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Opening New Frontiers in Space:
Choices for the Next
New Frontiers Announcement of Opportunity

Committee on New Opportunities in Solar System Exploration:
An Evaluation of the New Frontiers Announcement of Opportunity

Space Studies Board

Division on Engineering and Physical Sciences
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Preface

NASA has initiated two missions in the New Frontiers Program and plans to issue an announcement of opportunity in 2008 to enable teams led by a principal investigator to compete for the third New Frontiers mission. NASA has asked the National Research Council to provide criteria and guiding principles for determining the list of candidate missions for this new competition.

The New Frontiers Program was established at the recommendation of the 2003 National Research Council solar system exploration decadal survey, *New Frontiers in the Solar System: An Integrated Exploration Strategy*.[1] The decadal survey recommended five medium-size missions as options for the New Frontiers Program. Three of those options remain to be implemented. In addition, the decadal survey listed five other medium-size missions that it did not specifically recommend for implementation. The Committee on New Opportunities in Solar System Exploration has sought to follow the guidance of the decadal survey in recommending principles for the next New Frontiers competition.

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

Acknowledgment of Reviewers

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

Richard M. Amasino, University of Wisconsin,
Scott Bolton, Southwest Research Institute,
Wesley T. Huntress, Jr., Carnegie Institution of Washington,
John Mustard, Brown University,
Francis Nimmo, University of California, Santa Cruz,
Emery Reeves, Independent Consultant,
Norman H. Sleep, Stanford University, and
Ann L. Sprague, University of Arizona.

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

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Summary

In 2007 NASA began planning to initiate a new competition for a New Frontiers mission. Because NASA has now selected two of the five recommended missions, and because the decadal survey recommended that the agency ask the National Research Council (NRC) for further advice on the New Frontiers Program after several selections had been made, in March 2007 NASA asked the NRC to:

> [P]rovide criteria and guiding principles to NASA for determining the list of candidate missions. These issues include the following:
>
> - Should the next New Frontiers solicitation be completely open relative to any planetary mission, or should it state a candidate list of missions as was done in the previous AO?
> - If a candidate list of missions is preferred, what is the process by which candidate missions should be determined? Specifically, there is a need to review the mission categories identified in the previous AO and see if the list needs to be revised or augmented in light of developments since the release of the last AO. Should consideration be made to a candidate list of appropriate science themes from the NRC decadal survey on solar system exploration rather than specific missions?[1]

The committee's original statement of task included the words "excluding Mars" in the first question. In September 2007 NASA amended the statement of task so that Mars could be considered in discussion of the future direction of the New Frontiers Program.

NASA's New Frontiers Program is a series of principal investigator-led solar system exploration missions with a cost cap of $750 million. These missions are larger than the principal investigator-led Discovery-class missions (with a cost cap of $425 million), but smaller than "flagship" missions, which are led by a NASA center and are defined as larger than $750 million, but in actuality cost several billion dollars. The New Frontiers Program is operated as a *program*, similar to the Discovery- and Mars Scout-class missions, meaning that Congress and the White House have agreed to support the existence of a class of missions and NASA does not have to seek special approval for each individual mission.

The New Frontiers Program was created at the recommendation of the NRC's decadal survey, *New Frontiers in the Solar System: An Integrated Exploration Strategy* (hereafter the "decadal survey").[2] The decadal survey recommended that, in order to optimize solar system exploration, NASA's solar system exploration program required a series of principal investigator-led missions larger than the Discovery class, but not as large as flagship missions. Because teams led by a principal investigator compete to produce a mission, these mission proposals are often innovative and unique, producing ingenious solutions to difficult challenges and demonstrating many of the best characteristics of U.S. science. However, unlike Discovery, New Frontiers missions must be firmly grounded in scientific priorities established by the decadal survey and not merely take advantage of new scientific or technology developments.

The decadal survey specified five mission candidates and ranked them according to priority:

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[1] Colleen N. Hartman, Acting Associate Administrator for Science Mission Directorate, letter to Dr. Lennard A. Fisk, Chair, Space Studies Board, March 21, 2007.

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

- Kuiper Belt Pluto Explorer,
- South Pole-Aitken Basin Sample Return,
- Jupiter Polar Orbiter with Probes,
- Venus In Situ Explorer, and
- Comet Surface Sample Return.

The decadal survey stated that although this list was ranked by scientific priority, NASA should not automatically select on the basis of that priority and should first consider the overall viability of the proposed mission. NASA followed this advice. For the 2005 New Frontiers announcement of opportunity, NASA clearly stated that the "'strawman' missions are in no order of priority" and in fact the announcement of opportunity did not list them in the same order as the decadal survey. In addition, for the 2005 competition NASA selected the Jupiter polar mission instead of the scientifically higher-ranked (in the decadal survey) lunar mission.

To date there have been two New Frontiers missions selected, the New Horizons mission to Pluto and the Kuiper Belt and the Juno mission to orbit Jupiter. New Horizons launched in 2006, flew past Jupiter in early 2007, and is scheduled to fly past Pluto in 2015. Juno is scheduled to launch in 2011 and reach Jupiter in 2015. Both missions will accomplish fundamental science goals defined in the decadal survey and significantly enhance scientific understanding of our solar system.

The decadal survey listed five additional missions that were not recommended for reasons of "mission sequencing, technological readiness, or budget."[3] These missions were listed in the following order in the decadal survey, which also stated that this list was <u>not</u> ranked according to scientific priority:

- Network Science
- Trojan/Centaur Reconnaissance
- Asteroid Rover/Sample Return
- Io Observer
- Ganymede Observer

Notably, Mars was not included in the New Frontiers Program. In essence, New Frontiers was created to ensure that a medium-size class of missions for the rest of the solar system (excluding Mars) was funded. The decadal survey treated Mars as a separate program with its own integrated list of scientific priorities and missions, some of which were in the same cost range as the New Frontiers missions. In particular, the decadal survey identified a Mars Long-Lived Lander Network as its second highest-priority medium-size Mars mission, after the Mars Science Laboratory, which is currently scheduled for launch in 2009.

In drafting this report, the committee used the decadal survey as its guide and the decadal survey's list of other potential medium-size solar system missions as its starting point. The committee solicited information from a broad range of sources, including NASA's own solar system advisory groups, and heard about other possible missions and science that were not included in the decadal survey's review of medium-size missions.

The committee recognized that it lacked the scope and time of the decadal survey, and did not have the expertise or authority to substantially question the decadal survey—as a result, the committee chose to defer to the insight and authority of the decadal survey whenever possible. However, the committee also acknowledged that scientific discoveries have been made since the decadal survey was presented to NASA in summer 2002, and that new technologies and technological approaches may be available today.

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[3] *New Frontiers in the Solar System*, p. 197.

During its deliberations, the committee also recognized that including Mars in the New Frontiers Program was outside the scope considered in the development of the decadal survey. The decadal survey treated Mars as a program, and the committee sees no reason why that should change.

Furthermore, the committee believes that allowing any medium-size Mars mission to compete in the New Frontiers Program would run the risk of undercutting the overall Mars Exploration Program, and be counter to the decadal survey. The committee believes that this would be bad for both the New Frontiers Program and the Mars Exploration Program. However, the committee ultimately determined that only within the context of comparative terrestrial planetology (i.e., network seismic *and* meteorological science) is the New Frontiers Program open to Mars missions.

The committee strongly believes that the New Frontiers Program is a valuable and vital part of NASA's solar system exploration program. The committee's philosophy was to provide NASA with sufficient options and to provide potential proposers with sufficient flexibility in their proposals to enable NASA to select a mission that can be done within the constraints of the New Frontiers Program, particularly the cost cap. The health of the New Frontiers Program was an overriding priority for the committee. New Frontiers has so far been successful in selecting missions that accomplish science that is not possible under the Discovery program. These missions will make fundamental contributions to scientific understanding of the formation and evolution of the solar system.

In reviewing the decadal survey, and listening to presentations by proposers in the previous New Frontiers competition, the committee was concerned that the mission options presented in the decadal survey were overly specific about the methods of accomplishing the science missions—the so-called "mission architectures." For example, the "Jupiter Mission With Probes" described in the decadal survey essentially required atmospheric probes to return data from Jupiter's atmosphere rather than specifying the information to be gained and leaving the method of obtaining it to those intending to propose a mission. Ultimately, the mission selected, named Juno, utilizes microwave radiometry only to return the water abundance.

The committee was concerned that such constraints could make it impossible for anyone to propose a mission that could be accomplished within the cost cap. The committee heard statements that allowing proposers greater latitude in how to return data not only increases ingenuity, but more importantly, provides the flexibility required to fit missions within the cost and other constraints. The committee determined that rather than specifying mission architectures, NASA should emphasize the science to be returned from such a mission and leave the implementation specifics to the teams competing for the opportunity.

Recommendation 1: In drafting the rules for the next New Frontiers announcement of opportunity, NASA should emphasize the science objectives and questions to be addressed, not specify measurements or techniques for the implementation.

The committee determined that the three remaining potential missions in the decadal survey's list—South Pole-Aitken Basin Sample Return, Venus In Situ Explorer, and the Comet Surface Sample Return— still have substantial scientific merit and should remain among the options in the next announcement of opportunity. However, the committee also determined that the list of candidate missions should be expanded to include the five other medium-size mission options from the decadal survey: Network Science, Trojan/Centaur Reconnaissance, Asteroid Rover/Sample Return, Io Observer, and Ganymede Observer. The committee also determined that an additional open option should be made available, which is discussed below.

The committee notes that compared to the original five New Frontiers missions identified in the decadal survey, the other five medium-size missions were discussed in less detail. Because of this, the committee has sought to devote significant attention to discussing the background and objectives of these missions in this report. In particular, the Io Observer and Ganymede Observer missions were not discussed in great detail in the decadal survey, and the committee has devoted more attention to them here in order to justify their inclusion.

Expanding the list accomplishes several important goals: it provides NASA with more options for the next mission selection; it provides potential proposers with more options to produce interesting, innovative, and competitive missions; it expands the cadre of participants and the science that will be evaluated by potential proposers, enabling the applicant pool to grow for future competitions; and it provides options to be considered by the next decadal survey. As with prior competitive mission opportunities, *NASA should select from this set of missions based both on science priority and overall mission viability.*

Recommendation 2: NASA should expand the list of potential missions in the next New Frontiers announcement of opportunity to include the three remaining candidate missions: South Pole-Aitken Basin Sample Return, Venus In Situ Explorer, and the Comet Surface Sample Return, and also the five additional medium-size missions mentioned in the decadal survey: Network Science, Trojan/Centaur Reconnaissance, Asteroid Rover/Sample Return, Io Observer, and Ganymede Observer. There is no recommended priority for these missions. NASA should select from this set of missions based both on science priority and overall mission viability.

The committee has not prioritized its list of eight missions. Each of these missions is discussed in greater detail in Chapter 2. The committee has also provided mission-specific recommendations for the science goals of each. The lists of goals are as comprehensive as possible, but should not be interpreted as all-encompassing. In some cases those mission-specific recommendations introduce significant changes into the possible mission, notably in defining the parameters for the Venus In Situ Explorer and the Network Science missions. The committee noted that these science goals may not all be achievable in a single mission, but believes that their choice and prioritization are best left to those proposing and evaluating the missions.

The committee was also impressed with arguments it heard about the importance of innovation not only in individual missions, but in the overall New Frontiers Program, and the risks of being overly specific on how to accomplish the goals of the decadal survey. Thus, in addition to the eight identified missions, the committee believes that NASA should offer an additional option for other missions in the same size class that can acquire compelling information answering high-priority science questions from the decadal survey. The committee believes that not only will this provide an opening for innovation, but it may also enable the applicant pool for future missions to grow. The committee believes that any such mission will have to meet a very high standard of scientific proof. Possible examples of such missions could include—but are not limited to—shallow atmospheric probes for the outer planets.

The committee realized that the New Frontiers mission line is a hybrid—incorporating aspects of both the Discovery and flagship class missions. As such, the committee concluded that the mission options for the next announcement of opportunity cannot be strictly drawn from the decadal survey, but must be interpreted in light of scientific discoveries made since the decadal survey was conducted in 2002. New scientific discoveries have been made about several of the targets evaluated in this mission class. In some cases, these discoveries enhance the importance of these scientific questions, and in some cases, they may undercut the original rationale for investigating a target. Planetary exploration is an ongoing endeavor. Paradigm-shifting scientific discoveries and mission-enabling technological advances have occurred since the decadal survey. NASA's New Frontiers Program will have to adapt to include them.

In addition, the committee also realized that new technologies and technological methods may now exist that were not available even five years ago. These technologies could include instrumentation (such as new seismic sensors) or mission-enabling equipment (such as radiation hardened electronics). The committee concluded that it is important to the health of the program that a method exist for including such innovation, while acknowledging that this will be a high standard to meet for those proposing missions.

Recommendation 3: NASA should consider mission options that are outside the 3 remaining and 5 additional medium-size missions from the decadal survey but are spurred by major scientific and technological developments made since the decadal survey. As with any New Frontiers mission, these proposals must offer the potential to dramatically advance fundamental scientific goals of the decadal survey and should accomplish scientific investigations well beyond the scope of the smaller Discovery program. Both mission-enabling technological advances or novel applications of current technology could be considered. However, NASA should limit its choices to the eight specific candidate missions unless a highly compelling argument can be made for an outside proposal.

The basis for these overarching recommendations is further provided in Chapter 1. However, the mission sections in Chapter 2 provide information that will be vital for drafting the next New Frontiers announcement of opportunity, and this report must be read in its entirety in order to understand the committee's findings and recommendations. The mission-specific recommendations from the missions in Chapter 2 are also included in Chapter 3 for ease of reference. Finally, the committee notes that the New Frontiers Program by its nature is intended to be both strategic—based on the science goals established in the decadal survey—and adaptable to new discoveries. The committee believes that it is important for NASA to find a method for incorporating new discoveries into the goals of the program for announcements made several years after a decadal survey has been produced. Seeking input from the scientific community via the NRC (in the form of this report) is one method to achieve this, but not necessarily the only method. The committee hopes that in the future NASA recognizes the importance of such a process.

1
Introduction

The New Frontiers Program was created by NASA as a direct result of the recommendations of the 2002 National Research Council (NRC) report *New Frontiers in the Solar System: An Integrated Exploration Strategy*.[1] This report is generally referred to as the decadal survey because it established science priorities for the period 2003-2013. The New Frontiers Program is a budget line program, similar to the Discovery- and Mars Scout-class missions, meaning that Congress and the White House have agreed to support the existence of a class of missions, and NASA does not have to seek special approval for each individual mission. However, New Frontiers is essentially a hybrid program that incorporates aspects of both the Discovery-class solar system missions and the much larger "flagship" class missions. Like Discovery, New Frontiers missions are led by a principal investigator and are competed. However, like flagship missions, New Frontiers missions are expected to answer the fundamental scientific questions that were defined in the decadal survey. In effect, they must achieve a significantly higher quality of science than Discovery-class missions and cannot simply be Discovery-class science that has grown too expensive for that mission line. The overall goal of these missions is to enhance scientific understanding of the solar system by producing high-quality science return through focused scientific investigations. At a minimum, New Frontiers missions *must* address one or more goals specified in the decadal survey, whereas no such requirement exists for Discovery missions.

The purpose of principal investigator-led New Frontiers missions is to encourage innovation and competition and to accomplish main science objectives developed by the scientific community in the solar system decadal survey. NASA holds competitions for the mission award where various teams, led by a principal investigator (and including not only other scientists, but also an institutional base and an industry partner), propose missions to NASA. The scientific community strongly believes that this produces better missions and clever solutions to problems, and the two New Frontiers missions selected to date, and discussed later, demonstrate this.

The committee strongly believes that the New Frontiers Program is a valuable and vital part of NASA's solar system exploration program. The committee's philosophy was to provide NASA with sufficient options and to provide potential proposers with sufficient flexibility in their proposals to enable NASA to select a mission that can be done within the constraints of the New Frontiers Program, particularly the cost cap. The health of the New Frontiers Program was an overriding priority for the committee. New Frontiers has so far been successful in selecting missions that accomplish science that is not possible under the Discovery program. These missions will make fundamental contributions to scientific understanding of the formation and evolution of the solar system.

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

Lessons Learned From the Previous Competition

To date two New Frontiers missions have been approved. The New Horizons mission to Pluto (see Figure 1.1) was approved during the decadal survey and was essentially “grandfathered” into the New Frontiers Program. Launched in early 2006, New Horizons conducted a successful Jupiter flyby in February 2007 en route to a Pluto flyby in 2015 and is to conduct another flyby of a Kuiper Belt object sometime later. The second New Frontiers mission, the Juno mission to Jupiter (see Figure 1.2), was selected in 2005 and originally scheduled for launch in 2009. The launch date was delayed due to cost phasing problems at NASA, and this substantially increased the cost of the overall mission. Juno will now launch in 2011 for arrival at Jupiter in 2015.

In both cases these missions were the result of lengthy efforts that predated the New Frontiers Program itself. New Horizons benefitted from nearly a decade of studies of Pluto missions. Juno resulted from three previously proposed Discovery-class missions. The committee was impressed by this fact and the lesson that successful proposals are the result of a lengthy process of study, refinement, competition, and scientific and technological advances. In order for the New Frontiers Program to remain healthy into the future, the committee adopted an approach that encourages not only the generation of new mission ideas and concepts, but also encourages their continual growth and development beyond simply the next announcement of opportunity.

