** **Trend: ↓**

NASA's immediate response in fiscal year (FY) 2003 to FY 2005 to this decadal survey recommendation was laudable, with an increase in the R&A budget from a base of 12 percent of a Solar System Division budget of $1.204 billion in FY 2003 to a maximum of 14 percent of the solar system exploration budget of $1.417 billion in FY 2005.[2] This was exactly the type of action recommended by the decadal survey. However, the situation changed dramatically in FY 2006 with significant across-the-board cuts to all R&A programs and a 50 percent cut to astrobiology research funding. These funding reductions in the Planetary Science Division have had serious negative impacts on research activities. While R&A funding actually kept pace with the rate of inflation over the 5-year interval from FY 2003 to FY 2007, it has not kept pace with the number of missions, amounts of data, and diversity of objects studied. The situation in astrobiology has been a particular problem. In some years, proposals were selected for funding but were never actually funded. In other years, no solicitations for new proposals were issued. In FY 2006, astrobiology research was reduced by 50 percent. This had a serious adverse impact on the training and support of students (graduate and postdoctoral) and, if sustained, could lead to established scientists turning their efforts to other scientific endeavors.[3] These large fluctuations in funding levels can seriously endanger the training of the next generations of scientists in this burgeoning field. For those who rely on continuing support for their astrobiology research activities, these funding fluctuations cause a loss of continuity in their research efforts that is both inefficient and damaging. Whereas engineers can easily transfer to other projects, scientists who do not get funding are likely to leave the field entirely. The committee is concerned that NASA made these large cuts without any consultation with the community about what level of funding was necessary to achieve the goals of the decadal survey. If NASA is to restore money to astrobiology research, the agency should consult with the community to develop an understanding of basic needs.

The instability of R&A funding is a particular problem for the solar system research community, which has traditionally had a very large percentage of its researchers on "soft money"—that is, grants from government or other organizations.

Recommendation: NASA should restore an adequate funding level for astrobiology research, based on consultation with the scientific community, that will lead to the achievement of the goals of the *New Frontiers in the Solar System* decadal survey. NASA should provide a stable and sustainable funding environment that is adequate to ensure the vitality and continued scientific productivity of all its research and analysis programs.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey encourages NASA to continue the integration of astrobiology science objectives with those of other space science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that address key questions in astrobiology and planetary science." (pp. 9, 158)	**Grade: B** **Trend: ↑**

The Mars science program has done extremely well in efforts to integrate astrobiology as a central element and thrust of the entire research effort. All of the Mars missions have a strong astrobiological component, and

[2]The name of the Solar System Division was changed to Planetary Science Division in 2004.

[3]See, for instance, A. Lawler, "Astrobiology Fights for Its Life," *Science* 315:318-321, 2007; K. Krajick, "Robot Seeks New Life—and New Funding—in the Abyss of Zacaton," *Science* 315:322-324, 2007; A. Lawler, "It Rains in Spain and Wilts in Australia," *Science* 315:320, 2007.

this is also reflected in the Mars-related R&A and DAP efforts. In the other solar system science disciplines, this level of integration has been started but is not nearly at the advanced state that it has reached in the Mars program. For example, astrobiology is a component of research efforts concerning Europa and Titan and is also a major explanation for interest in Enceladus.

Recommendation: NASA should continue to work to integrate astrobiology more completely into all solar system science disciplines.

***New Frontiers* Recommendations**	**Results of Midterm Review**
"The SSE Survey recommends that well before cosmic materials are returned from planetary missions, NASA should establish a sample-analysis program to support instrument development, laboratory facilities, and the training of researchers." (p. 9) "The SSE Survey recommends that NASA establish, well before samples are returned from planetary missions, a sample-return program to address analytical and facility issues and the training of researchers in an integrated manner. Such a program will allow focus on the optimization of science and technology resources." (p. 171)	**Grade: A Trend: →**

NASA responded well to these recommendations as demonstrated by preparations for Stardust and Genesis samples. This program has been established and running since 2003. In FY 2003, $4 million was awarded in new grants; this amount decreased to $2 million in FY 2004, and to $1.6 million in FY 2005, but rose again to $2.8 million in FY 2006. The Research Opportunities in Space and Earth Sciences (ROSES) 2007 solicitation suggests that $4.0 million will be available for new awards. The grants that were funded in FY 2006 appear to focus on techniques suitable for the analysis of Stardust and Genesis samples.

Many of the Stardust and Genesis samples from the Johnson Space Center in Houston have been distributed to the scientific community throughout the country. The committee applauds NASA for accomplishing this in a timely fashion. Decontamination of the Genesis samples will require continuing attention. The Mars Sample Return mission will require robust advance planning and research preparation that should begin within the next 5 years.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"In addition, planetary protection requirements for missions to worlds of biological interest will require investments, as will life-detection techniques, sample quarantine facilities, and sterilization technologies." (p. 9)	**Grade: B Trend: →**

NASA has a small planetary protection R&A program that funded 10 new grants from FY 2003 to FY 2006 for a total expenditure of $410,000. The total expenditure for grants has declined from $150,000 in FY 2003 to only $60,000 in FY 2005 and $100,000 in FY 2006. The two grants funded in FY 2005 were targeted to the protection of Earth when new material is returned and the protection of a planet when a spacecraft lands on it. By contrast, the four grants that were awarded in FY 2006 focused on spacecraft testing and decontamination. The committee has concluded that the planetary protection program is prudently using funds in a targeted manner to address specific questions associated with planetary protection.

***New Frontiers* Recommendation**	**Results of Midterm Review**
"The SSE Survey recommends the initiation of a program of Planetary Fellows, that is, a postdoctoral program analogous to the Hubble and Chandra fellowships, which have done so much to nurture the next generation of astronomers and astrophysicists." (p. 164)	**Grade: C Trend: ↑**

The committee commends NASA for establishing the Fellowships for Early Career Researchers program, which will contribute significantly to the training of the next generation of planetary scientists. However, few in the intended target community are aware of the program's existence. It is listed as element C.22 of the ROSES 2007 NASA Research Announcement (NRA), nearly invisible to the graduate and postdoctoral students who are looking for support. At present, proposals for early-career researchers may be submitted to 12 of the 26 solar system-related R&A programs of the ROSES 2007 NRA. Notably missing is the capability to submit early-career research proposals to the New Horizons or Cassini data analysis programs, or to the Origins of Solar Systems program. In order to have the same level of visibility and prestige as the Hubble Fellowships, the program would benefit from being targeted to young researchers, early in their careers, and should be advertised as a postdoctoral fellowship program rather than as an R&A program. For example, it would benefit from being listed on the American Astronomical Society Job Register and in the newsletter of the Division of Planetary Sciences. Brochures or flyers should be sent to all astronomy, planetary science, and planetary geology departments.

Recommendation: NASA should improve the visibility of its Fellowships for Early Career Researchers program and advertise it as a postdoctoral program. NASA should also expand the participating research program areas to include origins of solar systems, as well as all appropriate space mission data analysis programs.

PLANETARY ASTRONOMY

NASA has had a historic tradition of conducting ground-based planetary astronomy. Because missions for solar system exploration are infrequent and expensive, ground-based observations are essential for the support of current missions, particularly during the encounter phase. Such observations are also vital after mission termination, in order to make the best use of the data obtained from the spacecraft. Ground-based observations are also an essential element in planning for future missions. As we move well into the 21st century, the focus of planetary science continues to evolve, but much still depends on the use of ground-based facilities to advance the understanding of the solar system and to focus attention on important scientific questions to be investigated by NASA spacecraft. NASA's continued support of key facilities enables continued progress in the exploration of the solar system.

New Frontiers **Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends that NASA partner equally with the National Science Foundation to design, build, and operate a survey facility, such as the Large Synoptic Survey Telescope (LSST) described in *Astronomy and Astrophysics in the New Millennium*, to ensure that LSST's prime solar system objectives are accomplished." (pp. 9, 207)	**Grade: F**	**Trend: ↓**

The National Science Foundation (NSF) is formulating a project to build the Large Synoptic Survey Telescope, now in its early conceptual design phase. NASA has decided, however, not to participate in the project. While it is recognized that equal participation may not have been feasible for any number of valid reasons, some NASA share in the LSST would have been desirable from the perspective of planetary science. NASA's one-sixth share in the two Keck telescopes has borne fruit for planetary science, and a similar arrangement might have been possible for planetary science in the LSST. It appears that there has been little or no liaison activity between NASA and NSF concerning the LSST, even though there are significant solar system objectives for the telescope. In this early stage, the committee believes that some NASA contact with the LSST project would be helpful, in order to protect the solar system objectives from being compromised inadvertently in the planning, particularly if it becomes necessary to reduce the scope of LSST.

Recommendation: NASA should establish formal contacts with the Large Synoptic Survey Telescope project.

New Frontiers **Recommendations**	**Results of Midterm Review**
"Other powerful new facilities highlighted in [*Astronomy and Astrophysics in the New Millennium*]—for example, the James Webb Space Telescope (formerly the Next Generation Space Telescope)—should be designed, where appropriate, to be capable of observing moving solar system targets." (p. 9) "It is noted, however, that using Earth-orbiting facilities for planetary observations imposes special constraints—notably the need to track moving targets—and the SSE Survey endorses the incorporation of this technically difficult but essential capability on all relevant astronomical telescopes." (p. 166)	**Grade: F** **Trend: ↑**

NASA is currently undertaking a complex and expensive telescope program known as the James Webb Space Telescope and scheduled for launch in 2013 (Figure 5.2). The committee was informed that JWST requirements have never included tracking objects in the solar system. Apparently this recommendation from the solar system decadal survey was never passed on to the NASA Astrophysics Division so that such a capability could have been planned as part of JWST from the inception of the mission. The JWST project is now undertaking an initial study to determine if the telescope can be adapted to track moving solar system targets and to estimate how much this capability may cost. The committee was informed by representatives at NASA's Goddard Space Flight Center that it may be possible to include such a capability in the telescope by means of software changes and that this would not be prohibitively expensive.

Recommendation: NASA should incorporate into the James Webb Space Telescope as quickly as possible the capability to track moving solar system objects.

New Frontiers **Recommendations**	**Results of Midterm Review**
"The SSE Survey recommends that NASA continue to support ground-based observatories for planetary science, including the planetary radar capability at the Arecibo Observatory in Puerto Rico and at the Deep Space Network's Goldstone facility in California, the Infrared Telescope Facility on Mauna Kea in Hawaii, and shares of cutting-edge telescopes such as the Keck telescopes on Mauna Kea, as long as they continue to be critical to missions and/or scientifically productive." (p. 165) "The SSE Survey recommends that the planetary radar facilities, the Infrared Telescope facility and NASA support for planetary observations at large facilities such as Keck be continued and upgraded as appropriate, for as long as they provide significant scientific return and/or provide mission-critical service." (p. 206)	**Grade: B** **Trend: ↓**

The NASA Planetary Astronomy Program built the Infrared Telescope Facility (IRTF) on Mauna Kea in the 1970s and has operated it ever since to benefit ground-based planetary astronomy investigations. This facility has contributed significantly to our understanding of the solar system. The results from IRTF research have been absolutely crucial for the planning, development, and ongoing support of many of the recent and current NASA missions such as Galileo, Cassini, and New Horizons. NASA's continued support of IRTF will ensure that this very productive relationship between ground-based and spacecraft research will continue into the future.