The committee heard from members of both the New Horizons and Juno teams on their perspectives on the overall program as well as their thoughts about the next announcement of opportunity. These briefings were highly useful to the committee. In particular, discussions with those who proposed during the last New Frontiers selection highlighted the problems associated with the degree of mission specification in the announcement of opportunity. The cost profile and degree of specification of mission architecture impacted their creative efforts in approaching problems.

For example, one mission defined in the decadal survey was a “Jupiter polar orbiter with probes.”[2] However, the developers of the Juno mission determined that it was not possible to design both an orbiter *and* atmospheric probes and still stay within the required cost cap for the mission. They chose instead to utilize only a microwave sensor to determine the water content of Jupiter’s atmosphere—the scientific goal of the probes requirement for the mission. This decision made it difficult for the developers of the proposal to initially find sponsors for their project. Potential sponsors were concerned that omitting a key aspect of the mission as defined by the decadal survey would make it impossible for the mission to successfully compete. However, the Juno developers ultimately were able to convince a sponsor of the wisdom of their decision, and were also able to convince NASA’s selection team of the utility of a microwave instrument over the costly atmospheric probes. Although the accuracy of the water abundance derived from modeling of the remote microwave sensing may be less than that from an in situ probe, the degree of latitudinal-longitudinal sampling that will occur certainly elevates this mission as a precursor for site selection for sampling by a future, higher-cost multi-probe mission.

The lesson that the committee learned from this example was that being too specific about how to obtain desired scientific data not only hampers ingenuity, *but also can place otherwise excellent proposals at risk even before they can be submitted for evaluation by NASA. For this reason the committee to limit specifying how to collect data and instead seek to define what data are required.* The committee adopted this approach as much as possible throughout this report.

The committee notes that the Juno mission is particularly strong because it addresses fundamental science questions raised in three NRC decadal surveys (solar system exploration, astronomy and astrophysics, and solar and space physics). Even though the Jupiter polar orbiter was not the highest ranked New Frontiers mission in the solar system decadal survey, by selecting it NASA was also able to address significant goals of the solar and space physics and astronomy and astrophysics communities.

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[2] National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003. p. 16.

Global sensing of Jupiter's gravitational and magnetic fields and water content will yield more detailed knowledge of the internal mass distribution, the inner magnetic field, and water content. For astrophysics, a better understanding of water content and mass distribution are needed to determine how Jupiter and extra-solar planets formed. Because data related to near-planet, high-latitude magnetic field structure is needed to understand basic magnetospheric processes, the solar and space physics community assigned a Jupiter polar orbiter a high priority.

The Scope of the Committee's Findings and Recommendations

There are several threats to the viability of the New Frontiers mission line. The committee heard from various experts that one potential threat was that the announcement of opportunity could be so tightly constrained that it would produce no viable competitors. Certainly, as the number of candidate mission options is reduced (from the original five to the present three—South Pole-Aitken Basin Sample Return, Venus In Situ Explorer, and Comet Surface Sample Return), the possibility increases that no viable contenders for the New Frontiers Program will emerge. But another constraint was the one identified above—overly defining the method of acquiring scientific data rather than leaving the methods to the proposers. Because of the committee's desire to maintain the viability of the New Frontiers line and because of the statements by several persons who briefed the committee, the committee recommends that NASA should focus more on the science to be returned rather than specific methods for achieving it. The committee believes that scientific justification is fundamental to the health and future of the New Frontiers Program. New Frontiers is a strategic component of the planetary flight program and the committee's recommendation is intended to ensure that the announcement of opportunity will be based on the mission science priorities from the decadal survey and to maintain the strategic nature of the New Frontiers Program.

Recommendation 1: In drafting the rules for the next New Frontiers announcement of opportunity, NASA should emphasize the science objectives and questions to be addressed, not specify measurements or techniques for the implementation.

The decadal survey was a large study involving dozens of members working on various panels over a 12-month period. The smaller NRC Committee on New Opportunities in Solar System Exploration, however, did not possess the time or depth of expertise as the decadal survey. As a result, the committee sought to adhere to the guidance of the decadal survey as closely as possible while still recognizing the limitations of the original decadal survey work, *and* while remaining cognizant of advances in space science since the decadal survey was produced five years ago.

The committee identified several limitations in the decadal survey that constrained the committee's work. These included the fact that the decadal survey identified and ranked five New Frontiers missions, and identified *but did not rank* the five additional medium-size missions. Another limitation that the committee identified was that the decadal survey (and the 2003 NASA New Frontiers announcement of opportunity that was produced based on it) was overly specific about how to answer scientific questions, selecting options for how to address a science goal rather than leaving most of such details to the proposers.[3] In addition, the committee concluded that the decadal survey used unrealistic cost models, meaning that, if implemented as described in the decadal survey, the missions described would cost more than was predicted by the decadal survey.

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[3] See NASA, "New Frontiers Program and Missions of Opportunity Announcement of Opportunity," available at http://research.hq.nasa.gov/code_s/nra/current/AO-03-OSS-03/main.html.

SIDEBAR 1.1: The New Horizons Mission

The New Horizons mission to Pluto and the Kuiper Belt was selected by NASA in late 2001 in response to an announcement of opportunity for a principal investigator-led Pluto Kuiper Belt mission issued by NASA in January 2001. The 2001 announcement of opportunity, developed with guidance from a Science Definition Team, provided a prioritized list of specific science objectives and measurement objectives that should be addressed by the mission, and the New Horizons payload (visible imaging, far-ultraviolet and near-infrared imaging spectroscopy, plasma spectrometers, and radio science), was tightly focused towards achieving those objectives. Because a Kuiper Belt/Pluto mission was recommended as a top priority medium-class mission by the decadal survey, New Horizons was a good fit to the New Frontiers Program and was funded by New Frontiers after that program was created in 2002.

The New Horizons mission, using a small radioisotope thermoelectric generator (RTG)-powered spacecraft, was launched on an Atlas V rocket in January 2006. A gravity-assist flyby of Jupiter in early 2007 has demonstrated New Horizons' ability to produce high-quality science data, and a Pluto flyby is scheduled for July 2015. An extended mission, if funded, will enable New Horizons to encounter one or more additional Kuiper Belt objects sometime before the mid-2020s. The success of New Horizons demonstrates the feasibility of principal investigator-led missions and RTG-powered missions in the New Frontiers mission class. In the case of this mission, with its relatively simple architecture, the prioritized science goals and measurement objectives given in the announcement of opportunity were invaluable in providing a level playing field for proposers and in guiding spacecraft and mission design.

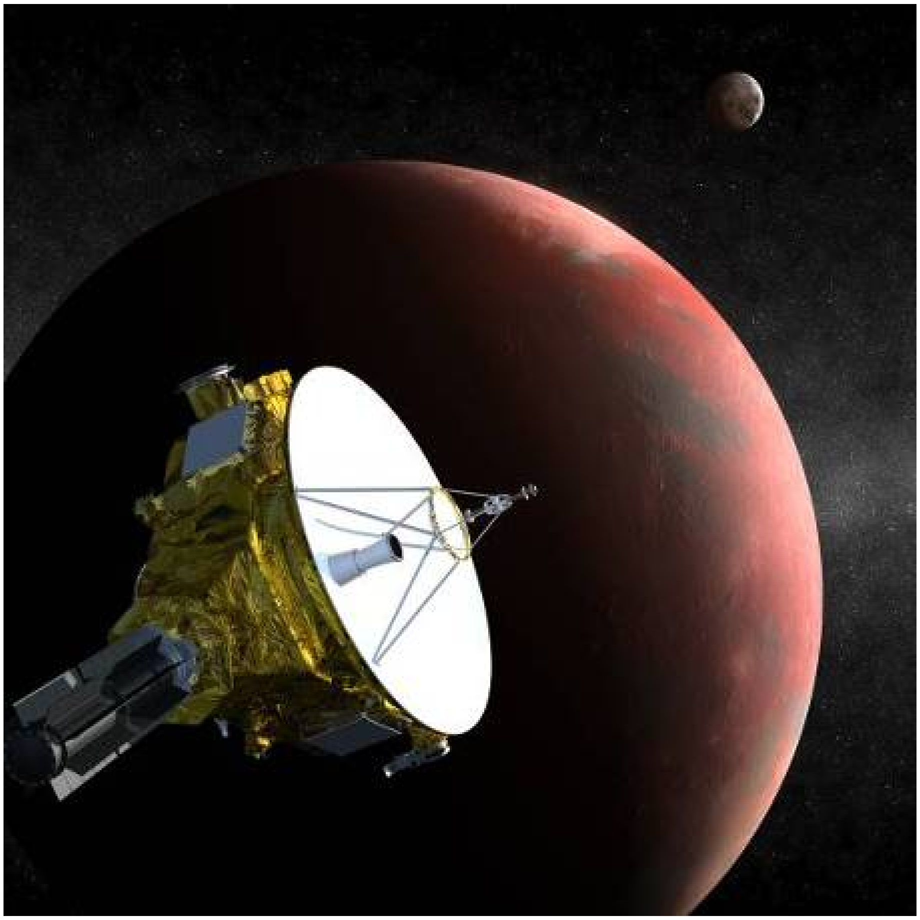

FIGURE 1.1 NASA's New Horizons spacecraft will fly past Pluto in 2015. New Horizons was the first of the New Frontiers missions, which were recommended in the decadal survey. SOURCE: Courtesy of NASA.

SIDEBAR 1.2: The Juno Mission

The Juno team proposed a low-risk, innovative approach to probe the magnetic and gravitational fields and map the water and cloud distribution of Jupiter. Despite resistance from institutional management and others who feared that the mission would be rejected because it did not adhere to the strawman architecture established in the decadal survey, the teams abandoned the direct entry probe and chose to utilize a microwave spectrograph with 6 frequency bands that sound to different atmospheric depths to address the question of water abundance and distribution at different altitudes. This approach could be accommodated by a spin-stabilized spacecraft in an elliptical, nearly atmospheric grazing, 11-day polar orbit, which would allow sampling of the magnetic and gravitational fields over a wide range of radial distances. The orbital period would be synchronized with the rotation of the planet so that the entire planet can be longitudinally sampled within 16 orbits, providing early yield in a hazardous environment. The spin-stabilized spacecraft would be operated in a passive mode for greatest sensitivity in determining gravitational fields, or oriented perpendicular to its orbital motion, allowing the microwave radiometers to scan in a latitudinal direction. With this mode, the spectrometer would view a given area of the cloud deck from multiple observational angles, providing vertical discrimination of the abundance of water and cloud structure.

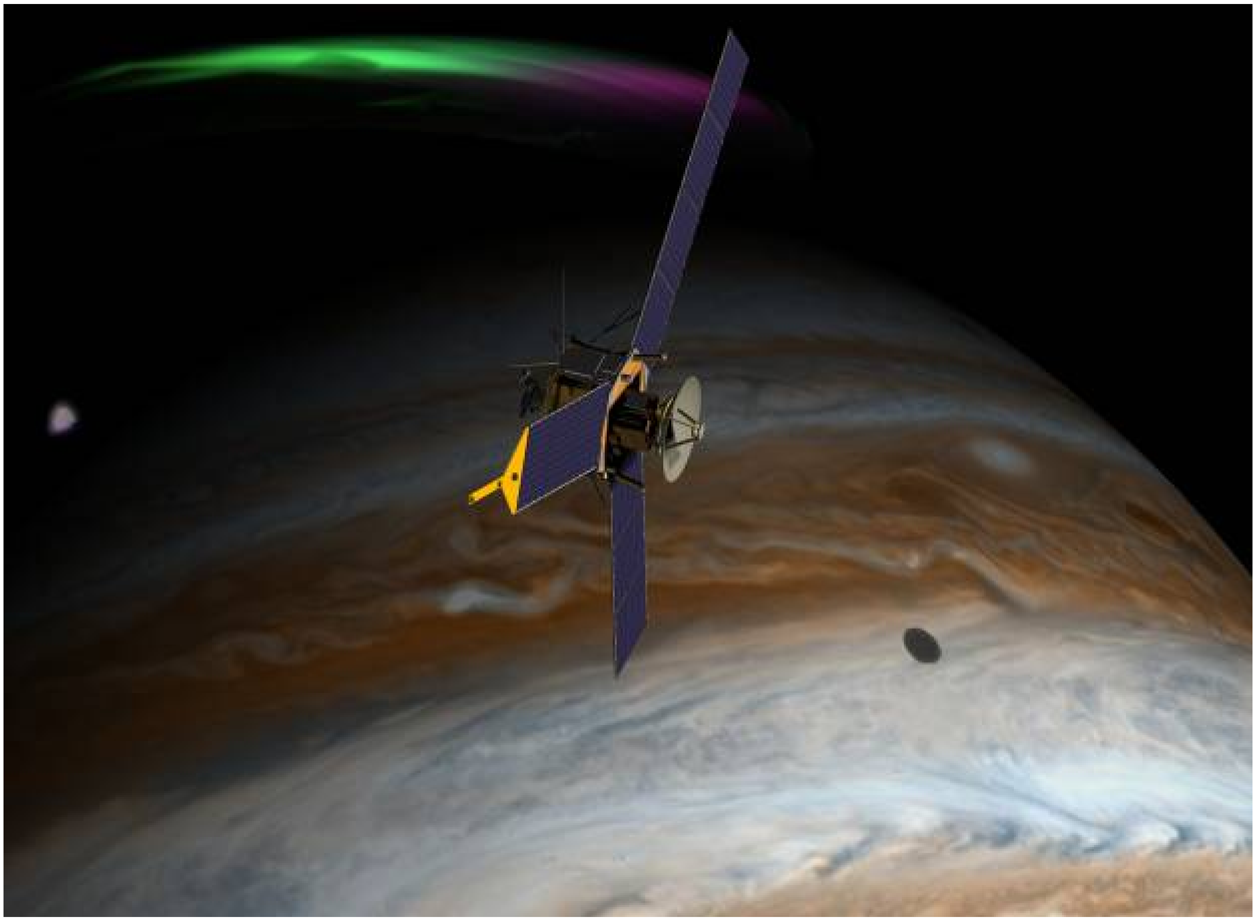

FIGURE 1.2 The Juno spacecraft which will travel to Jupiter and conduct measurements of its magnetosphere among other science objectives. Juno is unique as the first spacecraft to be designed to operate at Jupiter distance from the Sun and operate on solar panels. This opens the possibility of other missions at this distance also using this technology. SOURCE: Courtesy of Scott Bolton, Southwest Research Institute and Jet Propulsion Laboratory.

Because of the study's limited time and expertise and the new developments in space science and technology, the committee engaged NASA's solar system analysis groups and sought their input about science and technology developments and also their opinion of the New Frontiers Program. A list of speakers is included in Appendix A.[4] Many of the presentations and input from these groups were placed on their public websites, and the committee found their assistance to be extremely useful.

The NRC Committee on New Opportunities in Solar System Exploration's task was to consider the following issues:

- Should the next New Frontiers solicitation be completely open relative to any planetary mission, or should it state a candidate list of missions as was done in the previous announcement of opportunity (AO)?
- If a candidate list of missions is preferred, what is the process by which candidate missions should be determined? Specifically, there is a need to review the mission categories identified in the previous AO and see if the list needs to be revised or augmented in light of developments since the release of the last AO. Should consideration be made to a candidate list of appropriate science themes from the NRC decadal survey on solar system exploration rather than specific missions?

The committee determined that the next announcement of opportunity should state a candidate list of missions, as was done with the previous round, but with an important caveat which is discussed below. The committee further concluded that the candidate missions should be determined by including both the original prioritized list of medium-size missions from the previous announcement of opportunity and the additional list of non-prioritized missions developed for the decadal survey. As with prior competitive mission opportunities, NASA should select from this set of missions based on both science quality and overall mission viability.

Recommendation 2: NASA should expand the list of potential missions in the next New Frontiers announcement of opportunity to include the three remaining candidate missions: South Pole-Aitken Basin Sample Return, Venus In Situ Explorer, and the Comet Surface Sample Return, and also the five additional medium-size missions mentioned in the decadal survey: Network Science, Trojan/Centaur Reconnaissance, Asteroid Rover/Sample Return, Io Observer, and Ganymede Observer. There is no recommended priority for these missions. NASA should select from this set of missions based both on science priority and overall mission viability.

The committee concluded that each of these eight missions still has scientific merit, and in the past five years no new scientific objectives have emerged that can be accomplished within the New Frontiers cost constraints. The committee received input from various persons about the merits of preparing a mission list versus making the competition open to all proposals. However, given the limitations of this study—time and the number of presenters—the committee could not sample all of the potential mission ideas from the entire community, but felt that it could reasonably conclude that no new science objectives or goals have emerged since the decadal survey. The committee rejected the option of developing a candidate list of appropriate science themes from the NRC decadal survey on solar system exploration because the nature of the New Frontiers Program requires greater focus than this would provide. The committee's charge asked the committee to determine if a list of science themes would be more appropriate than a list of potential missions. The committee concluded that because the New Frontiers line is competed, must meet cost constraints, and because proposals must be ready in time for the next announcement of opportunity, a candidate list of missions (with their respective science goals

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[4] Note that in addition to the formal presentations by the analysis groups, the committee received written input from the groups. Much of this material is available on the groups' respective websites.

drawn from the decadal survey), rather than a list of science themes, would be of greater value to the proposers.

These five additional missions were not recommended in the decadal survey for reasons of "mission sequencing, technological readiness, or budget."[5] The decadal survey did not state what issues were relevant to which missions. The committee was not asked to evaluate the technological readiness or budget feasibility of any of these missions and lacked the time and resources to conduct such assessments. In some cases new technology or novel technological approaches may make some of these missions more achievable now than they were five years ago. However, the committee acknowledges that for all of the missions, including the three remaining from the original prioritized list, these factors may still pose some major challenges. For this reason, the committee chose to introduce greater flexibility into mission architecture (i.e., how to accomplish the mission) and the science requirements, and to adopt the general approach that within each mission, the decision about which science goals to pursue should be left to a competitor to select and to justify.

The eight candidate missions are more fully described in Chapter 2. For each mission option, the committee introduces the mission, provides background on why it is important, quotes sections of the decadal survey that called for such a mission, and explains how scientific advances made since 2002 affect the mission. In addition, the committee has provides mission-specific recommendations for each.

Although the decadal survey did not make a specific recommendation for a Mars mission within the New Frontiers line, the inclusion of Network Science as one of the mission categories leaves a potentially attractive option for a Mars Network mission (Figure 1.3). The decadal survey did refer to a Mars Network mission in Table ES.2 as the second highest priority for a medium-size Mars mission after the Mars Science Laboratory.[6] Such a mission would be important for comparative planetology and is not currently part of the Mars Exploration Program, which is focused on the search for water and life and sample return.

The committee was wary of making any Mars mission recommendations that could potentially upset the Mars Exploration Program, which it considers to be a carefully planned, integrated, and highly successful program to date. The committee concluded that the prominence of a Network Science mission in the New Frontiers line and the Mars Network mission in the Mars section of the decadal survey clearly warrants the inclusion of a Network Science mission in the next New Frontiers announcement of opportunity. Furthermore, the committee concluded that the meteorological component identified under Mars Long-Lived Lander Network was also important, but that it should not be a requirement for such a mission. See Chapter 2 for further details.

In describing these different mission options, the committee sought to identify the original language justifying them in the decadal survey. However, the committee found that not all of the missions were defined in the decadal survey in the same level of detail. Therefore, the committee sought to add further information about potential science objectives of these missions, clearly delineating that this information was not from the decadal survey. The committee believes that if these missions are included in the next decadal survey, it will be most helpful to future prospective proposers if the next decadal survey provides greater discussion and definition than they have previously received. This will assist not only the proposers, but NASA when selecting future New Frontiers missions.

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[5] *New Frontiers in the Solar System*, p. 197.

[6] *New Frontiers in the Solar System*, p. 5.

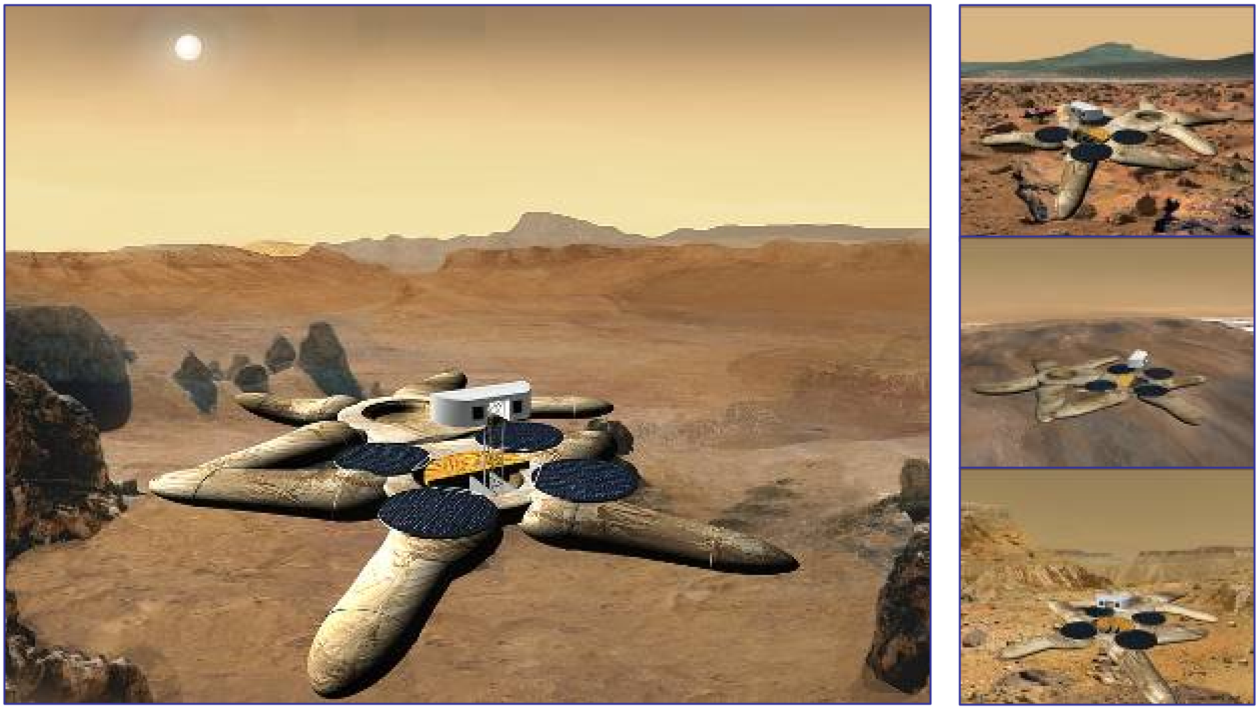

FIGURE 1.3 A Network Science mission was identified as a possible New Frontiers mission in the decadal survey, and the Mars Long-Lived Lander Network was also identified as a high priority mission for the Mars program. SOURCE: Courtesy of Jet Propulsion Laboratory, California Institute of Technology.

Opportunities for New Science

The committee acknowledges that scientific developments have occurred since 2002 which require some reinterpretation of the New Frontiers Program's goals. The committee also acknowledges that new technological developments have occurred in that time. For example, prior to the selection of the Juno mission, it was commonly accepted wisdom within the scientific community that solar power was inadequate for a spacecraft at Jupiter. Although Juno is constrained by its limited power using solar cells, the mission demonstrates that there are potential solutions to problems that have not yet been considered. Furthermore, the committee was also impressed by the wealth of ideas for other missions and other important science that could be conducted within the solar system that bear on decadal survey science goals. Because of these reasons as well as the limitations of the committee's knowledge, the committee determined that NASA should provide an "open option" so that mission developers with innovative ideas are given the opportunity to propose them to NASA.

In particular, considerable new scientific information has been obtained by missions and ground-based observations since the decadal survey was prepared. In addition, advances in technology may enable missions which were not considered, or were considered infeasible in the decadal survey, but might now be feasible within the New Frontiers constraints. Therefore, a mission proposed under New Frontiers could take advantage of new scientific discoveries *as well as new ideas*.

However, the committee believes that any mission proposed under this more open option should meet a very high standard of scientific content: *it cannot simply be a Discovery-class mission that scores high for its limited costs but relatively low scientifically, but must answer fundamental questions established in the decadal survey. The New Frontiers Program is a strategic program and its missions must be strategic in conception.* Such a proposal would undercut the justification for the New Frontiers Program as distinct from the Discovery Program.

The committee also acknowledges that the success of future New Frontiers missions after the currently planned announcement of opportunity requires that new ideas and innovations be constantly generated, and that they go through successive rounds of review, evaluation, and critique in order to become stronger and more competitive.

Recommendation 3: NASA should consider mission options that are outside the 3 remaining and 5 additional medium-size missions from the decadal survey but are spurred by major scientific and technological developments made since the decadal survey. As with any New Frontiers mission, these proposals must offer the potential to dramatically advance fundamental scientific goals of the decadal survey and should accomplish scientific investigations well beyond the scope of the smaller Discovery program. Both mission-enabling technological advances or novel applications of current technology could be considered. However, NASA should limit its choices to the eight specific candidate missions unless a highly compelling argument can be made for an outside proposal.

This chapter has only defined the committee's top-level findings and recommendations for the New Frontiers Program. The individual missions and mission-specific recommendations are described in the next chapter.

2
New Frontiers Mission Options

The 2003 solar system decadal survey,[1] *New Frontiers in the Solar System: An Integrated Exploration Strategy*, specified five mission candidates and ranked them according to priority:

- Kuiper Belt Pluto Explorer,
- South Pole-Aitken Basin Sample Return,
- Jupiter Polar Orbiter with Probes,
- Venus In Situ Explorer, and
- Comet Surface Sample Return.

To date there have been two New Frontiers missions selected—the New Horizons mission to Pluto and the Kuiper Belt and the Juno mission to orbit Jupiter. Three missions remain from the original decadal survey list of potential New Frontiers missions:

- South Pole-Aitken Basin Sample Return,
- Venus In Situ Explorer, and
- Comet Surface Sample Return.

The committee believes that all three remain viable candidates for the New Frontiers Program and also recommends expanding the list of potential missions to include the five additional medium-size missions mentioned in the decadal survey:

- Network Science,
- Trojan/Centaur Reconnaissance,
- Asteroid Rover/Sample Return,
- Io Observer, and
- Ganymede Observer.

All eight of these missions are described below and are addressed in the same sequence as they appeared in the decadal survey. No science prioritization is implied by their order.

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

SOUTH POLE-AITKEN BASIN SAMPLE RETURN

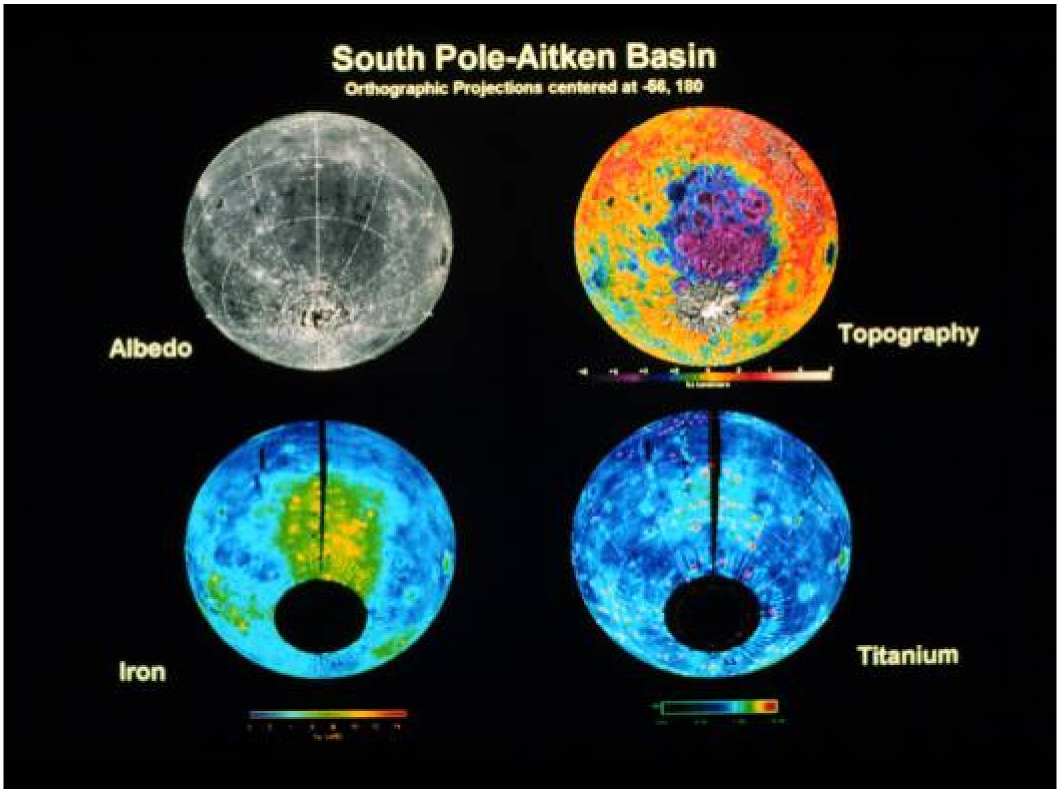

FIGURE 2.1 South Pole-Aitken Basin. The basin is clearly visible in both the topography and iron projections, illustrating how a large impact affected the Moon. The black area at the pole was not imaged.
SOURCE: Courtesy of Clementine Science Group, Lunar and Planetary Institute.

The South Pole-Aitken Basin Sample Return (SPA-SR) mission, as described in the decadal survey, is an inner solar system mission to understand basin-forming processes and impact chronology by returning samples from the deepest, most heavily cratered and, hence inferred to be the oldest impact structure preserved on the Moon (see Figure 2.1). The second goal of the mission is to use these same samples to understand the nature of the Moon's deep crust and upper mantle and the planetary processes that produced these features. Both of these goals are to be accomplished through the intensive study of the returned materials in terrestrial laboratories.

Heavy bombardment in the very early history of the solar system is a paradigm established from analysis of the samples returned by the Apollo and Soviet robotic Luna missions. Careful site selection and new sampling of the Moon will result in detailed verification and extension of this central concept for the formation and early history of the terrestrial planets and its implications for the earliest appearances and evolution of life. In particular, this mission would allow a test of the various theories that have been proposed for the early impact history of the inner solar system, notably the "lunar cataclysm" model.

Melting of planetary surfaces (magma oceans) during the early accretion process of planetary bodies in the inner solar system is an important concept resulting from the detailed analysis of Apollo and Luna samples in terrestrial laboratories. The detailed analysis of samples returned from the South Pole-Aitken Basin Sample Return should verify and extend this central concept for the differentiation of the early planetary body into crust and mantle. Sample return allows samples to be analyzed with the most sophisticated instruments on Earth (many of which cannot be transported to the sampling location). But it has other benefits as well, including the ability to share samples with many research teams for broad-based experimentation, and the archiving of samples for analysis in the future, when better instrumentation will exist. It is possible to conduct far more sophisticated analysis of Apollo samples today than it was when they were first returned to Earth.

Background

A South Pole-Aitken Basin Sample Return mission would directly address the following crosscutting themes and key questions identified in the decadal survey and contained within Table ES.1[2] of the decadal survey:

> ***New Frontiers in the Solar System*** **Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**
>
> ***The First Billion Years of Solar System History***
>
> 1. What processes marked the initial stages of planet and satellite formation?
> 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?
>
> ***Processes: How Planetary Systems Work***
>
> 11. How do the processes that shape the contemporary character of planetary bodies operate and interact?

In addition, the decadal survey's Table 2.1 identifies this mission as providing scientific return in three categories: highly significant scientific return, very useful scientific return, and supporting scientific return:[3]

> ***New Frontiers in the Solar System*** **Table 2.1: Summary of Priority Science Investigations Addressed by the Inner Planets Panel's Highest-Ranked Inner-Planet Missions**
>
> **Highly Significant Scientific Return**
>
> **Past: What led to the unique character of our home planet?**
>
> a. What are the bulk compositions of the inner planets and how do they vary with distance from the Sun?
>   1. Determine elemental and mineralogic surface compositions.
>   4. Determine interior (mantle) compositions.
>
> b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?
>   2. Determine compositional variations and evolution of crusts and mantles.
>
> c. What were the history and role of early impacts?
>   1. Determine large-impactor flux in the early solar system and calibrate the lunar impact record.
>   3. Investigate how major impacts early in a planet's history can alter its evolution and orbital dynamics.
>
> **Very Useful Scientific Return**
>
> **Past: What led to the unique character of our home planet?**
>
> b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?
>   3. Determine major heat-loss mechanisms and resulting changes in tectonic and volcanic styles.
>
> c. What were the history and role of early impacts?
>   2. Determine the global geology of the inner planets.

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[2] *New Frontiers in the Solar System: An Integrated Exploration Strategy*, p. 3.

[3] *New Frontiers in the Solar System: An Integrated Exploration Strategy*, pp. 56-57.

Present: What common dynamic processes shape Earth-like planets?

b. How do active internal processes shape the atmosphere and surface environments?
    2. Determine absolute ages of surfaces.

Future: What fate awaits Earth's environment and those of the other terrestrial planets?

d. What are the resources of the inner solar system?
    2. Assess mineral resources.

Supporting Scientific Return

Past: What led to the unique character of our home planet?

a. What are the bulk compositions of the inner planets and how do they vary with distance from the Sun?
    3. Measure oxygen isotopic ratios of the unaltered surface and atmosphere.
b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?
    1. Determine horizontal and vertical variations in internal structures.
d. What is the history of water and other volatiles and how did the atmospheres of inner planets evolve?
    2. Determine the composition of magmatic volatiles.

Present: What common dynamic processes shape Earth-like planets?

c. How do active external processes shape the atmosphere and surface environment?
    3. Quantify regolith processes on bodies with tenuous atmospheres.

Future: What fate awaits Earth's environment and those of the other terrestrial planets?

b. How do varied geologic histories enable predictions of volcanic and tectonic activity?
    1. Assess the distribution and age of volcanism on the terrestrial planets.
c. What are the consequences of impacting particles and large objects?
    1. Determine the recent cratering history and current flux of impactors in the inner solar system.