Similarly, the investment by NASA in the two Keck telescopes has been extremely successful and beneficial. This investment has given planetary astronomers access to the state-of-the-art instruments on the largest telescopes in the world. The Keck telescopes have been particularly productive in the search for extrasolar planets. The Keck Observatory also played a vital role in the Deep Impact comet encounter by imaging the moment of impact. Access to the Keck telescopes enabled by NASA has led to exciting and unexpected results that have helped to shape current and future research directions.

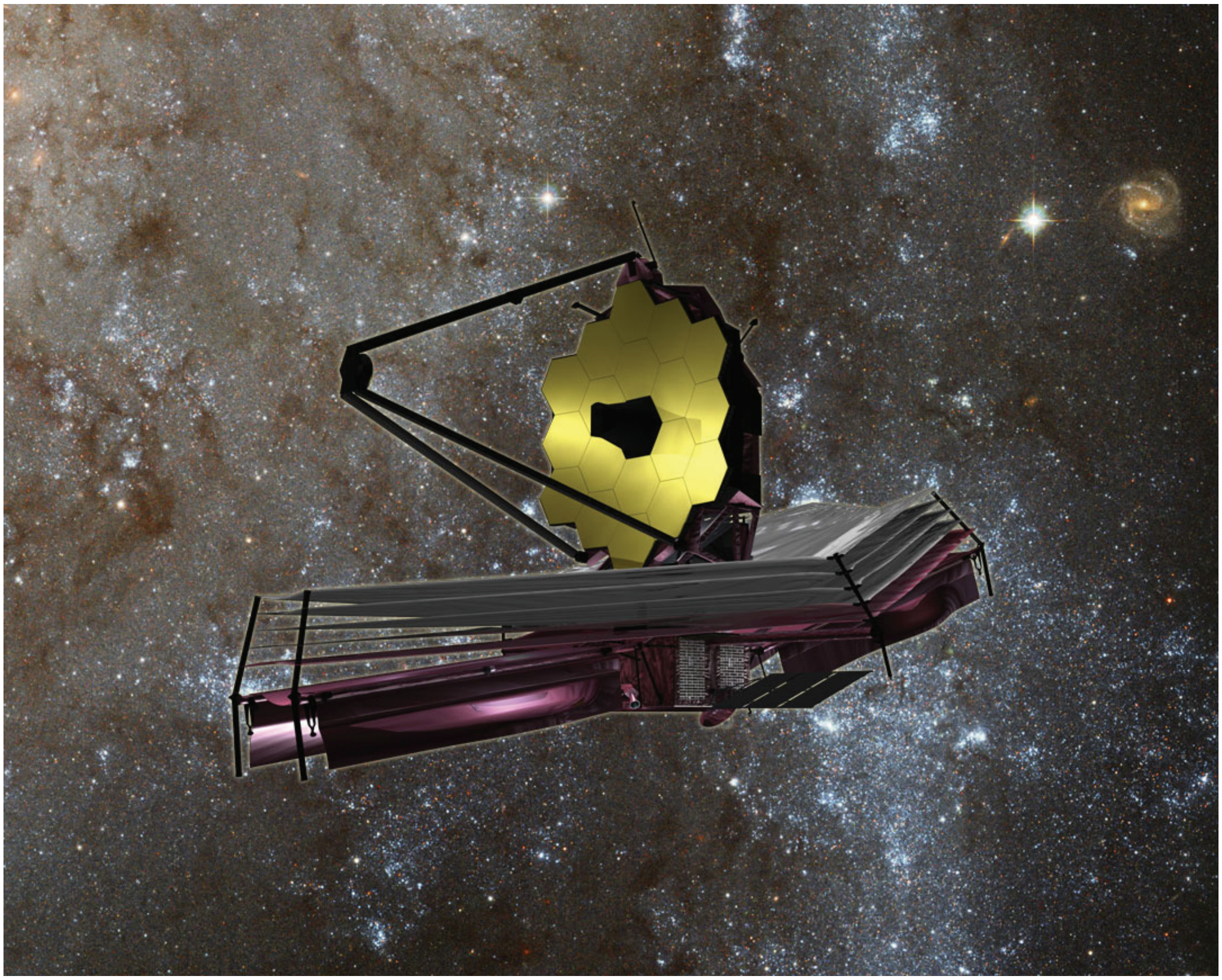

FIGURE 5.2 The James Webb Space Telescope. SOURCE: NASA Goddard Space Flight Center.

Use of the Deep Space Network Goldstone facility and the Arecibo antenna for active radar studies of many solar system bodies has been extremely productive. This includes not just the well-known imaging of numerous asteroids, but also the measurement of surface topographies, including fine-scale surface structure and mineral properties and rotation rates of Mercury, Venus, and the Moon. After a Senior Review of the Arecibo facility by the National Science Foundation, it appears as if NSF will discontinue funding for Arecibo's radar, and NASA has not agreed to take over the funding. Thus, within 1 year, Arecibo's radar may be discontinued. While it is probably unrealistic for NASA to consider a complete takeover of Arecibo, NASA could investigate partnering with NSF and other interested parties to ensure the continued availability of this facility for solar system research.

New Frontiers **Recommendation**	**Results of Midterm Review**
"The SSE Survey endorses the 2001 astronomy and astrophysics decadal survey recommendation for a Giant Segmented Mirror Telescope and further recommends that it be utilized for the physical characterization of solar system objects." (p. 208)	**Grade: N/A**

There was no clear "action item" for NASA in the decadal survey's endorsement of the Giant Segmented Mirror Telescope (GSMT), and indeed NASA has taken no action. NSF has led U.S. involvement in the next generation of very large telescopes, through its National Optical Astronomy Observatory Giant Segmented Mirror Telescope Program Office. The two consortia that have responded to the GSMT initiative, the Thirty Meter Telescope and the Giant Magellan Telescope, both target solar system science and planetary system formation and evolution in their science justifications. It would be helpful to have a NASA liaison with the National Optical Astronomy Observatory Giant Segmented Mirror Telescope Program Office to ensure that NASA science objectives can be achieved in this project. See also Box 5.1.

FLIGHT MISSION DATA ANALYSIS

New Frontiers **Recommendation**	**Results of Midterm Review**	
"The SSE Survey strongly encourages exploration of ways to accomplish the following: improve the early involvement of the PDS with missions." (p. 167)	**Grade: A**	**Trend: ↑**

The Planetary Data System (PDS) project has been proactive in early involvement with missions. The PDS project has discussed archiving requirements with the people writing mission Announcements of Opportunity and has made sure that the most recent archiving documents are available to potential principal investigators. The PDS project has worked with Discovery and Scout proposal PIs to have realistic costs of data archiving put into proposals. The PDS project has been involved in the proposal review process to evaluate the data-archiving plans of missions.

Recommendation: NASA Announcements of Opportunity should require each space mission proposal to estimate and budget explicitly for archiving activities.

New Frontiers **Recommendation**	**Results of Midterm Review**	
"The SSE Survey strongly encourages exploration of ways to accomplish the following: . . . Increase the PDS budget and streamline its procedures, while not lowering standards or eliminating peer reviews, in order to deal with the data, perhaps considering the function to be funded at a fixed fraction, such as 1 percent of the mission development and operations budget in addition to a small base budget, to ensure that the PDS can cope with varying amounts of archiving . . . ." (p. 167)	**Grade: A**	**Trend: →**

BOX 5.1
Important Science Falling Through the Bureaucratic Cracks: A Note on the Study of Exoplanets

The many exoplanets that have been discovered have presented several fundamental scientific problems for planetary studies. There were no explicit recommendations in the *New Frontiers in the Solar System* decadal survey concerning the study of exoplanets despite their direct relevance to the understanding of solar system formation.[1] The Committee on Assessing the Solar System Exploration Program does not know if our solar system is an exceptional example of a planetary system or whether it is a typical example. There are probably many possible planetary system morphologies, but whether they fall into well-defined classes or a general scattering of disparate types is not known; nor is this likely to be known until a variety of new observing programs have been undertaken.

The principal techniques that have been exploited so far are as follows:

- *Radial velocity studies of stars*, detecting the exoplanet by the reflex motion of the parent star about the barycenter, and
- *Photometry*, observing the transit of an exoplanet across the stellar disc.

A third method, *stellar astrometry*, observes the wobble of the parent star about the barycenter and is complementary to the radial velocity method, obtaining the mass of the exoplanet without the *sin i* indeterminacy of the radial velocity method. The radial velocity method is most sensitive for small values of the semi-major axis, revealing a completely new category of Jupiter-like planets within a few tens of astronomical units. Astrometry is the more sensitive method for large values of the semi-major axis and thus is best suited to detecting systems that might be analogous to our solar system. The photometric method requires a star where the planetary plane is seen edge-on; its highest probability occurs when the exoplanet is close to the star, and detection probability drops as the semi-major axis increases; for exoplanets with several-year orbital periods, the probability of detection diminishes severely.

The organization of exoplanet studies within NASA appears to be inefficient, split between the Planetary Science Division and the Astrophysics Science Division. Research is supported by the Origins of Solar Systems Research and Analysis Program in the Planetary Science Division, and the Astrobiology Research and Analysis Program; the Keck funding is supported by the Astrophysics Science Division, as is the forthcoming (photometric) Kepler mission. Astrometry had been supported by the Astrophysics Science Division, but for budgetary reasons NASA has canceled the Keck outrigger program and dropped both the Stellar Interferometry Mission and the Terrestrial Planet Finder programs to a very low level. At the same time, the budget available to support a wide variety of exoplanet studies has been diminished severely, despite the unprecedented successes in this field over the past several years. This seems to be a clear example of an interdisciplinary program that is in danger of falling through the cracks between administrative divisions. It is not within the charge of this committee to recommend what action should be taken, but it is clear that NASA's Science Mission Directorate should review its various exoplanet activities in order to work out a more orderly process.

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

The PDS budget has gradually increased over the past several years. PDS archiving procedures have become more streamlined. The PDS archiving preparation guides have recently been revised, replacing data preparation workbooks that were difficult to use. The PDS project has prepared calculators to determine archiving costs for missions.

Since the cost of archiving depends critically on the type of data produced by a mission and its instruments, fixing the costs at some fraction of total mission cost is probably not realistic. Instead, the PDS has developed good cost estimation models and algorithms and will work with mission PIs to ensure accurate cost estimates for data-archiving needs.

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"The SSE Survey strongly encourages exploration of ways to accomplish the following: . . . Ensure that missions as well as R&A projects producing large data sets have adequate funding for proper archiving." (p. 167)	**Grade: B**	**Trend: ➜**

NASA has become properly aware of data-archiving needs for missions. As explained above, mission proposal reviews now explicitly examine data-archiving plans. However, data archiving in the much smaller R&A programs is a neglected area. There have never been archiving requirements for R&A PIs. The average R&A grant is so small that data archiving is normally ignored.

Recommendation: NASA should consider encouraging principal investigators to offer archival data sets in their initial proposals so that the review panels can assess the desirability of the data sets.

FIGURE 6.1 The Deep Space Network allows NASA to communicate with distant spacecraft. However, future missions will seriously strain its capabilities. SOURCE: NASA.

6

Enabling Technologies

Advanced technology to enable planetary exploration missions is addressed in the *New Frontiers in the Solar System* decadal survey.[1] Subjects under the heading of Advanced Technology in that report are (1) technology development, (2) generic technologies, (3) mission-specific technologies, (4) technologies for the following decade, and (5) the Deep Space Network.[2]

NASA defines technology for future space missions according to technology readiness levels (TRLs) on a scale of 1 to 9. Technologies that have a low TRL rating are the most immature and require the most funding to make them available for incorporation into spacecraft missions. For example, a TRL of 1 means that the basic principle has been observed and reported, whereas a TRL of 9 means that the hardware has actually flown on a mission and proven successful. In the past, NASA has funded technologies at all levels of readiness through different programs. However, in recent years the agency has cut funding, starting with funding for technologies with the lowest levels of readiness and then eventually for those higher up the scale. Today the agency is funding very little technology development except at the highest TRL levels. NASA has ceased sponsoring the development of cutting-edge technology and has made severe cuts to the New Millennium technology development program.