Developments Since the Decadal Survey

Significant advances have been made in modeling the early history of our solar system, in particular the timing of accretion of the large planets in the outer solar system and the dynamical effects of their subsequent orbital evolution. Recent work has shown that the earliest crust on Earth may have formed very early, potentially providing a foothold for the early development of life. However, the intense bombardment of the earliest history of the solar system may have prevented or delayed the development of life until more quiescent times.

It has long been known that the dated major basins on the Moon are clustered around 4 billion years in age. A major question is whether all major basins formed within about 200 million years around that time, a "lunar cataclysm," or whether the dated basins simply represent the end of a declining flux of large impacts starting at 4.5 billion years. Argon-argon dating of impact-produced glasses in lunar meteorites, which plausibly sample the entire lunar surface, suggests that there was a lunar cataclysm. If this is correct, some mechanism must be found to dislodge asteroids from the main belt 500 million years after solar system formation. Two not necessarily incompatible models have been proposed.

One model for the evolution of the outer solar system postulates that the eccentricities of Jupiter and Saturn were pumped up as they passed through 2:1 orbit:orbit resonances, sweeping resonances through the main belt and dislodging main belt asteroids. These asteroids then produced cataclysms on all terrestrial planets and satellites, including the Moon.[4]

The other model notes that the size-frequency distribution of the highland craters on the Moon is the same as the main belt and distinct from the modern population of near-Earth asteroids. The near-Earth asteroids seem to be responsible for cratering the lunar maria, i.e., more recently than 3.9 billion years ago.[5] Strom et al. postulate the formation of Neptune and, possibly, Uranus 500 million years after the formation of the other planets, around 4 billion years ago.[6] The resultant migration inwards of Jupiter caused resonances to sweep through the main belt, with the same consequences.

Conclusions

The committee concludes that this mission remains a highly scientifically important mission that should be considered for the New Frontiers Program. Although the committee is concerned that NASA should not be too specific in defining how New Frontiers missions should be conducted, it has concluded that in this case, given the maturity of the science questions and the precise design of the mission as stated in the decadal survey, the requirement of returning samples is a reasonable and irreducible requirement of the mission. Furthermore, the South Pole-Aitken Basin is the preferred lunar region for targeting this mission. However, other sample return sites may exist that can address the preponderance of the objectives for this mission; it is the responsibility of the proposer to convincingly defend the merits of an alternative site.

After exhaustive and extended laboratory analysis of Apollo and Luna lunar samples, as well as meteorites from the Moon, no evidence has been found for water in any form in lunar rocks and soils.[7] While the search for water on the Moon is not a science objective for this mission, returned samples from the deep crust and/or upper mantle may contain trace water. Discovery of lunar water in returned samples, even in the minutest quantities, would constitute a major scientific discovery.

Mission-Specific Recommendations

A South Pole-Aitken Basin Sample Return mission is tenable under the New Frontiers Program and can address a majority of the decadal survey objectives for such a mission. The committee recommends that the South Pole-Aitken Basin Sample Return mission as described in the decadal survey remain a high priority for the New Frontiers mission class. The committee has identified no changes to recommend for the scientific objectives or engineering implementation of this mission from the decadal survey. However, the committee recommends that NASA not overly prescribe specific approaches to

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[4] See R. Gomes, H.F. Levison, K. Tsiganis, and A. Morbidelli, Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial plants, *Nature* 435:466-469; K. Tsiganis, R. Gomes, A. Morbidelli, and H.F. Levison, Origin of the orbital architecture of the giant planets of the solar system. *Nature* 435:459-461, 2005; and A. Morbidelli, K. Tsiganis, A. Crida, H.F. Levison, and R. Gomes, Dynamics of the giant planets of the solar system in the gaseous protoplanetary disk and their relationship to the current orbital architecture, *The Astronomical Journal* 134:1790-1798, 2007.

[5] See R.G. Strom, R. Malhotra, T. Ito, F. Yoshida, and D.A. Kring, The origin of planetary impactors in the inner solar system, *Science* 309(5742):1847-1850, 2005.

[6] See R.G. Strom, R. Malhotra, T. Ito, F. Yoshida, and D.A. Kring, The origin of planetary impactors in the inner solar system, *Science* 309(5742):1847-1850, 2005.

[7] As the committee was finishing its report, it learned of a presentation at the fall meeting of the American Geophysical Union that may indicate the presence of significant water in lunar volcanic glasses. See Sael, A.E., Hauri, E.H., Lo Cascio, M., Van Orman, J., Rutherford, M., and Cooper, R., Volatiles in the lunar volcanic glasses, evidence for the presence of indigenous water in the Moon's interior, AGU Fall 2007 Meeting.

address the scientific objectives. Instead, NASA should allow proposers to develop their own innovative approaches.

The committee believes that the following science goals, not in priority order, should be established for this mission:

- Elucidate the nature of the Moon’s lower crust and/or mantle by direct measurements of its composition and of sample ages;
- Determine the chronology of basin-forming impacts and constrain the period of late, heavy bombardment in the inner solar system, and thus, address fundamental questions of inner solar system impact processes and chronology;
- Characterize a large lunar impact basin through “ground truth” validation of global, regional, and local remotely sensed data of the sampled site;
- Elucidate the sources of thorium and other heat-producing elements in order to understand lunar differentiation and thermal evolution; and
- Determine ages and compositions of far-side basalts to determine how mantle source regions on the far side of the Moon differ from regions sampled by Apollo and Luna basalts.

VENUS IN SITU EXPLORER

Permission Pending

FIGURE 2.2 Image taken of the surface of Venus by Venera 13 in 1982. The Soviet Union successfully conducted several Venus lander missions with 1980s era technology. These images depict the distorting effects of the thick Venusian atmosphere. SOURCE: C.M. Pieters, J.W. Head, W. Patterson, S. Pratt, J.B. Garvin, V.L. Barsukov, A.T. Basilevsky, I.L. Khodakovsky, A.S. Selivanov, A.S. Panfilov, Y.M. Getkin, and Y.M. Narayeva, The color of the surface of Venus, *Science* 234:1379-1383, 1986.

A Venus In Situ Explorer (VISE) mission would address fundamental unanswered questions of the history and current state of Venus through a characterization of the chemical composition and dynamics of the atmosphere on Venus, and/or measure surface composition and rock textures. *While it is questionable that within the New Frontiers cost constraints any mission concept would address all the objectives delineated in the decadal survey, a scenario that addresses a subset of these objectives would provide critical new information to constrain the present state and past history of Venus.* The current European Space Agency (ESA) Venus Express mission has greatly expanded our knowledge of the upper atmosphere and exosphere, and has contributed to understanding of those regions of the atmosphere nearer to the planetary surface. However, characterization of the noble gas and isotopic signatures of the well mixed lower atmosphere would greatly expand our understanding of the formation and evolution of the atmosphere of Venus, illuminate important elements of the present day climate, including the drivers for the Venus greenhouse effect, and potentially provide constraints on the early tectonic evolution of the planet. Prior landed missions of Soviet Venera and Vega spacecraft (Figure 2.2) have provided some information on crustal compositions and textures, but they have been confined to lowland areas comprised of basaltic lava flows. Landed missions in highland regions or on older terrains could answer a number of questions related to presence of more silicic rock compositions or earlier phases of tectonism, but they present significant technological challenges.

Background

The science questions targeted by a Venus In Situ Explorer mission address directly the following crosscutting themes and key questions identified in the decadal survey and contained within Table ES.1:[8]

***New Frontiers in the Solar System* Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

Volatiles and Organics: The Stuff of Life

6. What global mechanisms affect the evolution of volatiles on planetary bodies?

The Origin and Evolution of Habitable Worlds

9. Why have the terrestrial planets differed so dramatically in their evolutions?

Processes: How Planetary Systems Work

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?

As noted in the decadal survey, a Venus New Frontiers mission proposal should address a number of the following objectives, which were <u>not</u> prioritized:[9]

Science mission objectives for VISE are as follows:

- Determine the composition of Venus's atmosphere, including trace gas species and light stable isotopes;
- Accurately measure noble gas isotopic abundance in the atmosphere;
- Provide descent, surface, and ascent meteorological data;
- Measure zonal cloud-level winds over several Earth days;
- Obtain near-infrared descent images of the surface from 10-km altitude to the surface;
- Accurately measure elemental abundances and mineralogy of a core from the surface; and
- Evaluate the texture of surface materials to constrain weathering environment.

The context for the mission objectives are provided in the decadal survey in the context of Atmospheric and Surface Science Objectives:[10]

Atmospheric Science Objectives:
The composition of the lower atmosphere of Venus is unknown. Without this knowledge, comparisons of the factors that affect climate on Earth and on Venus, including photochemistry, clouds, volcanism, surface-atmosphere interactions, and the loss of light gases to space, are impossible. VISE will measure

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[8] *New Frontiers in the Solar System*, p. 3.
[9] *New Frontiers in the Solar System*, p. 58.
[10] *New Frontiers in the Solar System*, p. 59.

the abundance of trace gas species in the lower atmosphere of Venus to parts per million accuracy, enabling an understanding of how these processes affect terrestrial planetary climates. A fundamental quest is to understand how and why Venus, roughly the same size, composition, and distance from the Sun as Earth, has evolved to such a different state. The record of planetary atmospheres is contained in the isotope ratios of the most inert gases—xenon, krypton, argon, and neon. Are planetary atmospheres the remnants of gases that were originally solar in composition but then suffered massive hydrodynamic escape, or did they require atmospheres from volatiles that had already been differentiated? What was the role of impacts on the ultimate compositions and evolution of the terrestrial planets? Discrimination between these events for each of the inner planets is possible if noble gas isotopic ratios can be measured with a state-of-the-art neutral mass spectrometer. Previous spacecraft measurements have been inadequate to address these issues. VISE will determine the noble gas abundances and isotope ratios to sufficient accuracy to distinguish between hypotheses of the origin and evolution of Venus's atmosphere. A meteorological package will measure atmospheric pressure and temperature profiles down to the surface, and pressure, temperature, and winds at the surface. Cloud-level winds will be determined by tracking the ascent balloon during its 3.5-day lifetime, providing improved data on atmospheric dynamics and the origin of Venus's mysterious atmospheric superrotation.

Surface Science Objectives:
The former Soviet Union's Venera landers returned basic elemental chemistry and images of four sites on the surface, and Magellan data provided evidence of possible evolved volcanic deposits. However, we lack sufficient information on surface elemental abundances and mineralogy to determine the degree of crustal evolution on Venus. The VISE mission would measure elemental compositions at a surface site complementary to those of the Veneras. Mineralogy of a surface sample core will be obtained for the first time, allowing analysis of any weathered layer and testing for depth of alteration and occurrence of unaltered material. Textural analysis of the sample using a microscope imaging system would provide information on the formation and nature of surface rocks. These data will be used to constrain questions outlined above. Despite global radar coverage of Venus by Magellan, little is known of the surface morphology at scales of 1 to 10 m. Without such information, it is difficult to determine how the plains formed and to understand the nature of mobile materials on the surface. A descent camera on the lander will provide the first broadscale visible images of the surface, with images returned from about 10 km altitude to the surface. These images will enhance interpretation of the Magellan radar images by providing ground-truth data on the surface texture of the lava flows that make up Venus's plains. The morphology and texture of these flows can be related to emplacement rate, volatile content, and rheology, which are needed in order to understand the role of volcanism in shaping the atmosphere and surface of Venus. Images of Venus's surface will also be returned from the lander, with filters chosen to provide compositional information. These images will help to determine the recent geological history of Venus and will resolve differences in the interpretation of Venus's resurfacing history.

Developments Since the Decadal Survey

Since the decadal survey, NASA's Venus Exploration Analysis Group (VEXAG) worked with the Venus science community to develop Venus exploration goals, with prioritized objectives.[11]

Goal 1: Origin and Early Evolution of Venus: How did Venus originate and evolve?

The highest priority objectives are

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[11] The committee has only cited the top three VEXAG goals, but notes that the VEXAG committee has produced a valuable document that can be used as a reference on Venus science objectives. This document, *Venus Exploration Goals, Objectives, Investigations, and Priorities: 2007*, is available at www.lpi.usra.edu/vexag/vexag_goals_2007.pdf.

1. Determine the elemental and isotopic composition of the atmosphere to identify earlier epochs of Venus' history, and clues to Venus' origin, formation and evolution.
2. Map the mineralogy and chemical composition of Venus' surface on the planetary scale for evidence of past environmental conditions and for constraints on the evolution of Venus' atmosphere.
3. Characterize the history of volatiles in the interior, surface and atmosphere of Venus, including volatile additions due to cometary impacts, degassing and atmospheric escape, to understand the planet's geologic and atmospheric evolution.

Goal 2: Venus as a Terrestrial Planet: What are the processes that have shaped and still shape the planet?

The highest priority objectives are:

1. Constrain the coupling of thermochemical, photochemical and dynamical processes in Venus' atmosphere and between the surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles.
2. Constrain the resurfacing history of Venus, and the nature of the resurfacing processes, including the role of tectonism, volcanism, impacts of asteroids or comets, sedimentation/erosion, and chemical weathering.
3. Constrain the nature and timing of volcanic activity on Venus, including thermal evolution, current and past rates of volcanic activity, and the effects of outgassing on atmospheric and interior processes.

Goal 3: What does Venus tell us about the fate of Earth's environment?

The highest priority objectives are:

1. Search for evidence of past global-climate changes on Venus, including chemical-and-isotope evidence in the atmosphere, as well as rock chemistry and characteristics of surface weathering. In particular, seek evidence for the presence or absence of past oceans.
2. Search for evidence of past changes in interior dynamics, volcanics and tectonics, including possible evolution from plate tectonics to stagnant-lid tectonics, which may have resulted in significant changes in the global climate pattern.
3. Characterize the Venus greenhouse effect, including the interplay of chemistry, dynamics, meteorology, and radiative physics in the atmosphere, especially in the clouds.

In addition, since the decadal survey the ESA's Venus Express has entered Venus orbit and returned new data. Venus Express has expanded our understanding of the upper atmosphere and exosphere and has contributed to our knowledge of the mid- to lower atmosphere. However, the majority of the science targeted in the objectives listed below from the decadal survey requires in situ measurements that are beyond the measurement capabilities of an orbital mission such as Venus Express.[12]

Conclusions

The committee concludes that this mission remains a highly scientifically important mission that should be considered for the New Frontiers Program. The VEXAG goals and objectives align well with the Venus New Frontiers mission objectives, further validating the selection process in the decadal

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[12] *New Frontiers in the Solar System*, p. 58.

survey. However, these Venus New Frontiers objectives, while addressing fundamental science themes for Venus exploration, likely cannot be fully addressed within a single New Frontiers mission. Cost and technology risk factors may preclude the inclusion of all objectives in a single New Frontiers Venus mission proposal. *Consequently, a mission that addresses a major subset of the objectives would be consistent with the recommendations of the decadal survey. For example, a successful mission might not necessarily include a landed component, if it addressed the major atmospheric objectives identified above.* In addition, the objectives should be interpreted as an indication of the important data to be collected, rather than a prescription for any particular measurement technique or mission scenario. While no attempt is made here to prescribe or define implementation strategies, potential technical challenges related to the Venus environment include the high temperatures, high pressures, and corrosive atmosphere in the near-surface environment, as well as use of non-traditional (though previously demonstrated) mobility systems, such as balloons—technology that also has some applications on other atmospheric bodies. The committee also notes that most of the technologies required to address the decadal survey objectives have been demonstrated on prior missions. For instance, Soviet-era Venus missions not only successfully reached the surface, but operated there for up to an hour, proving that surface missions are possible.

In the decadal survey, the Venus New Frontiers mission concept was discussed in terms of what it could contribute to a future flagship-class Venus sample return mission. While such an approach contains significant merit, the committee warns that placing technology demonstration for a future Venus mission in the critical path for mission success is unwise, particularly given the technical challenges for Venus sample return. Nonetheless, future Venus exploration beyond Venus New Frontiers requires major technology development and demonstration, justifying inclusion of demonstration technologies on a non-interference, non-critical path basis.

Mission-Specific Recommendations

The committee concluded that a Venus New Frontiers mission that addresses a significant number of the decadal survey objectives is tenable. Such a mission would make use of technologies that have been successfully demonstrated in prior missions to the Venus surface and near-surface environment. The committee also concluded that several of the VEXAG goals should be included with the goals established in the decadal survey, particularly the VEXAG goals concerning understanding the thermal balance of the atmosphere and gathering global mineralogic data.

The challenges associated with landing in a region not previously sampled, collection of a sample, and lofting to a more clement altitude are the source of greatest technology and cost risk. Consequently, *the New Frontiers announcement of opportunity should not preclude a mission that addresses the major goals for chemical sampling of the mid- to lower atmosphere on Venus and for characterizing atmospheric dynamics, but that lacks a surface sampling component.* On the other hand, a mission that only addressed surface sampling would not be acceptable.

The science goals for this mission, which are not in priority order, should be:

- Understand the physics and chemistry of Venus' atmosphere through measurement of its composition, especially the abundances of sulfur, trace gases, light stable isotopes, and noble gas isotopes;
- Constrain the coupling of thermochemical, photochemical and dynamical processes in Venus' atmosphere and between the surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles;
- Understand the physics and chemistry of Venus' crust, for example through analysis of near-IR descent images from below the clouds to the surface and through measurements of elemental abundances and mineralogy from a surface sample;

- Understand the properties of Venus' atmosphere down to the surface through meteorological measurements and improve our understanding of Venus' zonal cloud-level winds through temporal measurements over several Earth days;
- Understand the weathering environment of the crust of Venus in the context of the dynamics of the atmosphere of Venus and the composition and texture of its surface materials; and
- Map the mineralogy and chemical composition of Venus' surface on the planetary scale for evidence of past hydrological cycles, oceans, and life and constraints on the evolution of Venus' atmosphere.