Enabling Technologies **OVERALL ASSESSMENT: Grade: D Trend: ↓**

The committee is seriously concerned that NASA has severely cut back its technology development programs, making it extremely difficult for the agency to conduct remaining missions recommended by the decadal survey. Many of the technologies addressed individually in this chapter have received grades as high as they are only because of past progress, but have suffered substantially in recent years. Overall, NASA's enabling technologies program lacks funding and strategic direction yet is vital to future progress in implementing the decadal survey goals. Because of this, the committee has given the agency a grade of D with a downward trend.

Unlike other areas of this report, enabling technologies is one area in which the committee must conclude that the only realistic solution to the lack of progress in technology development is for NASA to reinvigorate its

[1] See the section entitled "Advanced Technology" in Chapter 8, "Recommended Flight Investigations and Supporting Ground-Based Activities: 2003-2013," in National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy,* The National Academies Press, Washington, D.C., 2003, pp. 202-206.

[2] The complex subject of enabling technologies is further discussed by this committee in Appendix C (providing greater detail on technology programs) and Appendix D (providing an explanation of technology readiness levels).

technology development program and to create a technology development program that is independent of flight programs. This independence is vital because when flight programs have gone over budget in the past, technology development funding has often been one of the first things to be cut by program managers, thereby creating a situation in which technology development is never properly funded. An independently funded technology development program would be insulated from such pressures. The committee stresses that it is important that safeguards are put in place so that the independence from flight programs does not result in a nonalignment with future mission needs.

Recommendation: NASA should develop a strategic plan for technology development and infusion independent of flight programs. In addition, NASA should restore funding to its New Millennium program.

TECHNOLOGIES FOR THE FOLLOWING DECADE

Low-TRL technology programs are the most conceptual and hence are focused on the long-range technology needs. The Cross-Enterprise Technology Development Program (CETDP) funded many technologies needed for planetary exploration. When NASA formed the Exploration Mission Systems Directorate, the agency moved the CETDP/Space Technology Program to that directorate and reprogrammed the resources ($300 million to $400 million) to exploration needs (i.e., human spaceflight). As a result, NASA no longer has a dedicated major source of funding for long-range technology needs for planetary exploration. Mid-TRL funding in the Science Mission Directorate (SMD) is in three current programs—in Space Propulsion, Radioisotope Power, and the Mars Technology program. All of these programs can address significant needs for mid-TRL technology or advanced development, but all have seen substantial funding reductions in the past 3 years. At high TRLs, spaceflight validation has been important in infusing a number of spaceflight technologies into flight missions. The New Millennium program has played a key role in flight experiments, including subsystem experiments on the ST-6 and ST-8 spacecraft, as well as a system experiment on the ST-5 and ST-7 spacecraft. However, funding reductions in the FY 2008 New Millennium budgets have already delayed the ST-8 flight (testing a lightweight solar array, commercial off-the-shelf processor) and indefinitely postponed the ST-9 project.

The committee considers NASA's recent actions concerning enabling technologies—like its recent actions concerning research and analysis—to be examples of the agency's making short-term budgetary decisions that threaten the long-term viability of its overall program. Many of the remaining missions recommended in the decadal survey *cannot* be accomplished only with existing technology. There are enabling components that are required:

- *Venus In Situ Explorer:* Multiple technology developments are required;
- *South Pole-Aitken Basin:* Guidance and associated autonomy technologies are required;
- *Comet Surface Sample Return:* The sample return can be accomplished now, but is too expensive;
- *Jupiter deep atmosphere probes:* NASA's Juno mission accomplishes some of the Jupiter atmosphere science, but the decadal survey calls for probes deep into the atmosphere to provide more details; and
- *Europa Geophysical Explorer:* The current Jet Propulsion Laboratory design with eight Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) cannot be flown by 2020—there is insufficient plutonium fuel to accomplish the mission with MMRTGs. Without the Advanced Stirling Radioisotopic Generators, future missions to the outer solar system become increasingly difficult, if not impossible.

The committee is concerned because NASA has not invested in required technology and shows little indication of reversing this trend. If this trend is not reversed immediately, the number and types of missions that the agency will be able to undertake in the future will be severely reduced.

TECHNOLOGY DEVELOPMENT

***New Frontiers* Recommendation**

"The SSE Survey recommends that NASA commit to significant new investments in advanced technology so that future high-priority flight missions can succeed." (p. 8)

The committee has chosen to highlight below 13 separate areas from the decadal survey.

	Results of Midterm Review	
Advanced Radioisotope Power Systems	**Grade: B**	**Trend: ↑**

The decadal survey noted that advanced radioisotope power systems (RPSs) are required to replace the depleted inventory of first-generation RPSs. Solar power is generally insufficient beyond the asteroid belt, provides limited power for spacecraft systems, and severely limits the lifetime of landed spacecraft.

Full qualification and use of the Multi-Mission Radioisotope Thermoelectric Generator on the Mars Science Laboratory scheduled for launch in 2009 provides an advanced system that will be fully qualified for other landers. While the specific power is low, the MMRTG offers a reliable system, and NASA has made significant progress. NASA plans work on Stirling converters, and if this is successful it will reduce the requirement for plutonium on future missions and enable new missions using radioisotope electric propulsion (REP).

	Results of Midterm Review	
In-Space Fission-Reactor Power Source—Nuclear-Electric Propulsion	**Grade: Withdrawn from effort**	**Trend: ↓**

These decadal survey recommendations were based on the assumption of a continuing nuclear power and propulsion program in NASA under the Prometheus program. With the demise of Prometheus, these recommendations are now moot, although the loss of the technology is regrettable. However, a significant amount of work was accomplished that allows better appreciation of the inherent issues in bringing this technology to fruition. Energy conversion systems for surface power systems are still being worked on as part of the Constellation program; these efforts should be monitored for possible use in future robotic solar system exploration missions.

	Results of Midterm Review	
Advanced Ion Engines	**Grade: A**	**Trend: →**

In 2005, NASA canceled work on the Prometheus program to develop a fission reactor to power spacecraft. Without a nuclear reactor, the only way of continuing to accomplish high (≥3 km/s total in-space) delta-V missions is with solar electric propulsion (SEP), or potentially REP. The 30 cm thruster used for the Deep Space-1 and Dawn spacecraft was not optimized for specific power. The NASA Evolutionary Xenon Thruster (NEXT) and High Voltage Hall Accelerator (HiVHAC; an advanced Hall effect thruster) should contribute to lower mass, lower costs, and lower risks and will help to enable more challenging science missions.

	Results of Midterm Review	
Aerocapture	**Grade: C**	**Trend: ↓**

While there have been advances in aerocapture, flight qualification is required before its use in planetary missions will be acceptable. Currently the only approach to flight qualification is the New Millennium program. With the budget downturn through FY 2010, there is no mechanism to qualify aerocapture under the current approach prior to the end of 2013. In the absence of a flight test, there should be a detailed study of how far the ongoing testing of thermal protection system concepts for the Crew Exploration Vehicle (CEV) can help qualify the needed systems for aerocapture in robotic exploration of the solar system.

	Results of Midterm Review	
Ka-band Communications	**Grade: A**	**Trend: ↓**

NASA continues to move toward use of the Ka band as the standard for deep-space communications. Advanced coding and compression for part of the Ka-band architecture are in development, and all Deep Space Network (DSN) 34-meter stations are now upgraded to use Ka band. Future needs have been quantitatively assessed, and a way forward using arrays of small antennas has been articulated. The aging 70-meter antennas are in desperate need of both current maintenance and eventual replacement with Ka band with the same equivalent aperture area. Failure to address the need to maintain and upgrade the DSN could place the entire NASA planetary exploration program in jeopardy of suffering a single-point failure should any 70 meter antenna system fail.

Recommendation: NASA should conduct a study of the trade-offs of the cost versus risk of developing a Ka-band array system to handle the required transmissions (uplink and downlink) and determine whether optical communications are required for data delivery during the 2013-2023 time frame. Prior to the next decadal survey, NASA should present the results of such a study to the science community.

	Results of Midterm Review	
Optical Communications	**Grade: F**	**Trend: →**

The development of first-generation optical communications has been put off until 2018. The Deep Space Network Roadmap suggests that an optical communications infrastructure may be operational by 2022. However, the committee was informed that these dates and the system are only notional and that NASA does not have a plan to even select a basic architecture. Optical communications will require technology developments on the spacecraft side (transmitter, receiver, guidance and control, and software developments) as well as infrastructure on the ground side.[3] NASA should determine whether optical communications are required for data delivery during the 2013-2023 time frame and scope the technology development, operations, and maintenance required for a notional system.

	Results of Midterm Review	
Spacecraft Autonomy	**Grade: C**	**Trend: ↓**

The New Millennium ST-6 Autonomous Science Experiment on Tacsat 2 validated orders-of-magnitude increases in science per bits downlinked. The AutoNav technology qualified on Deep Space-1 was used on the impactor on the Deep Impact mission. However, there is no clear path for these focused technologies to have a general impact on subsequent missions. The autonomy program was canceled in 2004 with no funding for further development of either of these focused technologies. The state of the art and realistic expectations need to be well articulated to the science community prior to the next decadal survey.

	Results of Midterm Review	
Advanced Avionics Packaging and Miniaturization	**Grade: B**	**Trend: ↓**

[3]Unlike the existing Deep Space Network with the receiving stations located on the ground, current concepts for optical communications networks envision receiving spacecraft in Earth orbit; these receiving spacecraft would intercept the beamed information and relay it to the ground.

In the recent past, NASA made significant progress on developing advanced avionics packaging and miniaturization. NASA has made progress under previously funded programs, such as X2000, the CETDP, and the Prometheus/Deep Space Avionics program. But with the exception of the Mars Technology Program, most of the funding in these areas has been eliminated. The progress noted above has fed new technologies into many of the current missions, but without these programs many future programs are in jeopardy. The X2000 and Prometheus/Deep Space Avionics programs were focused on the outer planets and specifically on a Europa mission. If NASA is to comply with the decadal survey recommendation to fund a Europa mission (see Chapter 3 in this report), the agency will have to develop radiation-hardened electronics. There has been no continued development of the CETDP high-temperature/high-pressure/corrosion-resistant technologies required for the Venus In Situ mission. Cold-temperature/thermal cycling electronics are under development as part of the Mars program and should be assessed for any relevance to the Comet Surface Sample Return mission and Titan missions.

	Results of Midterm Review	
Instrumentation Miniaturization	**Grade: C**	**Trend: ↓**

Programs for support of these developments are in place, but funding has been eroding for non-Mars programs. Four continuing Planetary Science Division research and develpment programs are addressing the instrument technology needs: Planetary Instrument Definition and Development (PIDDP), Mars Instrument Development Project (MIDP), Astrobiology Science and Technology Instrument Development (ASTID), and Astrobiology Science and Technology for Exploring Planets (ASTEP). Only MIDP (Mars) covers mid-TRL technologies; no comparable program exists for non-Mars technology. Reductions in astrobiology funding have impacted both ASTID and ASTEP. How well the developments under MIDP can be leveraged to support non-Mars missions remains to be seen. Instrumentation for the South Pole-Aitken Basin and Comet Surface Sample Return missions is apparently not funded. No instruments for the Venus-environment mission are being supported, nor are instruments for outer-planet entry probe missions.

	Results of Midterm Review	
Autonomous Entry and Precision Landing	**Grade: C**	**Trend: ↓**

NASA has made progress in the important technology area of autonomous entry and precision landing. The Mars Exploration Rovers used the Descent Image Motion Estimation System to estimate lateral velocity and ensure a safe landing. The Mars Science Laboratory mission will reduce landing uncertainty by autonomously controlling the direction of the lift vector of the entry vehicle and will use Skycrane technology for heavy-vehicle deployment (although hazard avoidance at landing was removed from the mission). Future missions to Mars need more-advanced methods of detecting, avoiding, or tolerating landing hazards, and capabilities that enable "pinpoint landing" within tens of meters to 1 kilometer of a target site. Also, NASA needs to make an assessment of which elements of the Mars Technology Program are enabling for a Mars Sample Return mission. NASA will have to conduct an independent assessment of the analogous technology needs for the Moon, Venus, asteroids, and other targets.

Recommendation: NASA should make an assessment of which technologies will be required for Mars Sample Return and conduct an independent assessment of the analogous technology needs for the Moon, Venus, asteroids, and other targets.

	Results of Midterm Review	
In-Situ Sample Gathering, Handling, and Analysis	**Grade: C**	**Trend: ↓**

While there has been extensive development of Mars technologies in support of the Mars Science Laboratory mission, there are no SMD technology programs for the development of technology needs related to Venus and comets other than through the NASA Small Business Innovation Research program. In addition, planetary protection funding is focused largely on compliance with requirements and not on technology to develop alternative ways of meeting requirements. Lack of attention to development of methods to gather samples without damage and to analyze them for their value may preclude the selection of scientifically compelling samples for any sample return mission, whether to Mars, Venus, asteroids, or comets. There is no obvious initiative in place to continue even the limited Mars-focused component for missions following the Mars Science Laboratory.

	Results of Midterm Review	
Autonomous Mobility	**Grade: C**	**Trend: ↓**

In the area of surface rover technology, the overarching goal is to increase the navigational range, access, precision, safety, and time efficiency of autonomous mobile Mars surface science exploration. "Mobility" to access regions below the surface is also being pursued using both drills and "robotic moles." The Mars program is attempting to bring subsurface access to a high TRL for deep drilling to 20 meters, shallow drilling to 0.5 meter, and permafrost drilling. Work on robotic moles has focused on subsurface ice access with cryobots (i.e., robots capable of operating in icy conditions), but these are still at a low level of maturity.

With respect to aerial vehicles, the Mars Technology Program is working on Mars balloon technology, but for Titan and Venus there has been no concept development or technology work except through the Small Business Initiative Research program. Work that has been accomplished tends to be Mars-centric, and applicability to the other targets called out in the decadal survey is questionable owing to the environmental differences, for example among Venus, Titan, asteroids, and comets. The Mars-centric nature of the work is good for Mars exploration, but it does not support other developments required to accomplish missions to other targets in the decadal survey.

	Results of Midterm Review	
Ascent Vehicles	**Grade: F**	**Trend: ↓**

Ascent vehicles are spacecraft designed to lift off a planetary surface in order to bring samples back to Earth. NASA has made little progress on these. The Mars Exploration Program has terminated all work on ascent vehicles for Mars Sample Return. The agency is also not conducting any technology development on the South Pole-Aitken Basin Sample Return ascent vehicle. The agency has also dismissed Venus ascent vehicle requirements and is not pursuing any technology development in this area owing to its high level of difficulty. All activities are shut down with no plans for restarting them, yet this task is on the critical path for all landed sample return missions.

THE DEEP SPACE NETWORK

***New Frontiers* Recommendation**	**Results of Midterm Review**	
"The SSE Survey recommends upgrades and increased communications capability for the DSN [Deep Space Network] in order to meet the specific needs for this program of missions throughout the decade, and that this be paid from the technology portion of the Supporting Research and Technology (SR&T) line rather than from the mission budgets." (p. 206)	**Grade: B**	**Trend: ➜**

The decadal survey noted a significant need for upgrading the Deep Space Network to deal with "insufficient communications capability and occasional failure as it ages." A variety of potential solutions were mentioned, along with the admonition that "any upgrade cannot realistically be charged to the first mission that uses it. . . ."[4] The decadal goal is the provision of upgrades and increased communications capability for the DSN to deal with

[4]National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy, The* National Academies Press, Washington, D.C., 2003, p. 206.

the missions flown during the decade. NASA's detailed assessment and plan drawn up by the DSN to deal with current and anticipated DSN traffic constitutes significant progress toward reaching the goal. The committee notes that doing nothing will lead to the failure of the current system. The 70-meter antennas may begin to fail before 2015 in a way that cannot be repaired. Such failure would put at risk continued data collection from the Voyager spacecraft as well as from the New Horizons spacecraft during its 2015 flyby of Pluto. The DSN enables all that the Science Mission Directorate does; the assigned grade and trend are contingent upon following through with a replacement/upgrade plan for the DSN stations.

Recommendation: NASA should fund the Small Aperture Receive Array for the Deep Space Network and plan to replace the 70-meter antennas with arrays of small-diameter antennas by 2015.

LAUNCH VEHICLE INFRASTRUCTURE

Access to space remains a significant cost issue that is getting worse with the phaseout of the Delta II and associated launch complex 17 at the Cape Canaveral Air Force Station (Figure 6.2). This problem was exacerbated when a commercial launch market boom failed to appear in the late 1990s and early part of the new decade. The problem is the large cost of infrastructure maintenance as part of overall launch service costs.

NASA's share of the Expendable Launch Vehicle market is insufficient to drive prices; hence NASA is at the mercy of the same market forces that have driven unit costs up as projected launch rates have decreased. In any event, NASA will have to figure out how to deal with larger and more expensive Delta IVs and Atlas Vs rather than the workhorse Delta II. The committee notes that access to affordable launch vehicles enables all of the Science Mission Directorate's programs, not only the planetary ones.

To deal with this situation, NASA could begin looking for a negotiated contract price for evolved expendable launch vehicles that will guarantee launch prices for the rest of this decade as well as the next. Under public law, and given the requirements for New Frontiers and flagship missions, NASA needs to negotiate appropriate purchases with the United Launch Alliance to fill the gap left by the phaseout of the Delta IIs.

FIGURE 6.2 Launch of the Dawn spacecraft aboard a Delta II rocket. The Delta II is slated for retirement by NASA in the next few years. SOURCE: NASA.

Appendixes

A

Statement of Task

In Section 301(a) of the NASA Authorization Act of 2005, the Congress directed NASA to have "[t]he performance of each division in the Science directorate . . . reviewed and assessed by the National Academy of Sciences at 5-year intervals."[1] In late 2006 NASA asked the National Research Council (NRC) to conduct such an assessment for the agency's Planetary Science Division. The committee's statement of task is to:

Review the alignment of NASA's Planetary Exploration Division program with previous NRC advice—primarily the reports *New Frontiers in the Solar System: An Integrated Exploration Strategy* and several recent studies concerning Mars, such as *Assessment of Mars Science and Mission Priorities*.[2] More specifically, the committee shall address the following:

1. The degree to which NASA's current solar system exploration program addresses the strategies, goals, and priorities outlined in Academy reports;
2. NASA progress toward realizing these strategies, goals and priorities; and
3. Identify any actions that could be taken to optimize the science value of the program in the context of current and forecasted resources available to it.

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[1]SEC. 301. PERFORMANCE ASSESSMENTS.

(a) IN GENERAL.—The performance of each division in the Science directorate of NASA shall be reviewed and assessed by the National Academy of Sciences at 5-year intervals.

(b) TIMING.—Beginning with the first fiscal year following the date of enactment of this Act, the Administrator shall select at least one division for review under this section. The Administrator shall select divisions so that all disciplines will have received their first review within six fiscal years of the date of enactment of this Act.

(c) REPORTS.—Not later than March 1 of each year, beginning with the first fiscal year after the date of enactment of this Act, the Administrator shall transmit a report to the Committee on Science of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate—

(1) setting forth in detail the results of any external review under subsection (a); (2) setting forth in detail actions taken by NASA in response to any external review; and (3) including a summary of findings and recommendations from any other relevant external reviews of NASA's science mission priorities and programs.

[2]The recommendations made in *Assessment of Mars Science and Mission Priorities* (NRC, 2003) were summarized in the *New Frontiers* decadal survey, and therefore including the former was essentially redundant. However, the committee did include recommendations from *Assessment of NASA's Mars Architecture 2007-2016* (NRC, 2006). This was the most recent of three Mars assessment reports and, in the committee's view, was the most up-to-date NRC guidance on NASA's Mars plans.

B

Biographical Sketches of Committee Members and Staff

WESLEY T. HUNTRESS, JR., *Co-chair,* is a staff member and former director at the Geophysical Laboratory of the Carnegie Institution of Washington, where fundamental laboratory research is conducted in geochemistry, geobiology, and physical chemistry at high pressures related to Earth and planetary science. Dr. Huntress began his career in 1968 at the California Institute of Technology's Jet Propulsion Laboratory (JPL) as an astrochemist specializing in chemical processes in the interstellar medium, comets, and planetary atmospheres. He was director of solar system exploration at NASA Headquarters (1990-1992), and then as associate administrator for space science (1993-1998) he was responsible for NASA's robotic science missions to explore the solar system and to observe the universe. At the Carnegie Institution, he continues today as a spokesman and strategist for the scientific exploration of space. Dr. Huntress received his bachelor of science degree in chemistry (1964) and an honorary doctorate of science (2005) from Brown University and his Ph.D. in chemical physics (1968) from Stanford University. His list of awards includes NASA's Distinguished Service Medal, the U.S. Presidential Distinguished Executive Award, the Robert H. Goddard Award from NASA, the Carl Sagan Award from the American Astronautical Society, and a National Endowment for the Arts/Federal Design Achievement award for the Mars Pathfinder mission. Asteroid 7225 has also been named after him. Dr. Huntress is former president of the Planetary Society, an Academician in the International Academy of Astronautics, a lifetime associate of the National Academies, an associate of the Royal Astronomical Society, and a distinguished visiting scientist at JPL. His National Research Council (NRC) experience includes membership on the Committee on Setting Priorities for NSF-Sponsored Large Research Facility Projects (2003-2004) and the Solar System Exploration Survey Steering Group (2000-2002).

NORINE E. NOONAN, *Co-chair,* is dean of the School of Science and Mathematics of the College of Charleston. Previously she was assistant administrator for research and development at the U.S. Environmental Protection Agency (EPA). In that position, Dr. Noonan served as the principal science adviser to the administrator with line responsibilities for national research programs in pollution sources, fate, and health and welfare effects; pollution prevention and control, waste management, and utilization technologies; and environmental sciences and monitoring systems. Before her service at EPA, Dr. Noonan was vice president for research and dean of the Graduate School at the Florida Institute of Technology. Dr. Noonan also served as chief of the Science and Space Programs Branch of the Energy and Science Division for the Office of Management and Budget (1987-1992). She has served as a budget and program analyst for the Science and Space Programs Branch (1983-1987) and as an American Chemical Society Congressional Science Fellow for the Senate Committee on Commerce, Science, and Transportation (1982-1983). Dr. Noonan has also served as an expert consultant for the congressional Subcommittee on Science, Research, and Technology (1981-1982). She is a member and fellow of the American Association for the Advancement of Science and a member of the American Society for Cell Biology. Dr. Noonan's NRC experience includes service on the Board on Radioactive Waste Management (2002-2005) and on the Steering Committee for a Workshop on an Earth Science Enterprise Federation (vice chair, 1996-1997).