COMET SURFACE SAMPLE RETURN

FIGURE 2.3 The European Space Agency's Rosetta mission to a comet. This is a rendezvous and landing mission. Sample return would double the length of such a mission and add additional risk. SOURCE: Courtesy of European Space Agency.

Scientific community interest in a comet sample return mission has been very high for many years. The advantages of such a mission have been stated in many documents including the decadal survey. Flyby missions to comets are fairly simple and Deep Space-1, Stardust, and Deep Impact missions have produced remarkable data. Rendezvous missions such as the ESA's Rosetta mission (Figure 2.3) are more challenging, and a sample return mission can take twice as long as a rendezvous mission, thereby increasing cost and risk. The decadal survey concluded that bringing back a warm (i.e., non-cryogenic) sample was within the New Frontiers budget. While the cometary science goals make the return of a cryogenic core sample highly desirable, such a mission may not fit within the fiscal and programmatic timescale limits of the New Frontiers Program. On the other hand, the science yield from a warm return will have to be strongly defended by proposers.

Background

The decadal survey recommended that a comet mission be included in the New Frontiers Program, stating that it: “will collect materials from the near surface of an active comet and return them to Earth for analysis. These samples will furnish direct evidence on how cometary activity is driven. Information will be provided on the manner in which cometary materials are bound together and on how small bodies accrete at scales from microns to centimeters. By comparing materials on the nucleus against the coma’s constituents, Comet Surface Sample Return will indicate the selection effects at work. It will also inventory organic materials in comets. Finally, Comet Surface Sample Return will yield the first clues on crystalline structure, isotopic ratios, and the physical relationships between volatiles, ice, refractory materials, and the comet’s porosity. These observations will give important information about the building blocks of the planets.”[13]

The rationale for such a mission was well described in the Primitive Bodies Section of the decadal survey. The key questions addressed by this mission were summarized in Table ES.1 and are given below:[14]

New Frontiers in the Solar System **Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

The First Billion Years of Solar System History

1. What processes marked the initial stages of planet and satellite formation?

Volatiles and Organics: The Stuff of Life

4. What is the history of volatile compounds, especially water, across the solar system?
5. What is the nature of organic material in the solar system and how has this matter evolved?

Processes: How Planetary Systems Work

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?

Developments Since the Decadal Survey

The nucleus images of Halley, Borrelly, Wild and Tempel 1 have shown the diversity of comets. The Deep Impact mission showed that one portion of the surface contained very fine particles and gave clues to the organic composition. The diversity question has added a new dimension to cometary research.

In addition, the ESA in March 2004 launched the Rosetta mission, which will reach its target, 67P/Churyumov-Gerasimenko, in 2014. The Stardust mission launched on February 7, 1999, and returned to Earth with a sample from a comet on January 15, 2006. The returned samples show that the comet dust has minerals that formed near the Sun or other stars, indicating that this material ejected by the early sun can travel to the outer-most reaches of the solar system where comets formed. Stardust data also indicates that comets may resemble asteroids more than scientists previously believed.[15]

Finally, comets have been discovered in the asteroid belt. Unlike other known comets, these main belt comets appear to have formed in the much warmer inner solar system, where they are found today, and so likely contain ice that is quite different in chemical and isotopic composition from that in other comets.

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[13] *New Frontiers in the Solar System*, p. 6.

[14] *New Frontiers in the Solar System*, p. 3.

[15] H.A. Ishii, J.P. Bradley, Z. Rong Dai, M. Chi, A.T. Kearsley, M.J. Burchell, N.D. Browning, F. Molster, “Comparison of Comet 81P/Wild 2 Dust with interplanetary dust from comets,” *Science* 319(5862):447-450, 2008.

Conclusions

The committee concludes that this mission remains a highly scientifically important mission that should be considered for the New Frontiers Program. The questions posed in the decadal survey remain extremely relevant. However, the committee notes that the challenge of choosing the “right” comet with an efficient rendezvous and return trajectory may be incompatible with a fixed timescale dictated by the announcement of opportunity.

Mission-Specific Recommendations

For this mission candidate the committee recommends that the science goals should be as they were originally stated in the decadal survey (and not from the 2003 New Frontiers announcement of opportunity). These science goals are not in priority order, and not all of them must be answered. Such a mission should seek to answer the following scientific questions:[16]

- What is the elemental, isotopic, organic, and mineralogical composition of cometary materials?
- How is cometary activity driven?
- How do small bodies accrete?
- What are the scales of physical and compositional heterogeneity?
- How are the particles on a cometary nucleus bound together?
- What are the macroscopic mineralogical and crystalline structure and isotopic ratios in cometary solids?

The committee further recommends that the New Frontiers announcement of opportunity should leave the choice of target comet to the proposer and that the choice of target should be a major evaluation factor.

Finally, the committee notes that proposers for warm comet sample return missions must demonstrate that significant progress towards the goals of the decadal survey will be achieved by non-cryogenic sample return.

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[16] This text is taken from several sections in the decadal survey. *New Frontiers in the Solar System*, pp. 25, 180, 182-183, 195.

NETWORK SCIENCE

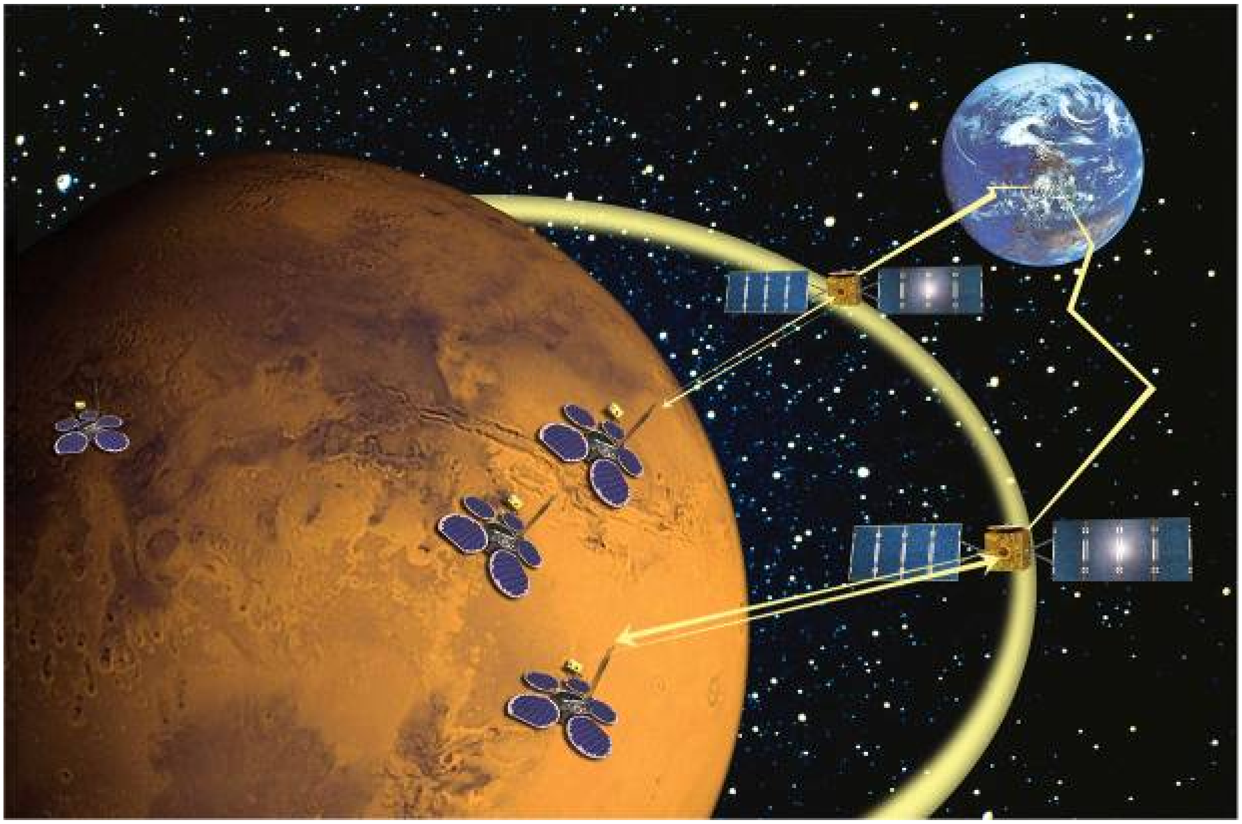

FIGURE 2.4 Artist's conception of a possible Mars Network Mission. Such a mission would involve placing several spacecraft on the surface of the planet which would send data through orbiting spacecraft that would relay it back to Earth. Mars is one possible site of a geophysical network, but not the only one. SOURCE: Courtesy of Jet Propulsion Laboratory and Centre National d'Études Spatiales.

Though remote measurements of a planet's gravitational field, magnetic field, and rotational state provide constraints on its internal structure, only seismological observations can definitively determine the nature of a planet's interior, including the size and physical state of its metallic core, the thickness of its crust, spatial variations in crustal thickness, and the occurrence and locations of subsolidus phase changes and regions of partial melting in its crust and mantle. The required seismic data can only be obtained with a globally distributed seismic network (Figure 2.4). The interiors of Mercury, Venus, the Moon, and Mars are poorly characterized and geophysical network missions to these bodies are needed to learn what is inside them. A geophysical network can also be supplemented with measurement of planetary heat flow, magnetic field, atmospheric properties and winds, climate variations, surface-atmosphere interactions, and surface mechanical and thermal properties. A variety of developments since the decadal survey, when combined with the strong initial rationale, elevates this mission concept into consideration.

Background

Discussion of network-based science missions appeared throughout the decadal survey. The decadal survey recommended the Mars Long-Lived Lander Network as its second highest priority Mars Medium Class mission after the Mars Science Laboratory: "The highest-priority objectives for network science on Mars are the determination of the planet's internal structure, including its core; the elucidation of surface and near-surface composition as well as thermal and mechanical properties; and extensive synoptic measurements of the atmosphere and weather. In addition, atmospheric gas isotopic observations (to constrain the size of currently active volatile reservoirs) and measurements of subsurface oxidizing properties and surface-atmosphere volatile exchange processes will be valuable."[17] (The committee also notes that a Mars network mission was strongly endorsed in another NRC report, *Assessment of NASA's Mars Architecture 2007-2016*.)[18]

Although specific network missions were not recommended for the other terrestrial planets, the decadal survey was quite clear about the importance of geophysical network science for these bodies. For Mercury, the decadal survey stated that "Basic information is needed on surface composition, internal structure, and distribution of mass, each of which provides important constraints on bulk major-element composition."[19] The decadal survey advocated the emplacement of "a geophysical network (seismic, heat flow) to determine internal structure, distribution of heat producing elements, lateral and vertical heterogeneity of crust and mantle, and the true density of the core. Geophysical network science would address how small bodies differentiate and how the bulk composition of Mercury is related to the composition of the terrestrial planets."[20] For the Moon, the decadal survey said "seismic data would resolve the internal structure, permitting a much-improved estimate of bulk composition."[21] It recommended "geophysical network science (seismic, heat flow) to determine internal structure, distribution of heat producing elements, lateral and vertical heterogeneity of crust and mantle, and the possible existence of an iron rich core. Geophysical network science would address how small planetary bodies differentiate, how the bulk composition of the Moon is related to the composition of Earth, and how planetary compositions are related to nebular condensation and planetary accretion processes."[22] This is also important for understanding the South Pole-Aitken Basin. Seismology would provide both the structure of the pristine highland crust and the after basin crust. This should aid computing energy and probably velocity of the projectile. For Venus, the decadal survey noted that "geothermal heat flow measured at multiple locations to determine rates of heat flow within the planet and between the surface and atmosphere." The decadal survey concluded that such measurements would "lead to better understanding of volcanism and tectonics of the crust and mantle."[23]

The Mars Long-Lived Lander Network satisfied some of the cross-cutting themes identified in Table ES.1 of the decadal survey:[24]

***New Frontiers in the Solar System* Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

The Origin and Evolution of Habitable Worlds

9. Why have the terrestrial planets differed so dramatically in their evolutions?

Processes: How Planetary Systems Work

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?

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[17] *New Frontiers in the Solar System*, p. 3.

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

[19] *New Frontiers in the Solar System*, p. 42.

[20] *New Frontiers in the Solar System*, p. 62.

[21] *New Frontiers in the Solar System*, p. 42.

[22] *New Frontiers in the Solar System*, p. 62.

[23] *New Frontiers in the Solar System*, p. 62.

[24] *New Frontiers in the Solar System*, p. 3.

It is the committee's view that a geophysical network in general could also satisfy many of these crosscutting themes and key scientific questions. The committee merely notes that the decadal survey was more detailed in its discussion of network missions for Mars than it was in its discussion of network missions elsewhere in the solar system.

Without the geophysical data from a network mission, the "Foundation Question" put forth by the Inner Planets Panel of the decadal survey—i.e., How do the compositions, internal makeup, and geologic history of the planets explain the formation and sustainment of habitable planetary environments?—cannot be answered.[25] The importance of learning about the internal structure of the planets is a pervasive theme of the Inner Planets Panel. For example, the panel noted that "knowledge of the internal structure of the planets is fundamental to understanding their history after accretion. Key issues include dissipation of internal heat, core formation and associated issues concerning magnetic-field generation, distribution of heat-producing radioactive elements, and styles and extent of volcanism."[26] Under "Future Directions" the panel emphasized that "seismic data for each of the inner planets are ultimately needed to constrain the structure, mineralogy, and composition of the deep planetary interiors. Key investigations that address evolution of the crust, mantle, and core include the following:

- Determination of the horizontal and vertical variations in internal structures,
- Determination of the compositional variations and evolution of crusts and mantles,
- Determination of the major heat-loss mechanisms and resulting changes in tectonic and volcanic styles, and
- Determination of the major characteristics of iron-rich metallic cores (size and the nature of liquid and solid components)."[27]

In its "Long-Term Exploration Strategy for the Inner Planets," the panel recommended a focus on "essential network science" involving the establishment of "multiple surface stations operating concurrently on a planet."[28] In addition, the decadal survey's Table 2.1 identifies geophysical network science as providing scientific return in three categories: highly significant scientific return, very useful scientific return, and supporting scientific return:[29]

***New Frontiers in the Solar System* Table 2.1: Summary of Priority Science Investigations Addressed by the Inner Planets Panel's Highest-Ranked Inner-Planet Missions**

Highly Significant Scientific Return

Past: What led to the unique character of our home planet?

b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?
    1. Determine horizontal and vertical variations in internal structures.
    4. Determine characteristics of Fe-rich metallic cores (size; liquid and solid components).

Present: What common dynamic processes shape Earth-like planets?

a. What processes stabilize climate?
    1. Determine the general circulation and dynamics of the inner planets' atmospheres.
    3. Determine how sunlight, thermal radiation, and clouds drive greenhouse effects.

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[25] *New Frontiers in the Solar System*, p. 39.
[26] *New Frontiers in the Solar System*, p. 42.
[27] *New Frontiers in the Solar System*, p. 43.
[28] *New Frontiers in the Solar System*, p. 63.
[29] *New Frontiers in the Solar System: An Integrated Exploration Strategy*, pp. 56-57.

b. How do active internal processes shape the atmosphere and surface environments?
    1. Characterize current volcanic and/or tectonic activity and outgassing.

Very Useful Scientific Return

Past: What led to the unique character of our home planet?

a. What are the bulk compositions of the inner planets and how do they vary with distance from the Sun?
    4. Determine interior (mantle) compositions.

b. What is the internal structure and how did the core, crust, and mantle of each planet evolve?
    2. Determine compositional variations and evolution of crusts and mantles.
    3. Determine major heat-loss mechanisms and resulting changes in tectonic and volcanic styles.

c. What were the history and role of early impacts?
    2. Determine the global geology of the inner planets.
    3. Investigate how major impacts early in a planet's history can alter its evolution and orbital dynamics.

Present: What common dynamic processes shape Earth-like planets?

a. What processes stabilize climate?
    4. Determine processes and rates of surface/atmosphere interaction.

b. How do active internal processes shape the atmosphere and surface environments?
    3. Characterize magnetic fields and relationships to surface, atmosphere, and the interplanetary medium.

Future: What fate awaits Earth's environment and those of the other terrestrial planets?

a. What do diverse climates of the inner planets reveal about the vulnerability of Earth's environment?
    1. Characterize the greenhouse effect through meteorological observations.

c. What are the consequences of impacting particles and large objects?
    1. Determine the recent cratering history and current flux of impactors in the inner solar system.
    2. Evaluate the temporal storage and record of solar-wind gasses.

Supporting

Future: What fate awaits Earth's environment and those of the other terrestrial planets?

b. How do varied geologic histories enable predictions of volcanic and tectonic activity?
    1. Assess the distribution and age of volcanism on the terrestrial planets.

d. What are the resources of the inner solar system?
    1. Assess volatile resources.
    2. Assess mineral resources.