SUSHIL K. ATREYA is professor of atmospheric and space science at the University of Michigan. His current research interests include composition, chemistry, structure, and the origin and evolution of planetary and satellite atmospheres, particularly the giant planets, Titan, Mars, and Venus, and the formation of solar systems. Dr. Atreya is at present a member of the science teams of Cassini-Huygens, Mars Science Laboratory, Juno-Jupiter Polar Orbiter, Venus Express, and the Mars Express missions. He has received the NASA Award for exceptional scientific contributions to the Voyager missions to the giant planets (1981), the NASA Group Achievement Award for outstanding scientific contributions with the Voyager Ultraviolet Spectrometer (1981, 1986, 1990), and NASA group achievement awards for outstanding scientific contributions with the Galileo Probe mass spectrometer and outstanding contributions to the Galileo Project at Jupiter (1996). He is a fellow of the American Association for the Advancement of Science, an Academician of the International Academy of Aeronautics, and a Distinguished Visiting Scientist at the Jet Propulsion Laboratory. He is the author of *Atmospheres and Ionospheres of the Outer Planets and Their Satellites* and editor of *Origin and Evolution of Planetary and Satellite Atmospheres* and three other books. He is at present co-chair of the Venus Exploration Analysis Group (VEXAG) and a member of the Steering Committee of the Outer Planets Assessment Group (OPAG). Dr. Atreya has served three 1-year terms on the NRC Panel on Space Sciences of the Policy and Global Affairs Division's Associateship Program (1984-1985, 1986-1987, 1989-1990).

CARRINE BLANK is a research assistant professor in the Department of Geosciences at the University of Montana, Missoula. Her research focuses on microbial evolution and how microorganisms have co-evolved with the early Earth. She studies microbial populations in boiling silica-depositing springs, with a focus on determining metabolic capabilities of the uncultured earliest branches in the tree of life and their ecological distributions. Her work on phylogenomic dating has led to insights into the early evolution of cyanobacteria and archaea, and aims to identify new age constraints in the tree of life and to reconstruct ancient biogeochemical cycles on Earth.

WILLIAM V. BOYNTON is a professor in the Department of Planetary Sciences at the Lunar and Planetary Laboratory of the University of Arizona. Dr. Boynton's current research interests concentrate on the geochemical evolution of Mars, with special emphasis on water and carbon dioxide. His past research interests include theoretical studies on the nebular condensation of elements and mineralogic and trace-element studies of meteorites, with particular emphasis on primitive meteorites and their Ca- and Al-rich inclusions. He was the team leader for the Gamma-Ray Spectrometer on the Mars Observer Mission, co-investigator on the Mars Polar Lander responsible for the Thermal and Evolved-Gas Analyzer (TEGA) on the Mars Polar Lander, and co-investigator on the NEAR-Shoemaker mission. Currently he is principal investigator for the Gamma-ray Spectrometer on the 2001 Mars Odyssey mission, co-investigator on the Phoenix Mars Lander mission responsible for the TEGA instrument, co-investigator on the MESSENGER mission as the geochemistry lead, and co-investigator on the Cassini mission. He has received several NASA group achievement awards for his work on these missions, and he has received the NASA public service medal for his discovery of subsurface ice in the polar regions of Mars. Dr. Boynton served on the NRC Committee on Planetary and Lunar Exploration (1998-2001).

WILLIAM D. COCHRAN is a senior research scientist at the McDonald Observatory of the Department of Astronomy at the University of Texas. His research interests include extrasolar planetary systems, high-precision measurements of stellar radial velocity variations, variable stars, planetary atmospheres, comets, and asteroids. A leader in the study of planetary systems, Dr. Cochran is a co-investigator on NASA's Kepler mission and has served as chair of the Division for Planetary Sciences of the American Astronomical Society. Dr. Cochran served on the NRC Committee on Planetary and Lunar Exploration (2003-2006) and the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion: A Vision for Beyond 2015 (2004-2006).

LARRY W. ESPOSITO is a professor at the Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder. He is the principal investigator of the Ultraviolet Imaging Spectrograph (UVIS) experiment on the Cassini space mission to Saturn. He was chair of the Voyager Rings Working Group and, as a member of the Pioneer Saturn Imaging Team, he discovered Saturn's F ring. His research focuses on the nature and history of planetary rings. Dr. Esposito has been a participant in numerous U.S., Russian, and European space missions and used the Hubble Space Telescope for its first observations of Venus. He was awarded the Harold C. Urey Prize from the American Astronomical Society, the Medal for Exceptional Scientific Achievement from NASA, and the Richtmyer Lecture Award from the American Association of Physics Teachers and the American Physical Society. Dr. Esposito has extensive NRC experience, including service on the Task Group on the Forward Contamination of Europa (chair, 1999-2000) and the Committee on Planetary and Lunar Exploration (chair, 1989-1992).

G. SCOTT HUBBARD has been recognized as an innovator and leader in science, technology, and management for more than 30 years—including 20 years with NASA. He currently is a consulting professor in the Department of Aeronautics and Astronautics at Stanford University and also holds the Carl Sagan Chair for the Study of Life in the Universe at the SETI Institute. From 2002 to 2006, Dr. Hubbard was the director of NASA's Ames Research Center. In 2003 he served full time as the sole NASA representative on the Columbia Accident Investigation Board, directing impact testing that demonstrated the definitive physical cause of the loss of the space shuttle *Columbia*. In 2000, Dr. Hubbard served as NASA's first Mars program director and successfully restructured the entire Mars program in the wake of mission failures. He is the founder of NASA's Astrobiology Institute. He conceived the Mars Pathfinder mission with its airbag landing and was the manager for NASA's highly successful Lunar Prospector Mission. Earlier in his career, Dr. Hubbard led a small start-up high-technology company in the San Francisco Bay area and was a staff scientist at the Lawrence Berkeley National Laboratory. He has received many honors, including NASA's Distinguished Service Medal. He was elected to the International Academy of Astronautics, is a fellow of the American Institute of Aeronautics and Astronautics (AIAA), and was awarded the Von Karman medal by the AIAA. He has authored more than 50 scientific papers on research and technology. Dr. Hubbard received his undergraduate degree in physics and astronomy at Vanderbilt University and his graduate education in solid-state and semiconductor physics at the University of California, Berkeley.

WILLIAM M. JACKSON is a Distinguished Research Professor for the Department of Chemistry at the University of California, Davis (UCD). He was chair of the department (2000-2005). Before moving to UCD, Dr. Jackson taught at Howard University and worked at the NASA Goddard Space Flight Center. He has been a Guggenheim fellow, received a Humboldt Senior Research Award, received the AAAS Lifetime Mentor Award, and is a fellow of the American Physical Society as well as a fellow of the AAAS. Dr. Jackson was a founder of the National Organization for the Professional Advancement of Black Chemists and Chemical Engineers. His principal areas of expertise are in astrochemistry, chemical kinetics, photochemistry, and laser chemistry. In the field of astrochemistry, he led the team that first used the International Ultraviolet Explorer telescope to observe comets. His laboratory was the first to use tunable dye lasers to detect free radicals from the photodissociation of stable molecules. He was also the first to use them for the measurement of the lifetimes of individual rotational levels that demonstrated that perturbations between electronic states could change the lifetimes of these levels. He has continued to measure the photochemical properties of cometary molecules in the laboratory and has demonstrated plausible mechanisms for the formation of C_2, C_3, and CS radicals in comets. He has published more than 160 scientific papers and has one patent. Dr. Jackson served on the NRC Panel on Chemical Sciences (1983-1985).

MARGARET G. KIVELSON is Distinguished Professor of Space Physics in the Institute of Geophysics and Planetary Physics and the Department of Earth and Space Sciences at the University of California, Los Angeles. Her research interests are in the areas of solar-terrestrial physics and planetary science. She is known for work on the particles and magnetic fields of Earth and Jupiter and for investigations of properties of Jupiter's Galilean moons. She was the principal investigator for the magnetometer on the Galileo Orbiter that acquired data in Jupiter's magnetosphere for 8 years. She is a fellow of the American Geophysical Union (AGU), the American Physical Society, the International Academy of Astronautics, the American Association for the Advancement of Science, and the American Philosophical Society. She was awarded the Alfven Medal of the European Geophysical Union and the Fleming Medal of the AGU in 2005. She is a member of the American Academy of Arts and Sciences and the National Academy of Sciences and has served on several NRC committees and boards, including the Space Studies Board (2002-2005) and the Workshop Committee on Issues and Opportunities Regarding the Future of the U.S. Space Program (2003-2004).

RALPH L. McNUTT is a senior space physicist at the Johns Hopkins University Applied Physics Laboratory. Dr. McNutt is currently the project scientist and a co-investigator on the MESSENGER program and the Voyager Plasma Spectrometer and Low Energy Charged Particle experiments. He is the Applied Physics Laboratory study scientist for the Solar Probe; a member of the Ion Neutral Mass Spectrometer Team, Cassini Orbiter spacecraft; and a co-investigator on the New Horizons mission to Pluto. He has worked on the physics of the magnetospheres of the outer planets, the outer heliosphere (including solar wind dynamics and properties of the very-low-frequency radiation), Pluto's atmosphere, pulsars, high-current electron beams, the physics of active experiments in the mesosphere/thermosphere (artificial aurora), and the solar neutrino problem. Dr. McNutt previously served as a member of the NRC Committee for the Study of the Next Decadal Mars Architecture (2006) and the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion: A Vision for Beyond 2015 (2004-2006).

WILLIAM B. MOORE is an assistant professor in the Department of Earth and Space Sciences of the University of California, Los Angeles. His research explores geodynamics with applications to the terrestrial planets and icy satellites of the solar system. He is a member of the Institute of Geophysics and Planetary Physics. Dr. Moore served as a member of the NRC Solar System Exploration Survey Panel on Large Satellites (2001-2002).

JANET L. SIEFERT is a faculty fellow in the Department of Statistics at Rice University. She also serves as a faculty mentor at the W.M. Keck Center for Computational and Structural Biology. Her research interests are phylogeny reconstruction, prokaryotic biochemical systems and ecosystem evolution, origins of life, RNAs, and astrobiology. Dr. Siefert is the recipient of numerous awards, including the 2004 NASA Discretionary Award, the Ruth Satter Memorial Citation of Merit, the Award of the Association for Women in Science, and the Boehringer Ingelheim Fonds short-term fellowship for study at the Gesellschaft fur Biotechnologische Forschung. Dr. Siefert's NRC experience includes membership on the Committee on the Origins and Evolution of Life (2003-2006).

SPENCER R. TITLEY is a professor in the Department of Geosciences at the University of Arizona. He previously worked on NASA's Lunar Orbiter program and was also a member of the Apollo Field Geology Investigation Team with the U.S. Geological Survey, mapping the geology of potential lunar landing sites for various Apollo missions including Apollo 16 and 17. His current research involves the study of the origin of mineral deposits and the distribution and location of mineral and mineral fuel resources. His research has also included the study of chemical baselines of trace elements in rocks and ores for environmental purposes. Dr. Titley is a member of the National Academy of Engineering.

Staff

DWAYNE A. DAY, study director, has a Ph.D. in political science from the George Washington University and has previously served as an investigator for the Columbia Accident Investigation Board. He was on the staff of the Congressional Budget Office and also worked for the Space Policy Institute at the George Washington University. He has held Guggenheim and Verville fellowships and is an associate editor of the German spaceflight magazine *Raumfahrt Concret*, in addition to writing for such publications as *Novosti Kosmonavtiki* (Russia), *Spaceflight*, and *Space Chronicle* (United Kingdom). He has served as study director for several NRC reports, including *Space*

Radiation Hazards and the Vision for Space Exploration (2006), and for the current study New Opportunities in Solar System Exploration (2007).

VICTORIA SWISHER is a research associate. She has supported Space Studies Board studies and workshops on the Beyond Einstein report, NASA workforce, Mars research, research enabled by the lunar environment, ITAR, and other topics. Before joining the Space Studies Board, she did research in x-ray astronomy and laboratory astrophysics, which included studying the x-rays of plasma and culminated in her senior thesis, "Modeling UV and X-ray Spectra from the Swarthmore Spheromak Experiment." A graduate of Swarthmore College, she majored in astronomy and minored in English literature.

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

CELESTE NAYLOR joined the Space Studies Board in June 2002 as a senior project assistant. She has worked with the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope and also with the Committee on Astronomy and Astrophysics and the Task Group on Research on the International Space Station. Ms. Naylor is a member of the Society of Government Meeting Professionals and has more than 10 years of experience in event management.

STEPHANIE BEDNAREK, a Space Studies Board 2006 and 2007 summer space policy intern, graduated from the University of Virginia with a B.S. in aerospace engineering with a minor in astronomy. Her previous internships include placements at the Aerospace Industries Association and Orbital Sciences Corporation. She is currently pursuing an M.A. in science and technology policy with a concentration in space policy at George Washington University.

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C

Technology Background

The Committee on Assessing the Solar System Exploration Program determined that NASA will be unable to implement the remaining goals of the *New Frontiers in the Solar System* decadal survey without new technology.[1] This will require spending on programs to develop the technology. This appendix discusses several important technologies in greater detail and summarizes in Table C.1 at the end of this appendix the advanced technology requirements discussed in the 2003 *New Frontiers* decadal survey.

ADVANCED RADIOISOTOPE POWER SYSTEMS

Radioisotope power systems (RPSs) utilize plutonium 238 in the form of plutonium dioxide pellets. Four pellets are housed in an assembly referred to as a general-purpose heat source. Such sources have been thoroughly analyzed and tested for appropriate safety standards. Two versions exist: (1) the standard ones previously used in the Radioisotope Thermoelectric Generators (RTGs) employed on Ulysses, Galileo, Cassini, and New Horizons, and (2) modified ones to use with future missions that employ Earth gravity assists for deep space missions.

At the time of the 2003 decadal survey, NASA was developing the Alkali Metal Thermoelectric Converter (AMTEC) as part of its X-2000 technology program. AMTEC would have offered substantial gains in specific power that were vital to the original Europa Orbiter. But those performance gains required a technology that could not be developed on the timescale needed for the Europa Orbiter project.

The AMTEC technology was essentially abandoned by NASA because of problems with some of the ceramic parts. Subsequently, NASA began the development of two RPSs based on more conservative converter technologies: the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) using traditional thermoelectric technology, and a higher-risk Stirling cycle technology. Both were designed for operation on the surface of Mars (for the Mars Science Laboratory) and in deep space.

NASA also initiated work on advanced converter technologies under the Radioisotope Power Converter Technology (RPCT) program initiated in 2002. Four advanced technologies were pursued, including dynamic (Stirling and Brayton) and static (thermoelectric and thermophotovoltaic). At this time, most remaining work in

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

the RPCT is focused on advanced versions of the converters used in the MMRTG and Stirling generators that are currently under development.

A shortage of available plutonium fuel has led NASA to pursue the development of the Advanced Stirling Radioisotope Generator (ASRG). Predicted efficiency for the ASRG is 28 percent as compared with ~6 percent for thermoelectric converters. Hence, ASRGs require about one-quarter of the plutonium of thermoelectric converters. At the same time, ASRGs produce less reject heat that can be used for other purposes, and they have moving parts that raise reliability, lifetime, and electromagnetic and mechanical system disturbance issues for other spacecraft systems.

The work on producing units using Stirling converters is planned out and, if successful, will take pressure off plutonium inventory issues for power supplies and also enable new missions using radioisotope electric propulsion (REP), providing that specific power in excess of ~8 W(e)/kg can be obtained. However, there are three significant issues that do not appear to have been adequately addressed:

1. Even if all design and testing goals are met on schedule by 2012, it is not clear that an ASRG will be baselined as the power unit on a science mission without a technology flight test.
2. Potential failure modes remain poorly understood, as well as ultimate lifetime limits that can be implemented in designs. Hence, dynamic systems such as these are viewed as inherently riskier than static systems such as the MMRTG.
3. Stirling converters use moving magnet assemblies, which create electromagnetic and vibrational disturbances that are transmitted to the rest of the spacecraft. NASA conducted tests of a primitive Stirling converter more than 2 years ago. However, International Traffic in Arms Regulations (ITAR) restrictions have limited the communication of test results to the potential user community.

NASA is currently making significant progress on MMRTGs, which will be employed on the Mars Science Laboratory scheduled for launch in 2009.

IN-SPACE FISSION-REACTOR POWER SOURCE

In-space fission reactor sources would enable significantly more complex spacecraft missions. However, the United States has only operated one, small fission reactor in space, in 1965. The Soviet Union developed and flew more than 30 radar-ocean reconnaissance satellites (RORSATs) in Earth orbit, powered with uranium-fueled fission reactors.[2]

NASA began Project Prometheus in January 2003 as a new effort to develop a space fission supply as an integral part of an overall nuclear-electric propulsion (NEP) system that could be used to enable multiple, challenging, high-payoff robotic missions throughout the solar system and beyond. A contractor was selected for the Jupiter Icy Moons Orbiter (JIMO) project in 2004. However, the Jet Propulsion Laboratory (JPL) estimated the life-cycle cost for JIMO at $21.5 billion, and the program was subsequently canceled in 2005.

NUCLEAR-ELECTRIC PROPULSION

Nuclear-electric propulsion consists of assembling a high-power-density heat source with a high-efficiency thermal-to-electric converter system, and electric propulsion engines. Unlike ground- or ship- and submarine-based reactors used for power production, space-based application concepts typically focus on low-power (~100 kWe) systems with minimum mass.

Project Prometheus was initiated to develop NEP as a system for use in robotic solar system exploration in March 2003. The first mission to be flown with this technology was to be the JIMO targeting the Jovian Galilean satellites in general and Europa in particular. Prometheus was a major study effort (~$464 million) involving seven NASA centers and two Department of Energy organizations.

[2] See http://www.svengrahn.pp.se/trackind/RORSAT/RORSAT.html.

Gridded-ion thrusters compatible with a nuclear power source began development as part of the program in addition to high-power and extreme life systems development consistent with fission power. Development stopped on all of these efforts at a low technology readiness level (TRL).

The Prometheus/JIMO effort provided an important benchmark study on the difficulties and costs of implementing NEP in general and on robotic missions in particular. Under Prometheus, NASA made significant progress in various spacecraft subsystems that can be used for flight.

ADVANCED ION ENGINES

Ion engines typically are classified as being either Kaufmann-type ion-bombardment thrusters (ion engines) or Hall effect thrusters (Hall thrusters) with operating powers of ~1 kW to several tens of kilowatts. Ion engines coupled with solar power were used to flight qualify solar electric propulsion (SEP) on the Deep Space-1 (DS-1) mission.

Solar electric propulsion is now being used as the prime propulsion system on the Dawn mission.

As part of a program under SEP, a flight experiment of a next-generation solar array to power these engines is being developed for flight on ST-8.

AEROCAPTURE

Aerocapture is the method of using drag in the atmosphere of a planet or moon to reduce the excess speed of a spacecraft sufficiently to be captured into orbit at the target body. This approach saves the equivalent propellant mass for a high-thrust system that can significantly reduce launch mass and therefore overall mission cost. This method has potential applicability to orbital planetary systems missions.

NASA has made progress in aeroshell technology and aerocapture systems development. Systems studies have shown the importance of this approach for Mars Sample Return and Titan Explorer.

This effort is funded under the In-Space Propulsion program. While there have been advances, flight qualification of aerocapture is required for its use in planetary missions at an acceptable level of risk. Currently the only approach to such qualification is a flight for the New Millennium Program. As part of that program, an aerocapture experiment was proposed to ST-9 to provide flight validation for this approach. The proposal was rejected for development and flight owing to the reduction in the New Millennium budget for FY 2008 to FY 2010. With the budget downturn through FY 2010, there is no mechanism to qualify aerocapture under the current approach prior to the end of 2013.

KA-BAND COMMUNICATIONS

NASA established the Deep Space Network (DSN) in the 1960s to enable communication with deep space, interplanetary (robotic) spacecraft. The centerpiece of the system consisted of the three 64-meter-diameter antennas established at facilities in the vicinities of Goldstone, Madrid, and Canberra, spread across longitudes to enable 24-hour coverage to a fixed point in the sky. NASA expanded the antennas to 70-meter-diameter to support the Voyager missions. Support of more spacecraft missions has led to the addition of 34-meter-diameter antennas, as well as the introduction of dual X- and Ka-band capability on them in order to improve the system performance. Much of the DSN hardware is now being used more often than originally expected and far past design lifetimes. In particular the 70-meter-diameter antennas are suffering various hardware problems and cannot be upgraded to Ka band owing to structural limitations. However, to meet upcoming needs, Ka band is the next evolutionary step in providing increased data-rate capability. Further increases in performance by using still higher frequencies in excess of Ka band are not feasible owing to water absorption in the atmosphere.

NASA has articulated clear plans to increase DSN capabilities by developing higher-power Ka-band transmitters for spacecraft (at high efficiency), developing advanced coding and compression, and implementing an array of antennas providing the equivalent of a 240-meter-diameter antenna at each of the three DSN stations.

OPTICAL COMMUNICATIONS

Optical communications hold the promise of delivering significantly more spacecraft bandwidth in uplink and downlink for less mass and power than radio-frequency (X- and/or Ka-band) deep-space communications systems. Various proposals have been made for ground-station locations in order to minimize signal interruption from cloud cover. Other concepts include a set of Tracking and Data Relay Satellite System satellites in Earth orbit which can be used as a relay that can rely on existing ground stations. The implementation would require the development of appropriate resilient (radiation-hardened) laser transponders as well as implementation of tighter pointing requirements on the spacecraft itself.

NASA has postponed the development of a first-generation optical communications terminal until 2018. The Deep Space Network Roadmap suggests that an optical communications infrastructure may be operational by 2022.

SPACECRAFT AUTONOMY

Increased autonomy of spacecraft operations can lower mission operations costs. Risk may be increased unless appropriate test protocols are developed and adhered to prior to launch. Differences in spacecraft missions, architectures, and needs make one-size-fits-all developments difficult. Greater spacecraft autonomy is also necessitating larger software and data uploads.

The New Millennium ST-6 Autonomous Science Experiment on the Air Force's Tacsat 2 spacecraft validated orders-of-magnitude increases in science per bits downlinked to the ground. However, the narrow focus of this technology limits its future use. The autonomy program was canceled in 2004, with no funding in this area since then.

ADVANCED AVIONICS MINIATURIZATION AND PACKAGING

Advanced avionics miniaturization and packaging are generally taken to mean increased performance, including increased spacecraft autonomy, increased radiation hardness, increased thermal range of operations, advanced software, and less mass. Previously funded programs made progress in this area, but with the exception of the Mars Technology Program, most of the funding in these areas has ended. NASA's X2000 program funded radiation-hardened electronics that have been flown on multiple missions. These include the RAD750 from BAE Systems—now flying on Deep Impact and the Mars Reconnaissance Orbiter (MRO)—and a flash-memory-based nonvolatile memory card (from SEAKR Engineering). Under the Prometheus/Deep Space Avionics Program (2003-2005), there was continuation of X2000 power electronics and development of analog/digital converters and focal plane sensors.