Developments Since the Decadal Survey

With the exception of the detection of a partially molten core in Mercury from Earth-based radar observations there is no new information on the interiors of the terrestrial planets.[30] There have been new

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[30] J.L. Margot, S.J. Peale, R.F. Jurgens, M.A. Slade, and I.V. Holin, Large longitude libration of Mercury

observations of the atmospheres of Mars and Venus by several Mars missions and the Venus Express mission. There are also several orbital missions to the Moon underway or planned, and MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) is planned to orbit Mercury in the near future. But there are no atmospheric measurements at or near the surface and at multiple surface locations at the same time, nor are there geophysical network missions planned. Finally, there have been significant technological advances in seismometer design for planetary missions, long-lived power supplies, data management and storage, telecom systems, and landing concepts that improve the readiness of such missions for flight. Even the technique of passively monitoring seismic surface waves generated by atmospheric noise should be adaptable to Mars.

Conclusions

The committee concludes that these missions remain scientifically important and should be considered for the New Frontiers Program. The committee concluded that the primary goal of any network science mission is geophysics. But for Mars, atmospheric measurements near the surface are an important secondary goal.

Mission-Specific Recommendations

The committee recommends a network science mission be included in the forthcoming NASA New Frontiers announcement of opportunity. The decadal survey identifies a network mission's primary objective as geophysics. For Mars, atmospheric measurements near the surface are a valuable supplement to the geophysics measurements, but cannot be a substitute for them.

In light of the decadal survey's recognition of the importance of network science on all the terrestrial planets and the Moon, the committee recommends that network missions to the Moon, Venus and Mercury also be considered as candidate missions for the New Frontiers announcement of opportunity in addition to a Mars mission.

The scientific objectives of such a mission should be drawn from a subset of the objectives (not in priority order) described in the decadal survey:[31]

For the Interior

- Determine the internal structure including horizontal and vertical variations in the properties of the crust and mantle, and evaluate implications for how the core, mantle and crust evolved.
- Determine the characteristics of the metallic core (e.g., size, density, and presence and distribution of liquid) and explain the strength or absence of a present day magnetic field.
- Determine the heat flow and the distribution of heat-producing elements in the crust and mantle.
- Determine interior composition and compositional variations to elucidate differentiation, crust-mantle evolution (plate tectonics, basin formation by impacts, conditions for life), and how the bulk composition relates to that of the Earth and other terrestrial planets and how planetary compositions are related to nebular condensation and accretion processes.

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reveals a molten core, *Science* 316:710-714, doi:10.1126/science.1140514, 2007.

[31] This list is culled from several places in the decadal survey. See *New Frontiers in the Solar System*, pp. 7, 42, and 62.

For the Surface/Atmosphere

- Measure the surface winds and their time variability and the near surface global circulation.
- Measure the temperature, pressure, humidity, and radiative flux.
- Measure the atmospheric, elemental and isotopic compositions.
- Understand the relationship between the near-surface general circulation and the physical processes that force it.
- Determine how the near-surface general circulation controls the exchange of dust, water, CO_2, etc., between the atmosphere and surface.
- Begin to establish a weather monitoring infrastructure to support future robotic and manned missions.
- Provide an enhanced assessment of year-to-year atmospheric mass exchange between the atmosphere and polar caps and regolith.
- Determine the mineralogic composition of the surface and its thermophysical properties.

TROJAN/CENTAUR RECONNAISSANCE

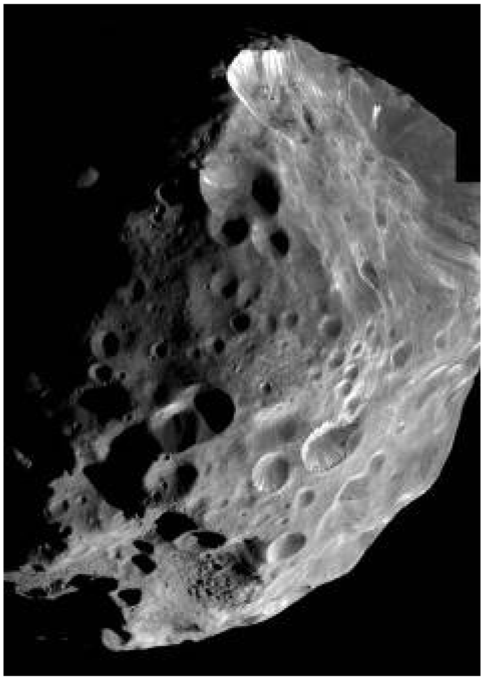

FIGURE 2.5 NASA close-up image of Saturn moon Phoebe by the Cassini spacecraft. Phoebe is roughly spherical and has a diameter of 220 kilometers. Some scientists believe that Phoebe is a captured Centaur object. SOURCE: Courtesy of NASA/JPL/Space Science Institute.

The Decadal Survey Primitive Bodies Panel recommended “reconnaissance of the Trojans and Centaurs.”[32] The decadal survey listed this as a deferred medium-class mission.[33] A variety of developments since the decadal survey, when combined with the strong initial rationale, elevate this mission concept into consideration.

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[32] *New Frontiers in the Solar System*, p. 35.

[33] *New Frontiers in the Solar System*, p. 197.

The Trojans, now known to number well over a thousand, are aggregated about the L4 and L5 equilibrium points along Jupiter's orbit. These objects, initially discovered in the early 20th century, tend to be spectral type D (asteroids with a low albedo and a featureless, reddish spectrum) and are thought to be primitive leftovers from early solar system formation, possibly captured during giant planet formation, although this remains a question of debate. At the time of the decadal survey, Trojans were thought to have formed in place and sample the region of the accretion disk from which Jupiter formed. (See Figure 2.6 which illustrates the Trojan orbits.)

The Centaurs occupy positions further from the Sun. The initial Centaur, 2060 Chiron, was discovered in 1977. Centaurs are generally described as objects with semi-major axes and perihelia lying between the heliocentric distances of Jupiter and Neptune. Although not as distant as Kuiper Belt objects (KBOs), they are still sufficiently small and distant to be difficult to study remotely. They exhibit a range of sizes and colors; 10199 Chariklo is the largest currently known, with an approximately 225 km characteristic diameter. Water ice has been unambiguously detected on some of the larger Centaurs (e.g., 2060 Chiron, 5145 Pholus, and 10199 Chariklo).[34] While the Trojans are spectrally homogeneous, the Centaurs are diverse ranging from spectrally neutral, but displaying cometary outbursts (like 2060 Chiron), to inactive and spectrally very red (for example, 5145 Pholus). The orbits are dynamically unstable and the current accepted theory is that these objects originated as KBOs, and thus provide a more accessible sample than KBOs much further out in the solar system. As a result of Cassini observations made since the last decadal survey, there is also a working hypothesis that the moon of Saturn, Phoebe (Figure 2.5), may be a Centaur captured in the Saturn system. Less than a hundred of these objects are currently known.

Background

The decadal survey stated that a Trojan Asteroid/Centaur Reconnaissance mission "would send a [Kuiper Belt Pluto]-like flyby reconnaissance spacecraft equipped with imaging, imaging spectroscopy, radio science, and, potentially other instruments to make the first explorations of both a Jovian Trojan asteroid and a Centaur. Beyond simply opening up these two new classes of primitive bodies to exploration, this mission has deep ties to understanding the origins of primitive bodies."[35]

In addition, the decadal survey stated that: "the Trojan flyby would sample primitive material from the Jovian accretion region of the nebula; it would also allow an important recalibration of the bombardment flux on objects in the Jovian system and would offer new insights into space weathering and other processes affecting asteroids, particularly in the main belt. The Centaur flyby would provide insights into the nature of the Kuiper Belt, the nature and origin of short-period comets and their parent bodies, and activity in distant comets."[36]

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[34] A. Delsanti and D. Jewitt, *The Solar System beyond the Planets. Solar System Update,* P. Blondel and J. Mason, eds., Springer, Berlin, 2006, p. 267.

[35] *New Frontiers in the Solar System*, p. 25.

[36] *New Frontiers in the Solar System*, p.25.

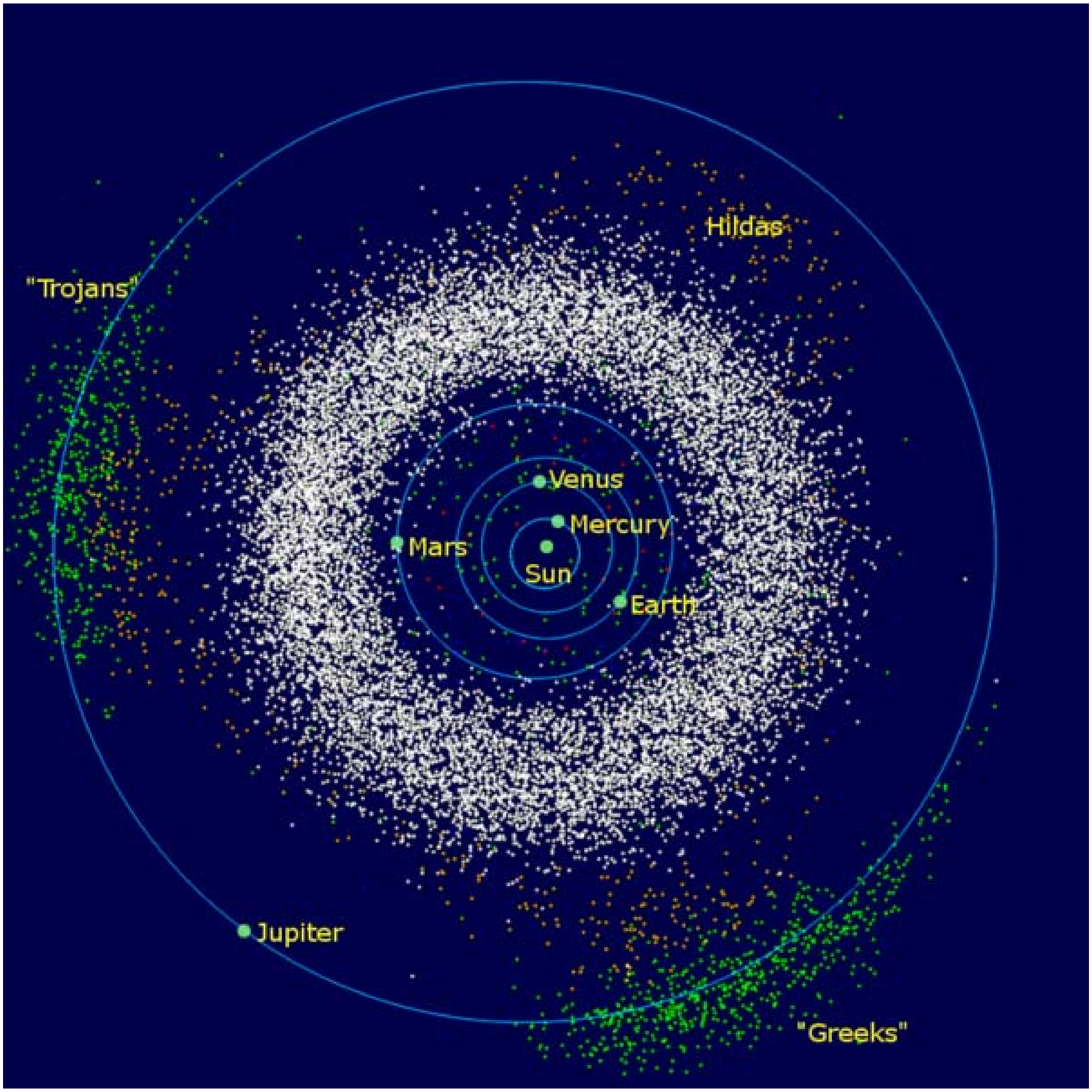

FIGURE 2.6 Illustration of asteroids in the solar system showing how the Trojan asteroids (also referred to as "Greeks" in this image) occupy positions in front of and trailing Jupiter's orbit around the Sun. SOURCE: Courtesy of NASA.

The decadal survey identified a number of cross cutting science themes that have been addressed by the New Horizons mission and could be addressed by a Trojan/Centaur Reconnaissance mission. These are listed in the decadal survey Table ES.1.[37] These include:

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[37] *New Frontiers in the Solar System*, p. 3.

New Frontiers in the Solar System **Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

The First Billion Years of Solar System History

1. What processes marked the initial stages of planet and satellite formation?
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?

The decadal survey also identified several other areas where a Trojan/Centaur Reconnaissance mission could answer key questions:

New Frontiers in the Solar System **Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

Volatiles and Organics: The Stuff of Life

4. What is the history of volatile compounds, especially water, across the solar system?

Processes: How Planetary Systems Work

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Trojans and Centaurs both formed beyond the solar system ice line and likely represent the transition from inner main belt, ice-free asteroids and outer solar system comets. Detailed study of these objects should greatly expand our understanding of the history of volatiles.

Trojans and Centaurs exist in regions of the solar system that are likely fundamentally different, for instance in respect to impact flux and solar energy than those sampled by main belt asteroids. Examination of these objects will expand our knowledge of the interaction of small bodies with the space environment throughout the solar system.

The Primitive Bodies Panel of the decadal survey identified the following high-level science questions that should be significantly addressed by the Trojan/Centaur Reconnaissance mission, dividing these into paradigm-altering, pivotal and foundation-building observations for each of the 2 themes: "Building Blocks of the Solar System" and "Organic Matter in the Solar System: Materials for the Origin of Life."[38] These questions include:

Paradigm-Altering

- What is the nature of the KBOs (Kuiper Belt objects)?
- Where in the solar system did building blocks form; which were transported and which were not?
- How is organic matter distributed throughout the solar system?

Pivotal

- What processes modify the surfaces of all categories of building blocks?

Foundation Building

- How do colors and albedos of small bodies relate to their compositions and histories of

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[38] *New Frontiers in the Solar System*, p. 34, Table 1.1.

alteration by various processes since their origin?

- What roles did various dynamical processes play in the origin and evolution of the primitive bodies in the solar system, and what were the time scales?

Given our recent experience with both comet and asteroid missions, it is clear that each body reveals only part of a synoptic view. A single KBO encounter by New Horizons will clearly not elucidate the full diversity of KBOs and an encounter with a Trojan asteroid or Centaur, each of which, counter to previous opinion, could be a scattered KBO, would provide valuable insights into that diversity.

A Trojan asteroid could prove particularly intriguing given the possibility that these asteroids either sample the Jovian accretion zone or represent asteroids captured during giant planet formation. Both Trojan asteroids and Centaurs could prove rich in organics, perhaps sampling regions of the nebula and types of organics not sampled on Earth or by previous missions. Basic characterization of these asteroids, coupled with knowledge gained about the alteration history of these objects, should strengthen our ability to relate ground-based spectra to geologic history. Study of Trojans and Centaurs in the context of both early (e.g., asteroid migration and capture) and late (e.g., space weathering) solar system evolution will elucidate the physical and dynamical processes through time.

The Primitive Bodies Panel further listed the following specific questions deserving of investigation:[39]

- Where in the solar system are the primitive bodies found, and what range of sizes, compositions, and other physical characteristics do they represent?
- Where in the solar nebula did the classes of primitive bodies form? Which were subsequently transported, and which remain in place?
- What are the basic physical properties (mass, density, size) of Kuiper Belt objects, Centaurs, and comets?
- What roles did various dynamical processes play in the origin and evolution of the primitive bodies in the solar system, and what were the time scales?
- What are the surface properties and compositions of these bodies, and how do endogenous and exogenous processes affect them?
- What are all of the space weathering processes that operate on the surfaces of bodies without atmospheres, and have these processes varied over time?
- What is the time-history of collisional events and their consequences at various distances from the Sun?

In many respects, our reconnaissance of the Trojans and Centaurs is only beginning. The increased sensitivity of ground-based telescopes is increasing the discovery rates not only of asteroids, but also Trojans and Centaurs. While the basic properties of the Trojans and Centaurs are emerging, little is known about individual objects and our view of the population as a whole is changing rapidly. While both Trojans and Centaurs are, to the best of our knowledge, primitive objects, our knowledge of their position of origin remains unresolved. Centaurs are known to be in orbits unstable over periods of tens of millions of years.

Knowledge of properties of both the Trojans and Centaurs are typically limited to single-pixel photometry and spectrometry due to their relatively small sizes and large distances.[40] To determine the homogeneity, heterogeneity, mass, and volume of these bodies in general, and Trojans and KBOs in particular, close flybys are required at a minimum. That flybys can accomplish such objectives to a level better than provided by remote measurements alone—objectives which can be met in no other way—is

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[39] *New Frontiers in the Solar System*, pp. 14, 15, 17 and 18.

[40] A. Delsanti and D. Jewitt, The solar system beyond the planets, pp. 267-294 in *Solar System Update*, Ph. Blondel and J. Mason, eds., Springer-Praxis, Germany, 2006.

demonstrated by the Cassini observations of Phoebe (Figure 2.5) and the Near Earth Asteroid Rendezvous (NEAR)-Shoemaker observations of the main belt asteroid 253 Mathilde (Figure 2.7).

Interpretations of the spectra of D-type asteroids, such as the Trojans, retain both ambiguities and uncertainties that will remain unresolved until these objects themselves can be resolved, at least down to their major features.

Both effects of "space weathering" on the short term, and impacts on the long term, can be addressed with close up images and spectral observations. The observations of Phoebe by Cassini are a case in point.