Because of past funding efforts, all of the pieces for a robotic mission to Europa, with the exception of the nonvolatile memory, are now at a midrange technology readiness level. However, because almost a decade has elapsed since some of this work was done, the fabrication processes may be a generation or more removed from those used for the devices that were fabricated under X2000.[3]

The Europa Explorer team is currently putting together a summary of the status of each of the key technologies for Europa Explorer. At this time the lack of dense radiation-hard nonvolatile memory may be close to a solution with the progress in Chalcogenide RAM. The Europa Explorer concept uses existing technologies (mass memory) but requires advanced development for instruments and sensors.

Some generic items are or will be qualified under the New Millennium Program:

- ST-6 Stellar Compass provides three-axis attitude determination with an accuracy of 0.1 degree (on each axis) at very low power (3.5 W) and mass (2.9 kg);
- ST-8 Commercial Off-the-Shelf-Based High Performance Computing for Space is to demonstrate 10 to

[3]Randal Blue, "Radiation Hardened Electronics Development," presentation to Europa Explorer Electronic Parts Radiation Workshop at the Jet Propulsion Laboratory, April 26, 2007.

100 times more delivered onboard computational throughput capability than any computer flying in space today and onboard processing throughput density of >300 GOPS/watt; and

- ST-8 Miniature Energy Saving Thermal Control Subsystem is a miniature loop heat pipe thermal control system consisting of two evaporators and two condensers/radiators that is capable of reliable start-up and heat load sharing and can maintain operating temperature control from 0°C to 35°C.

A recent assessment indicates that 54 technologies have been selected for validation in space by the New Millennium Program, of which 31 have been successfully validated and 7 are still in process.[4] Seven were lost as a result of the Deep Space-2 failure. A total of 19 of the technology advances have been infused into missions or into flight mission proposals, including the optical navigation used on Deep Impact and Stardust and the Small Deep Space Transponder used on the Mars Exploration Rovers, MRO, Deep Impact, Dawn, Spitzer, and other missions.

Electronics tolerant of cold-temperature thermal cycling are being developed as part of the Mars program; hence, any specific requirement tailoring will be focused on Mars conditions.

NASA terminated the Cross-Enterprise Technology Development Program (CETDP), which was developing technologies required for Venus lander spacecraft that can withstand high temperatures, high pressures, and corrosive environments. NASA has continued some limited work under Small Business Innovation Research programs and the Planetary Instrument Definition and Development Program (PIDDP).

INSTRUMENTATION MINIATURIZATION

Mass and power will continue to be major constraints on planetary missions. At the same time there will continue to be pressure to make more sophisticated measurements as well as to do more in situ processing in order to maximize and advance science returns.

Programs for support of these developments are in place, but funding has been eroding for non-Mars programs. Innovative instruments that will be inserted into the Mars Science Laboratory include Laser Induced Breakdown Spectroscopy (LIBS) that measures elemental abundances without contact.

Four continuing Planetary Science Division research and development programs are addressing the instrument technology needs: PIDDP, Mars Instrument Development Program (MIDP), Astrobiology Science and Technology Instrument Development (ASTID), and Astrobiology Science and Technology for Exploring Planets (ASTEP). Only MIDP covers mid-TRL technologies; no comparable program exists for non-Mars technology. Reductions in astrobiology funding have impacted both ASTID and ASTEP. How well the developments under MIDP can be leveraged to support other missions such as Titan remains to be seen. Instrumentation for the South Pole-Aitken Basin and Comet Surface Sample Return missions is apparently not funded.

No instruments for the Venus environment are being supported, nor are spectrometry instruments for gas giant in situ missions. Termination of the CETDP Advanced Measurements and Devices program has shut off innovation in device technology of the type that is currently making significant contributions, specifically in advanced diffraction gratings used on the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument on the Mars Reconnaissance Orbiter and thermal detectors used on MRO and Lunar Reconnaissance Orbiter. High-power, active, remote-sensing instruments are no longer under development.

AUTONOMOUS ENTRY AND PRECISION LANDING

Past Mars landing failures have highlighted the risks associated with landings of robotic probes on nonterrestrial bodies. Detailed observations from orbit can locate hazardous and nonhazardous landing sites. However, in the absence of precise targeting, that information cannot be acted upon to reduce the risk of mission failure. At the same time, such detailed observations from orbit also can be used to pinpoint sites of interest either for

[4]John Stocky, Chief Technologist, New Millennium Program, Jet Propulsion Laboratory, "New Millennium Technology Infusion Summary" and "New Millennium Program–Scorecard Summary," June 1, 2007.

network station deployment, rover deployment for in situ detailed studies, or for sample collection for a sample return mission. Missions beyond Mars will require greater autonomous action, owing both to longer round-trip flight times and to what will likely be less information concerning landing hazards.

IN SITU SAMPLE GATHERING, HANDLING, AND ANALYSIS

As orbiting spacecraft have given way to landers and rovers, there has been a growing need for more sophisticated capabilities in gathering samples, including adequate determination of context and keeping the samples pristine, moving these from the sampling mechanism(s) to instrument ports/receptacles, and subsequently providing analysis either for data transfer back to Earth only or for documenting the state of the sample prior to a sample return to Earth. This effort partially overlaps with the development of miniaturized instrumentation—and for many of the same reasons—and is heavily tied to, but not limited to, surface landers and/or rovers, for example, the Stardust sample return mission.

ASCENT VEHICLES

The selection and return of samples from a wide number of solar system bodies are required for detailed analysis of pristine material with respect to isotopic, elemental, and mineralogic properties. While comets and asteroids have negligible gravity fields that can easily be overcome with rocket engines that can also be used for interplanetary guidance and control, solid-surface planets and their moons will require dedicated systems to take the samples from the surface to a minimum orbit, from which an interplanetary transfer maneuver can be executed for the return to Earth.

A survey of potential sites from which samples can be retuned indicates that the required capabilities fall into four broad classes that can be separated by the equatorial escape speed requirements: (1) 10 to 12 km/s (Venus and Earth), (2) 4 to 5 km/s (Mercury and Mars), (3) 2 to 3 km/s (the Moon, Io, Europa, Ganymede, Callisto, Titan), and (4) 0.5 to 2 km/s (Iapetus, Rhea, Oberon, Titania, Umbriel, Ariel, Triton, Pluto, and Charon).

IN-SPACE PROPULSION TECHNOLOGY

The In-Space Propulsion Technology (ISPT) program was recently reviewed by external users in the NASA community who found that the program was underfunded for continuing appropriate progress. Several rounds of budget reductions in the FY 2002 to FY 2007 time period led to cuts of ISPT technologies within the portfolio, including solar sails, high-power electric propulsion, and advanced chemical propulsion. Additionally, the focus of ISPT use has shifted to implementation on Discovery, New Frontiers, and other missions of that class. The program began in FY 2002 with $20 million, increasing to $62 million in FY 2003 and continuing at roughly that level through FY 2007.[5] Funding is projected to be in the range of $15 million to $17 million for FY 2008.

Current work in advanced chemical propulsion includes a high-temperature bi-propellant thruster. Aerojet is working on high-performance engines for Discovery and New Frontiers missions that use iridium-coated rhenium to enable operation at higher temperatures.

High-energy combinations including the use of ozone and fluorine, as well as fluorine including compounds such as oxygen difluoride and chlorine pentafluoride, have been investigated for improved high specific impulse performance. Toxicity, handling, and accident and exhaust safety issues have led to liquid oxygen and liquid hydrogen as the high-energy chemical combination of choice.

[5]Paul Wercinski, NASA Headquarters, "An Overview of NASA's In Space Propulsion Program," November 19, 2002. Discovery Program Library, NASA Langley Research Center, Hampton, Virginia. Available at http://discovery.larc.nasa.gov/PDF_FILES/ISP_Overview_Wercinski.pdf.

TABLE C.1 Advanced Technologies Addressed in the 2003 *New Frontiers* Decadal Survey

Technology	Decadal Survey Commentary,[a] with Current Assessment of Status[b]
Advanced radioisotope power systems (RPSs)	Advanced RPSs are required to replace the depleted inventory of first-generation RPSs.
	Solar power is generally insufficient beyond the asteroid belt. It provides limited power for spacecraft systems and severely limits the lifetime of landed spacecraft.
	In the second half of this decade the RPS program can produce advanced flight-qualified radioisotope thermoelectric generators that could be flown on the Europa Geophysical Explorer and the Jupiter Polar Orbiter with Probes, and on the Mars Science Laboratory.
In-space fission-reactor power source	Decadal survey[a] recommendation: "Finally, a compact and efficient (high thrust-to-mass ratio) flight-qualified nuclear-fission reactor should be developed in parallel with the development of second- and third-generation ion drives for the high-power NEP [nuclear-electric power] systems required to reach the outer solar system. Development of aerocapture as a means to reduce in-space propulsion requirements will significantly improve mission performance to all planets with atmospheres" (p. 203).
	The fission-based technology will take a decade to develop.
	The survey recommends that a series of independent studies be conducted immediately to examine the scientific, technical, and public issues involved in the use of nuclear technologies on planetary spacecraft.
	The nominal recommendation of the decadal survey will not be achieved during the 2003-2013 decade. A significant amount of work was accomplished that allows better appreciation of the inherent issues in bringing this technology to fruition.
Nuclear-electric propulsion (NEP)	In-space chemical propulsion has limited capability, especially for missions to the outer planets, resulting in very long flight times and often limiting missions to rare launch windows requiring multiplanet flybys to gain the necessary energy.
	The development of in-space NEP, including its first qualification flight in space, will take almost the entire decade and will become available for advanced outer-planet missions at the beginning of the next decade.
	The nominal recommendation of the decadal survey will not be achieved during the 2003-2013 decade. In particular, in-space NEP systems will not be available for advanced outer-planet missions at the beginning of the next decade.
Advanced ion engines	For the New Horizons mission, consideration should be given to the use of a solar-electric propulsion stage to avoid reliance on a singular Jupiter gravity-assist opportunity in 2007.
	The use of advanced solar-electric propulsion (coupled with aerocapture) would markedly increase the performance of the Venus In Situ Explorer (VISE) (New Frontiers) mission.
	Advances in ion propulsion and solar and/or nuclear power sources would improve the performance of the Comet Surface Sample Return (New Frontiers) mission.
Aerocapture	Development of aerocapture as a means of reducing in-space propulsion requirements will significantly improve mission performance to all planets with atmospheres.
	The addition of aerocapture technology to next-decadal missions to Neptune, Titan, and Saturn's rings will yield enhanced capabilities, reduced launch vehicle needs, and/or reduced in-space propulsion system requirements.
	The use of aerocapture would markedly increase the performance of the VISE (New Frontiers) mission.
Spacecraft autonomy	In the area of spacecraft systems, the key demand is for considerable autonomy and adaptability through advanced architectures.
	Advances in automation . . . will improve the performance of the New Frontiers Comet Surface Sample Return mission.
	Lower-power, lower-mass spacecraft need to be developed commensurate with realistic cost and performance for the available expendable launch vehicles.
	The autonomy program was canceled in 2004, with no funding for either base of focused technologies in this area since then.

continued

TABLE C.1 Continued

Technology	Decadal Survey Commentary,[a] with Current Assessment of Status[b]
Advanced avionics packaging and miniaturization	The decadal survey noted a need for more capable avionics in a more highly integrated package to support spacecraft autonomy. The approach recommended advanced packaging and miniaturization of electronics with a standardized software operating system. Radiation-hardened electronics were noted as required for the New Frontiers Jupiter Orbiter with Probes mission as well as for the flagship Europa Geophysical Explorer. In addition to these more generic requirements, called out for outer-planet missions, specific requirements for electronics capable of extreme hot and cold environments were noted. The decadal survey also noted the specific need for the development of high-temperature, corrosion-resistant, and pressure-tolerant systems required for the exploration of Venus within the atmosphere and on the ground.
Instrumentation miniaturization	New and increased science measurement capability is needed in planetary science instruments, as is greater environmental tolerance for less mass and power. Miniaturization is the key to the reduction of mass and power requirements. In situ instruments: On planetary surfaces, there are requirements for new surface science instruments, including biological measurements; complex organic chemistry and microbiology laboratory packages are needed for exploring organic-rich environments, including Europa and Titan and perhaps even subsurface aquifers of Mars; the South Pole-Aitken Basin mission and future sample return mission need advanced in situ instrumentation, including radiometric age-dating and chemical and mineralogical analysis. In situ instruments—extreme environments: The VISE mission will require in situ instruments that can survive the Venus surface environment and that can accomplish radiometric age-dating and chemical and mineralogical analysis of surface samples; long-lived, high-temperature, and high-pressure systems will be required for Venus sample return and surface stations such as seismic networks; for the Jupiter Orbiter Probe mission, lightweight mass spectrometers for sampling at high pressures with internal gas processing for complex analysis are the key science instrument technology. Remote sensing: Active remote-sensing instruments, including synthetic-aperture radar and laser-activated techniques, will be enabled by fission power sources.
Autonomous entry and precision landing	As planetary exploration moves into the new century with more in situ and sample return missions, it will be necessary to develop planetary landing systems. The key requirements for landing systems are autonomous entry, descent, hazard avoidance, and precision landing systems.
In situ sample gathering, handling, and analysis	Some recommended missions will be sent to planets and satellites that are targets for biological exploration and will require meeting planetary protection requirements related to forward and back contamination. Technologies will be required to meet these requirements while reducing the costs to do so. For Mars Sample Return . . . planetary protection technologies (both forward and back) and attendant sample containment, Earth return, and handling [are needed]. The key technologies for the VISE (New Frontiers) mission are those for system survivability, shallow drilling, sample acquisition, and sample transfer at extreme high temperature and pressure in a corrosive environment. The key technology required for the CSSR (New Frontiers) mission is a sample-acquisition system without significant on-surface time, drilling, or sample manipulation and storage at cryogenic temperatures. For the Comet Cryogenic Sample Return mission, drilling and cryogenic sampling will be required for a completely preserved core sample of a comet nucleus.
Autonomous mobility	Once on the surface, a means for moving about a planet is needed: Rover technology should advance toward long-life and long-range capability, with autonomous hazard avoidance and the ability to operate on large slopes. Aerial platforms for Mars and Venus will be required; they will be the forerunners of systems to be deployed on Titan and the outer planets. Also, subsurface vehicles will be required for the exploration of Mars and perhaps Europa. Advanced autonomy will need to be built in to all of these mobile mechanisms.

TABLE C.1 Continued

Technology	Decadal Survey Commentary,[a] with Current Assessment of Status[b]
Ascent vehicles	The means to return planetary samples needs to be developed, beginning with small bodies and the Moon, advancing toward Mars, then Venus, and eventually to more distant targets such as Mercury and the satellites of the outer planets. The South Pole-Aitken Basin Sample Return mission to the farside of the Moon could be the first test of sample-return technologies to be used on Mars. The common elements include . . . an ascent vehicle. A Mars-Earth return system, including an ascent vehicle and in-space rendezvous and sample capture, comprises key technologies that can evolve from the vehicles developed for the South Pole-Aitken Basin Sample Return mission. The perfection of Mars sample-return technology should be followed by its adaptation for return of samples from the surface of Venus. Long-lived, high-temperature, and high-pressure systems (including ascent vehicles) will be required for Venus sample return.

[a]Commentary and recommendations drawn from National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 202-206.
[b]The assessments of the Committee on Assessing the Solar System Exploration Program are shown in italic type.

D

NASA Technology Readiness Levels

Technology readiness levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. TRLs were first introduced by NASA in the 1980s and initially included seven levels. The system was expanded, in a 1995 white paper,[1] to include nine levels. Table D.1 summarizes each TRL.

TABLE D.1 Summary of NASA Technology Readiness Levels

Level	Summary	Description
TRL 1	Basic principle observed and reported	This is the lowest level of technology maturation. At this level, scientific research begins to be translated into applied research and development. Examples might include studies of basic properties of materials (e.g., tensile strength as a function of temperature for a new fiber).
TRL 2	Technology concept and/or application formulated	Once basic physical principles are observed, at the next level of maturation practical applications of those characteristics can be invented or identified. For example, following the observation of high critical temperature superconductivity, potential applications of the new material for thin-film devices (e.g., superconductor-insulator-superconductor mixers) and in instrument systems (e.g., telescope sensors) can be defined. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.
TRL 3	Analytical and experimental critical formula and/or characteristic proof of concept	At this step in the maturation process, active research and development (R&D) is initiated. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2. For example, a concept for high energy density matter (HEDM) propulsion might depend on slush or supercooled hydrogen as a propellant: TRL 3 might be attained when the concept-enabling phase/temperature/pressure for the fluid was achieved in a laboratory.
TRL 4	Component and/or breadboard validation in laboratory environment	Following successful proof-of-concept work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. For example, a TRL 4 demonstration of a new fuzzy logic approach to avionics might consist of testing the algorithms in a partially computer-based, partially bench-top component (e.g., fiber-optic gyros) demonstration in a controls laboratory using simulated vehicle inputs.

[1]John C. Mankins, Advanced Concepts Office, Office of Space Access and Technology, NASA, *Technology Readiness Levels, A White Paper*, April 6, 1995.

TABLE D.1 Continued

Level	Summary	Description
TRL 5	Component and/or breadboard validation in relevant environment	At this level, the fidelity of the component and/or breadboard being tested must increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, subsystem-level, or system-level) can be tested in a simulated or somewhat realistic environment. From one to several new technologies might be involved in the demonstration. For example, a new type of solar photovoltaic material promising higher efficiencies would at this level be used in an actual fabricated solar array “blanket” that would be integrated with power supplies, supporting structure, and so on, and tested in a thermal vacuum chamber with solar simulation capability.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	At TRL 6, a representative model or system prototype or system would be tested in a relevant environment. At this level, if the only relevant environment is the environment of space, then the model/prototype must be demonstrated in space. Not all technologies will undergo a TRL 6 demonstration: at this point the maturation step is driven more by assuring management confidence than by R&D requirements. For example, an innovative approach to high-temperature/low-mass radiators, involving liquid droplets and composite materials, would be demonstrated to TRL 6 by actually flying a working, subscale (but scaleable) model of the system on a space shuttle or International Space Station pallet. In this example, the reason that this space is the relevant environment is that microgravity *plus* vacuum *plus* thermal environment effects will dictate the success or failure of the system—and the only way to validate the technology is in space.
TRL 7	System prototype demonstration in a space environment	TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. It has not always been implemented in the past. In this case, the prototype should be near or at the scale of the planned operational system, and the demonstration must take place in space. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission-critical and relatively high-risk. *Example:* The Mars Pathfinder Rover is a TRL 7 technology demonstration for future Mars micro-rovers based on that system design. *Example:* X-vehicles are TRL 7, as are the demonstration projects planned in the New Millennium spacecraft program.
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)	In almost all cases, this level is the end of true system development for most technology elements. *Example:* This would include design, development, testing, and evaluation through Theoretical First Unit (TFU) for a new reusable launch vehicle. This might include integration of new technology into an existing system. *Example:* Loading and testing successfully a new control algorithm into the onboard computer on Hubble Space Telescope while in orbit.
TRL 9	Actual system “flight proven” through successful mission operations	In almost all cases, the end of last “bug-fixing” aspects of true system development. For example, small fixes/changes to address problems found following launch (through “30 days” or some related date). This might include integration of new technology into an existing system (such as operating a new artificial intelligence tool into operational mission control at Johnson Space Center). This TRL does *not* include planned product improvement of ongoing or reusable systems. For example, a new engine for an existing reusable launch vehicle would not start at TRL 9: such technology upgrades would start over at the appropriate level in the TRL system.

SOURCE: Adapted from John C. Mankins, Advanced Concepts Office, Office of Space Access and Technology, NASA, *Technology Readiness Levels, A White Paper*, April 6, 1995.

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Acronyms

AFL	Astrobiology Field Laboratory
AMTEC	Alkali Metal Thermoelectric Converter
AO	Announcement of Opportunity
ASPERA	Analyzer of Space Plasma and Energetic Atoms
ASRG	Advanced Stirling Radioisotope Generator
ASTEP	Astrobiology Science and Technology for Exploring Planets
ASTID	Astrobiology Science and Technology Instrument Development
CDR	Critical Design Review
CETDP	Cross-Enterprise Technology Development Program
CEV	Crew Exploration Vehicle
CONTOUR	Comet Nucleus Tour
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CSSR	Comet Surface Sample Return
DAP	data analysis program
DARPA	Defense Advanced Research Projects Agency
DIXI	Deep Impact Extended Investigation
DS-1	Deep Space-1
DSN	Deep Space Network
EPOXI	Extrasolar Planet Observations and Characterization (EPOCh) and Deep Impact eXtended Investigation (DIXI)
ESA	European Space Agency
GSMT	Giant Segmented Mirror Telescope
HiVHAC	High Voltage Hall Accelerator

IMEWG	International Mars Exploration Working Group
IRTF	Infrared Telescope Facility
ISPT	In-Space Propulsion Technology
ITAR	International Traffic in Arms Regulations
JIMO	Jupiter Icy Moons Orbiter
JWST	James Webb Space Telescope
LIBS	Laser Induced Breakdown Spectroscopy
LRO	Lunar Reconnaissance Orbiter
LSST	Large Synoptic Survey Telescope
M3	Moon Mineralogy Mapper
MAVEN	Mars Atmosphere and Volatile Evolution (mission)
MEP	Mars Exploration Program
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MEX	Mars Express
MIDP	Mars Instrument Development Project
ML3N	Mars Long-Lived Lander Network
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MoO	mission of opportunity
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSO	Mars Science Orbiter
MSR	Mars Sample Return
MTP	Mars Technology Project
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NEP	nuclear-electric propulsion
NExT	(Stardust) New Exploration of Tempel 1
NEXT	NASA Evolutionary Xenon Thruster
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
OE	Orbital Express
PDS	Planetary Data System
PI	principal investigator
PIDDP	Planetary Instrument Definition and Development Program
PSD	Planetary Science Division
R&A	research and analysis
REP	radioisotope electric propulsion
RORSAT	radar-ocean reconnaissance satellite
ROSES	Research Opportunities in Space and Earth Sciences
RPCT	Radioisotope Power Converter Technology

RPS	radioisotope power system
RTG	Radioisotope Thermoelectric Generator
SAG	Science Analysis Group
SDT	science definition team
SEP	solar electric propulsion
SMD	Science Mission Directorate
SSD	Solar System Division
SSE	Solar System Exploration
TAG	Technology Assessment Group
TGE	Traverse Gravimeter Experiment
TRL	technology readiness level
VEX	Venus Express
VEXAG	Venus Exploration Analysis Group