FIGURE 2.7 The asteroid Mathilde was studied by the NEAR spacecraft during a flyby, providing better data than could be obtained by remote measurements alone. Mathilde is approximately 66 by 48 by 46 kilometers in size. SOURCE: Courtesy of NASA.

Developments Since the Decadal Survey

In the past several years our understanding of small bodies has been substantially enriched with the analysis of data from the NEAR mission, the successful encounter of asteroid Itokawa by the Japanese Hayabusa mission, and the encounters of comets with the Deep Impact and Stardust missions, as well as the initiation of the New Horizons mission to Pluto and the Kuiper Belt. In addition, since the decadal survey was written, there is now an appreciation that the Trojans could have formed elsewhere in the solar system and been captured by Jupiter during significant orbital migrations of the gas and ice giant planets, strengthening our need to understand where these objects formed and how they reached their current positions.[41]

Conclusions

Asteroidal bodies offer some of our best clues to the materials and processes that were dominant in the early history of the solar system. The importance of these bodies was clearly recognized by the decadal survey. A Trojan/Centaur reconnaissance mission would explore two classes of bodies that were thought to have formed in place, thus preserving the solid materials present in the region of the solar nebula in which Jupiter formed. The growing numbers of these asteroids and the recognition that they

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[41] A. Morbidelli, H.F. Levison, K. Tsiganis, and R. Gomes, Chaotic capture of Jupiter's Trojan asteroids in the early solar system, *Nature* 435:462-465, doi:10.1038/nature03540, 2005.

sample volatile-rich regions of the solar nebula strengthen our interest in these objects. Coupled with the idea that large planet migration might perturb Kuiper Belt objects into Centaur-like orbits, this mission is necessary to fully inventory the primitive bodies of our solar system and understand their origin.

Mission-Specific Recommendations

Coupling new science emerging in the past several years with the decadal survey, the mission originally described in the decadal survey should be modified so that NASA informs potential proposers of the kind of science questions that should be answered and does not prescribe how the mission should actually be accomplished. The mission requirements should also permit orbital encounters, and state that main belt asteroid flyby is not considered critical to this mission.

Such a mission should have the following science objectives:

- Determine the physical properties (e.g., mass, size, density) of a Trojan and a Centaur.
- Map the color, albedo, and surface geology of both a Trojan and a Centaur at a resolution sufficient to distinguish important features for deciphering the history of the object (e.g., craters, fractures, lithologic units).

Each of these objectives can be addressed by appropriate imagers and/or spectrometers/spectrographs that resolve the target. For example, spacecraft tracking could obtain a mass, so that a density can be determined. A full discussion of appropriate error bars on such science objectives that are achievable under this program require trade studies that are yet to be made and beyond the scope of this study. If the target Centaur has suspected cometary or quasi-cometary activity, then in situ instrumentation capable of addressing such activity and its constituents should be considered.

ASTEROID ROVER/SAMPLE RETURN

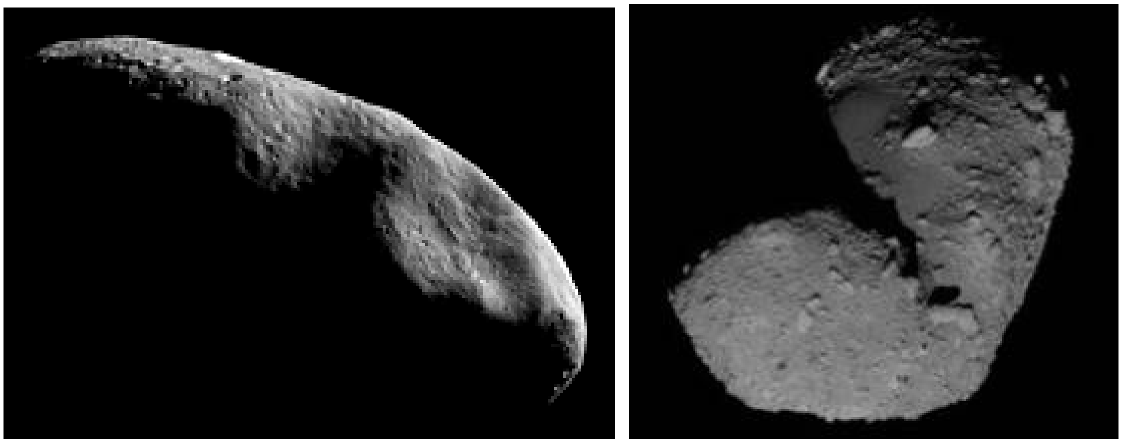

FIGURE 2.8 The S-type asteroids 433 Eros (left) and 25143 Itokawa (right). These asteroids were the targets of the NEAR and Hayabusa missions, respectively, which revealed the complexity in asteroid surfaces. Eros is approximately 33 by 13 by 13 kilometers in size, whereas Itokawa is much smaller, at 535 by 294 by 209 meters. SOURCE: Eros image courtesy of NASA, Itokawa image courtesy of JAXA (Japan Aerospace Exploration Agency).

Asteroids are planetesimals, largely found in the orbit between Mars and Jupiter, that escaped the melting and differentiation that shaped the larger terrestrial planets, although short-lived metamorphism and aqueous alteration occurred on many of these bodies. They offer a unique record of the complex chemical evolution that occurred in the early solar nebula, which has since been obliterated from the larger planets. In studying asteroids, we have the substantial advantage of having abundant asteroid samples in the form of meteorites, although these samples lack the geologic context that would allow us to examine, for example, radial heterogeneity in the solar system. The decadal survey Primitive Bodies Panel recommended an Asteroid Rover/Sample Return mission as their fourth ranked mission priority.[42] This mission was ultimately deferred from consideration by the decadal survey.[43] A variety of developments since the decadal survey, when combined with the strong initial rationale, prompts us to elevate this mission concept into consideration.

A primary motivation for an asteroid sample return mission is the desire to both acquire samples with known geologic context and to return materials that are either unlikely to survive passage to Earth (e.g., friable, volatile-rich material) or would be compromised by terrestrial contamination upon their fall (e.g., extraterrestrial organics).

Background

The decadal survey emphasized the value of a return to asteroid 433 Eros, which has already been the subject of global characterization during the Near Earth Asteroid Rendezvous (NEAR) mission which ended in early 2001. This mission emphasized the complexity of asteroidal regolith and the need to understand surface processes if remotely-sensed spectra of asteroids were to be interpreted.

The decadal survey in Table ES.1 identified a number of cross cutting science themes that were addressed by the New Horizons mission and would be addressed by a Asteroid Rover/Sample Return mission.[44] These include:

> ***New Frontiers in the Solar System* Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**
>
> ***The First Billion Years of Solar System History***
>
> 1. What processes marked the initial stages of planet and satellite formation?
> 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?

Organic-rich, water-rich asteroids have the potential to yield fundamental information about the source of water and prebiotic organics that contributed to the accretion of the terrestrial planets.

In addition to being the major source of impactors to the early Earth, the asteroid belt preserves a unique record of collisions, breakup and cratering over the past 4.5 billion years. Each asteroid has been shaped by these processes and provides insights into the influence of cratering through time. Individual asteroids preserve a record of the evolution of organics from the birth of the solar system to interactions of organics at the surface with the space environment. The decadal survey identified several questions relevant to this as well.

In addition, an asteroid mission would address several other questions asked in the decadal survey:

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[42] *New Frontiers in the Solar System*, p. 35.
[43] *New Frontiers in the Solar System*, p. 197.
[44] *New Frontiers in the Solar System*, p. 3.

***New Frontiers in the Solar System* Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

Volatiles and Organics: The Stuff of Life

4. What is the history of volatile compounds, especially water, across the solar system?
5. What is the nature of organic material in the solar system and how has this matter evolved?

Processes: How Planetary Systems Work

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?
12. What does the solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

Little is known about the surfaces of organic-rich asteroids and their interaction with the space environment, largely resulting from their near-featureless reflectance spectra. Returned samples may provide the only methods of assessing these processes.

The Primitive Bodies Panel for the decadal survey identified the following high-level science questions that an Asteroid Rover/Sample Return mission could provide breakthrough advances or significantly address, dividing these into paradigm-altering, pivotal and foundation-building observations.[45] These questions include:

Paradigm-Altering

- What are the compositions and origins of the organic and volatile materials in primitive bodies?
- How is organic matter distributed throughout the solar system?

Pivotal

- What processes modify the surfaces of all categories of building blocks?
- Did organic matter from comets and meteorites provide the feedstock for the origin of life on Earth?

Foundation Building

- How do colors and albedos of small bodies relate to their compositions and histories of alteration by various processes since their origin?
- What are the processes by which organic material forms on the surfaces of icy and other primitive bodies in the current epoch?
- What is the thermal and aqueous alteration history of the parent bodies of the organic-rich primitive meteorites?

The relationship of the colors and albedos of small bodies to their compositions and histories of alteration since their origin is essential information that will allow us to interpret remotely-sensed spectra of asteroids and, by extension, develop a geological map of processes occurring in the early solar system. Furthermore, very little is known or can be directly ascertained about the interactions of volatiles and organics without sample return.

The Primitive Bodies Panel further listed the following specific questions deserving of investigation:[46]

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[45] *New Frontiers in the Solar System*, p. 34, Table 1.1.

[46] *New Frontiers in the Solar System*, pp. 14, 15, and 20.

- Where in the solar system are the primitive bodies found, and what range of sizes, compositions, and other physical characteristics do they represent?
- What processes led to the formation of these objects?
- Since their formation, what processes have altered the primitive bodies?
- What is the composition, origin, and primordial distribution of solid organic matter in the solar system?
- What is its present-day distribution?
- What processes can be identified that create, destroy, and modify solid organic matter in the solar nebula, in the epoch of the faint early Sun, and in the current solar system?

Developments Since the Decadal Survey

In the past several years a number of developments have strengthened the case for asteroid sample return. The most important of these is the complete analyses of the data on 433 Eros returned from the NEAR mission and the successful encounter of the Japanese Hayabusa spacecraft with asteroid Itokawa. These encounters demonstrated the diversity of asteroids and their complexity both internally and on the surface.

The recognition of the diversity of organics in meteorite samples has prompted a re-evaluation of the astrobiological importance of asteroids.[47] A sample return from an organic-rich asteroid may offer insights into the distribution of biogenic compounds and allow an evaluation of whether the delivery of precursor exogenous materials might have contributed to the origin of life. The scientific consensus derived from the studies of carbonaceous chondrite meteorites is that abiotic syntheses may lead to prebiotically relevant organic molecules but only in complex mixtures, where the prebiotically "desirable" compounds are but a small fraction of the total.[48] Because life's biomolecules are, by contrast, the product of a strict compositional selection and function specific, current findings leave yet unresolved the question of whether the extraterrestrial material of meteorites is, in fact, prebiotically relevant. Attributes such as the molecular asymmetry described for some amino acids of the Murchison and Murray meteorites appear to offer such relevance, but their range and concentration need to be determined in a contamination-free sample.[49]

The committee recognizes that the exact correspondence between meteorites and possible parent asteroids is not well established. It is hoped that renewed effort in linking meteorite and asteroid spectra and new findings (e.g., see below about main belt comets) would better direct proposers toward an organic-rich target.[50]

The final major development is the detection of main belt comets (Figure 2.9). There are currently three known main belt comets: 133P/(7968) Elst-Pizarro (EP), P/2005 U1 (Read) (P/Read), and asteroid 118401 (1999 RE_{70}). Orbiting completely within the main asteroid belt, the main belt comets present a distinct contrast with other periodic comets, the Jupiter-family and Halley-family comets, which originate in the cold outer solar system in the Kuiper Belt or Oort Cloud and are later perturbed into highly eccentric orbits passing through the inner solar system where we observe them. Unlike the Jupiter-family and Halley-family comets, the main belt comets appear to have formed in the much warmer inner solar system, where they are found today, and so likely contain ice that is quite different in chemical and isotopic composition from that in other comets.

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[47] S. Pizzarello, G.W. Cooper, and G.J. Flynn, The nature and distribution of the organic material in carbonaceous chondrites and interplanetary dust particles, pp. 625-651 in *Meteorites and the Early Solar System II*, D.S. Lauretta and H.Y. McSween Jr., eds., University of Arizona Press, Tucson, Ariz., 2006.

[48] NRC, *The Astrophysical Context of Life*, pp.41-42.

[49] J. R. Cronin and S. Pizzarello, Enantiomeric excesses in meteoritic amino acids, *Science* 275:951-935, 1997.

[50] T.H. Burbine and R.P. Binzel, Small main-belt asteroid spectroscopic survey in the near infrared, *Icarus* 159(2):468-499, 2002.

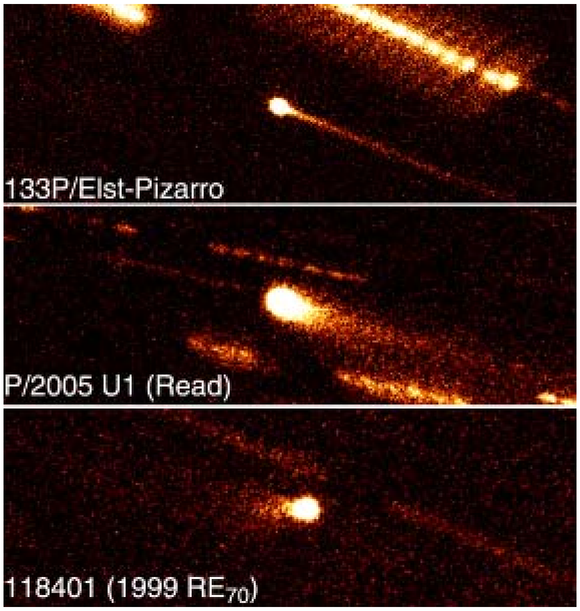

FIGURE 2.9 Images of known main belt comets (MBCs) from UH 2.2-meter telescope data. All MBCs are clearly cometary, at least in the observational and physical sense (i.e., they appear “fuzzy” and all indications are that this fuzziness is caused by the ejection of dust by the sublimation of volatile material, most likely water ice). SOURCE: courtesy of Henry H. Hsieh. Available at http://www.ifa.hawaii.edu/ ~hsieh/mbcs.html.

The committee notes that the distinction between comets and asteroids is narrowing. Because of this, comet sample return and asteroid sample return missions will share many characteristics.

Conclusions

Asteroidal samples offer a unique record of the complex chemical evolution that occurred in the early solar nebula. Despite having abundant samples in the form of meteorites, these samples lack geologic context. An asteroid sample return mission would acquire samples with known geologic context that are either unlikely to survive passage to Earth or would be compromised by terrestrial contamination upon their fall. Successful encounters of the NEAR and Hayabusa missions have demonstrated the diversity of asteroids and their complexity both internally and on the surface. The recognition of the diversity of organics in meteorite samples coupled with the detection of main belt comets that appear to have formed in the much warmer inner solar system strengthens the importance of this mission.

Mission-Specific Recommendations

The committee recommends that although the Asteroid Rover/Sample Return mission should be included as a possible mission for the New Frontiers Program, the mission objectives should be changed to reflect new scientific information acquired since the decadal survey. Specifically, the unique scientific value of organic-rich targets may elevate them for consideration when compared to the type of asteroid visited by the NEAR mission emphasized by the decadal survey.

Such a mission should have the following science objectives, which are not prioritized:

- Map the surface texture, spectral properties (e.g., color, albedo) and geochemistry of the surface of an asteroid at sufficient spatial resolution to resolve geological features (e.g., craters, fractures, lithologic units) necessary to decipher the geologic history of the asteroid and provide context for returned samples.

- Document the regolith at the sampling site in situ with emphasis on, e.g., lateral and vertical textural, mineralogical and geochemical heterogeneity at scales down to the sub-millimeter.
- Return a sample to Earth in amount sufficient for molecular (or organic) and mineralogical analyses, including documentation of possible sources of contamination throughout the collection, return and curation phases of the mission.

IO OBSERVER

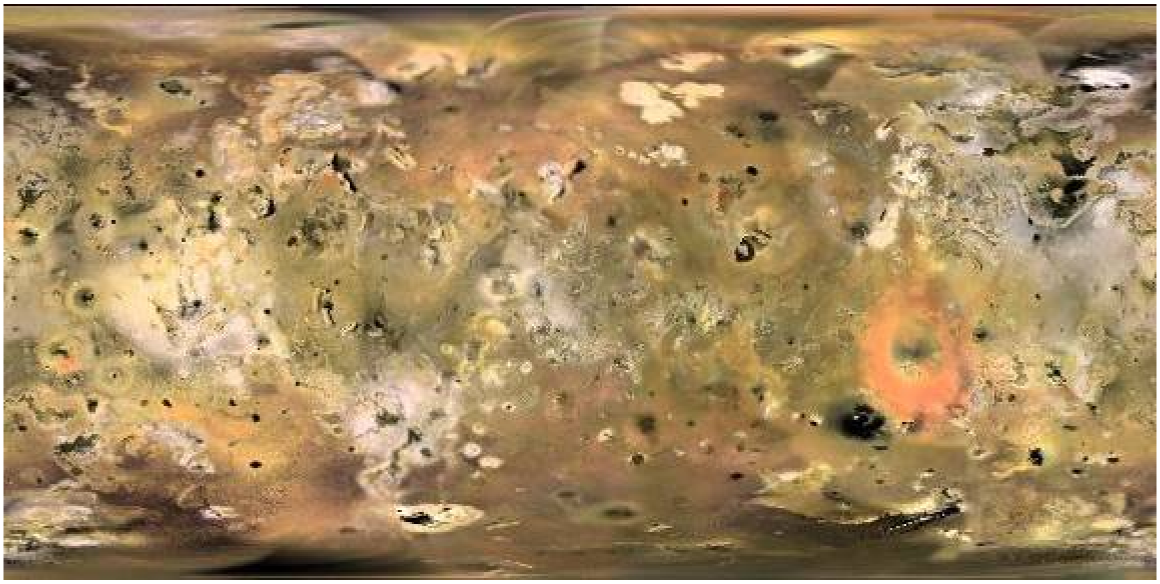

FIGURE 2.10 The turbulent surface of Io. The lack of visible craters is one indication that Io's surface is very young—any impact craters have been filled in due to volcanism and volcanic structures are readily visible. The colorful surface is also an indication of various materials being distributed by volcanic action. SOURCE: Courtesy of U.S. Geological Survey Astrogeology. Available at http://astrogeology.usgs.gov/Projects/JupiterSatellites/io.html.

The decadal survey Large Satellites Panel recommended an Io Observer as a potential medium class mission.[51]

As the most volcanically active body in the solar system, Io remains a unique target for study (see Figure 2.10). Notably, the causes and consequences of such active volcanism demand closer investigation. The decadal survey noted the salient, scientifically significant features of Io that emerged largely from the Voyager era, including new understanding of large-satellite tectonics, the discovery of eruptive activity, the effect of the eruptions on the global sulfur-rich chemistry of this body and its unique and little-understood atmosphere, the subsequent loss of volatiles (mostly sulfur and oxygen) to Jupiter's magnetosphere, and conducting satellite/plasma interaction, best illustrated by Io and Europa. While being one of the four Galilean satellites of Jupiter, all of which lie close to the planet and are of roughly similar size, Io has a significant metallic core with a silicate mantle and lacks the layer of water ice and/or water that plays a significant role with the other three. The coloring of the entire surface, and the lack of impact craters, results from the continued eruptions of sulfurous and silicate materials from the interior.[52]

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[51] *New Frontiers in the Solar System*, pp. 133 and 197.

[52] *New Frontiers in the Solar System*, pp. 121-129.

Galileo data were too sparse to fully understand Io, and a return mission with modern remote sensing instruments and a high data rate would revolutionize our understanding of this complex and dynamic body.

Background

The decadal survey identified top-level, cross-cutting science themes contained within Table ES.1.[53] While the survey did not specifically address how these cross-cutting themes and key questions would be addressed by an Io Observer mission, it is possible to map such a mission against many of these themes:

> ***New Frontiers in the Solar System*** **Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**
>
> ***The First Billion Years of Solar System History***
>
> 1. What processes marked the initial stages of planet and satellite formation?

Io's volcanic activity continues to resurface the large moon by circulating new material from the hot interior to the surface. While this activity has obliterated the original surface, it does provide a unique view into interior materials at this location in the solar system. The tidal processes that still dominate Io were probably important in the early evolution of many planetary satellites, and Io provides the only current example of how a planetary body responds to the very high heat flow that was a likely stage in the early evolution of most solid bodies in the solar system.

> ***New Frontiers in the Solar System*** **Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**
>
> ***Volatiles and Organics: The Stuff of Life***
>
> 4. What is the history of volatile compounds, especially water, across the solar system?
> 6. What global mechanisms affect the evolution of volatiles on planetary bodies?

Io is a water-poor world unlike its neighbors, especially Europa, in the Jovian system. Io is currently losing volatiles such as sulfur and sodium at the rate of about 1 ton per second via magnetospheric processes, and may have earlier lost its water by similar processes. Volatiles are transported rapidly across Io's surface by volcanic and atmospheric processes, and are lost from the moon and then transported outwards to the other moons and ultimately out of the system by complex and poorly-understood plasma processes. These processes illuminate volatile loss and redistribution mechanisms that are likely to have wider importance in the history and evolution of solar system volatiles, but are most easily studied at Io because they operate there with unique rapidity and intensity.

> ***New Frontiers in the Solar System*** **Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**
>
> ***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?

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[53] *New Frontiers in the Solar System*, p. 3.

Tidal heating, a process that can greatly expand the habitable zones in the solar system and elsewhere, is best studied at Io because it provides the most extreme example of this process in the solar system.

***New Frontiers in the Solar System* Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

Processes: How Planetary Systems Work

11. How do the processes that shape the contemporary character of planetary bodies operate and interact?

Io provides the best place in the solar system, beyond Earth, to study volcanism, a process of fundamental importance on many planetary bodies. Io also provides some of the most dramatic, freshest, and easily-studied examples of fundamental geological processes such as mountain-building and mass-wasting. The volcanic activity on Io drives interlocking processes on a variety of time scales. While resurfacing/recycling the surface, the activity also provides volatile contributions to the Jovian sulfur and sodium nebulae via a time-varying atmosphere and exosphere. By providing approximately 1 ton per second of material deep within the magnetosphere of Jupiter, Io is a primary driver for most magnetospheric activity. With transport of material to Europa and the rest of the system, re-energization processes, and the Alfvénic interaction between Io and the upper atmosphere of Jupiter itself, scientists know that multiple, non-linear feedback processes are present on many spatial and temporal scales.

The following boxes indicate more specific questions that would be addressed by an Io Observer mission, as delineated in Table 5.2 of the decadal survey:[54]

Questions an Io Observer could offer a breakthrough-level advance

A. Origin and Evolution of Satellite Systems

2. What affects differentiation, outgassing, and the formation of a thick atmosphere?
   —Characterization of internal heat sources
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?
   —Geologic processes/history (including impacts)
   —Tectonics/volcanism

D. Understanding Dynamic Planetary Processes

1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?
   —Heat flow and tidal heating
   —Global volcanism and tectonism
   —Secular variations of magnetic field
2. What are the currently active endogenic geologic processes (volcanism, tectonism, diapirism) and what can we learn about such processes in general from these active worlds?
   —Observations of dynamic processes with high spatial and temporal resolution
   —Search and discovery of new types of activity
3. What are the complex processes and interactions on the surfaces and in volcanic or geyserlike plumes, atmospheres, exospheres, and magnetospheres?
   —Dynamic of plumes, geysers, atmospheres, exospheres, and magnetospheres
   —History of volatiles
   —Atmospheric loss (fields and particles)

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[54] *New Frontiers in the Solar System*, pp. 140-143.

Questions an Io Observer could offer a major advance

A. Origin and Evolution of Satellite Systems

1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?
   —Characterization of magnetic fields in satellites
2. What affects differentiation, outgassing, and the formation of a thick atmosphere? (Why is Titan unique?)
   —Atmospheric composition
   —Production/loss rates
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?
   —Geologic processes/history (including impacts)
   —Map surface composition

B. Origin and Evolution of Water-Rich Environments in Icy Satellites

2. What combination of size, energy sources, composition, and history produce long-lived internal oceans?
   —Heat flow

Questions an Io Observer can offer a significant advance

A. Origin and Evolution of Satellite Systems

1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?
   —Interior structure and composition of (major) satellites
   —Secular variation of orbital parameters
2. What affects differentiation, outagassing, and the formation of a thick atmosphere? (Why is Titan unique?)
   —Atmospheric composition
   —Interior structure and composition
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?
   —Subsurface sounding
4. How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?
   —Observation of craters (on many different bodies)
   —Geology/modification

B. Origin and Evolution of Water-Rich Environments in Icy Satellites

1. What is the chemical composition of the water-rich phase?
   —Remote and in situ composition observations
2. What is the distribution of internal water, in space and in time?
   —Elemental and isotopic composition
4. Can and does life exist in the internal ocean of an icy satellite?
   —Characterization of surface radiation environment
   —Transport processes

C. Exploring Organic-Rich Environments

1. What is the nature of organics on large satellites?
   —Composition (elemental, isotopic, and molecular), remote and in situ
   —Production/loss (radiation, degassing, escape, lightning, and exogenic/endogenic)
   —Physical state

—Optical properties
—Reaction rates/kinetic information
2. What are the processes currently affecting organic-rich surfaces?
—Cryovolcanic processes
—Tectonic processes

D. Understanding Dynamic Planetary Processes

1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?
—Interior structure

While the decadal survey outlined the ways in which an Io mission could contribute to important questions about planetary satellites, it did not detail Io-specific science goals for an Io orbiter mission.[55] Similarly, while the decadal survey lacks a detailed proposed mission description, a précis of the mission concept is given in the decadal survey.

The mission concept for Io could involve either a Jupiter orbiter dedicated to multiple close flybys of Io, or a multirole mission, with part of the mission and payload being devoted to magnetospheric space physics goals and/or atmospheric and auroral observations. The assumption that this mission could achieve the stated goals within this cost category rests partially on assuming that heritage from the Europa Geophysical Explorer would allow significantly reduced costs. The committee notes that although the Europa Geophysical Explorer was not pursued, significant studies of the Jupiter radiation environment were performed as part of the Jupiter Icy Moons Orbiter program, and some radiation-hardened electronics have been developed in the interim. Nevertheless, an Io Observer spacecraft would definitely benefit from future studies and technology development, including work currently underway for the Juno mission.

More Io-specific goals can be drawn from the white paper provided to the decadal survey by the Io community.[56]

Developments Since the Decadal Survey

The decadal survey report was mostly written in 2001 after most of Galileo's Io flybys. Remote analyses of Io have continued using Earth-based assets. Near observations have been limited to the few, but spectacular, views provided during the New Horizons flyby of Jupiter on its way to Pluto in February 2007.

These additional views provide insights into the temporal variations in and extent of the eruptions, the presumed prime driver of phenomena throughout the Jovian magnetospheric system. This activity thus has consequences for understanding the dynamics and evolution of the Jovian system on time scales stretching from mere hours, to the age of the solar system.

The New Horizons Io images (see Figure 2.11) underscore the importance of temporal coverage, and open a new window on plume dynamics by showing how plume structure can be tracked to reveal rapid motions, while ground-based adaptive optics images underscore the importance of long-term temporal coverage in tracking volcanic eruptions.

Continuing work on Io's atmosphere, such as the recent identification of sodium chloride, hints at the atmosphere's likely chemical complexity, and its physical complexity is revealed in the large regional

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[55] Other top-level notes for such a mission are included in Table 5.3 and Table 7.1 of the decadal survey, *New Frontiers in the Solar System*, pp. 144 and 176.

[56] J.R.Spencer et al., The future of Io exploration, community white paper for the Planetary Decadal Survey, in *The Future of Solar System Exploration, 2003-2013*, M. Sykes, ed., *Astron. Soc. Pac. Conference Series* 270:201-216, 2002.

variations in atmospheric density revealed by new Hubble Space Telescope and ground-based observations, and global circulation patterns made available by disk-resolved millimeter-wave atmospheric observations. New Horizons' exploration of Jupiter's magnetotail also sheds new light on the processes of magnetospheric volatile loss from Io.

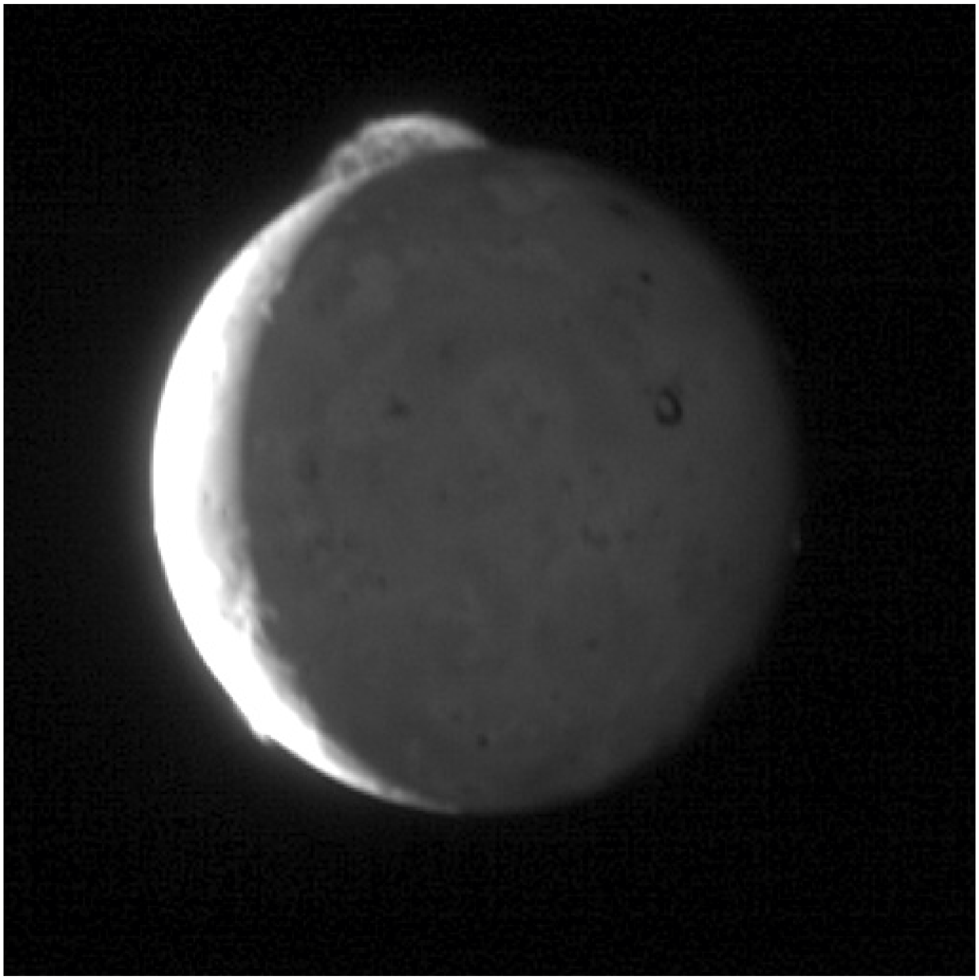

FIGURE 2.11 Image of Io taken during Jupiter flyby in February 2007. Io has a diameter of 3,642 kilometers. SOURCE: Courtesy of NASA.

Observations from the ground and by spacecraft such as Hubble, Cassini, and New Horizons can help provide clues to the system. Juno will also provide magnetic field data when it reaches Jupiter in 2015. But the lack of dedicated, targetable observations makes any approach to understanding the system extremely piecemeal. Resolution, or even significant advance in understanding, of the underlying physics is problematic without nearby, focused observations.

The committee notes that there have also been technological developments since the decadal survey that may make such a mission more feasible now than it was only five years ago. In particular, radiation-hardened electronics have been developed which would be vital to an Io mission. The 2007 flagship-class mission studies for the Europa Explorer and Jupiter System Observer (JSO) demonstrate the longevity possible with modern rad-hard electronics in the intense Jovian radiation environment. In particular Figure 4.4.4 of the JSO report shows that the spacecraft accumulates only 10 percent of its design radiation dose in its first three Io flybys, suggesting that a dedicated Io mission could survive a large number of Io flybys.[57] The Juno mission also demonstrates the feasibility of using radiation shielding and a solar powered satellite at Jupiter's distance from the Sun.

Conclusions

The Galileo mission to Jupiter provided relatively limited information on Io for several reasons: it had very limited ability to provide high-resolution spatial coverage of Io due to the low data rate; its instrumentation was limited (e.g., almost no ability to study Io's molecular atmosphere, and very limited spatial coverage possible during each flyby); and it was limited to seven Io flybys (many of which were late in the extended mission and compromised by spacecraft problems), not nearly enough to characterize Io's internal structure and determine if it has a magnetic field, or investigate temporal variability of the surface with high spatial resolution.

Several new technology developments have occurred which make an Io mission more feasible than it was only five years ago. The committee, like the decadal survey, envisions a possible mission concept involving a Jupiter orbiter in eccentric orbit with multiple Io flybys and extensive temporal monitoring at other times in its orbit.

Mission-Specific Recommendations

An Io Observer mission that addresses fundamental goals for solar system exploration may be possible. Consequently, an Io Observer mission should be included in the suite of possible missions included in the next New Frontiers announcement of opportunity. The mission should address some of the following science questions, which are not listed in order of priority. However, the committee acknowledges that there are more objectives here than can be included in a single New Frontiers mission and leaves it to potential competitors to pick and choose their science goals and defend their choices. These science questions that could be addressed for an Io Observer mission can include:

- Determine the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of Io's tidal heating.
- Determine Io's interior structure, e.g., does it have a magma ocean?
- Determine whether Io has a magnetic field.
- Understand the eruption mechanisms for Io's lavas and plumes and their implications for volcanic processes on Earth, especially early in Earth's history when its heat flow was similar to Io's, and elsewhere in the solar system.
- Investigate the processes that form Io's mountains and the implications for tectonics under high-heat-flow conditions that may have existed early in the history of other planets.
- Understand Io's surface chemistry, volatile and silicate, and derive magma compositions (and ranges thereof), crustal and mantle compositions and implications for the extent of differentiation, and contributions to the atmosphere, magnetosphere and torus.
- Understand the composition, structure, and thermal structure of Io's atmosphere and ionosphere, the dominant mechanisms of mass loss, and the connection to Io's volcanism.

These questions are probably best addressed within a New Frontiers budget by a Jupiter-orbiting spacecraft with multiple Io flybys. It is possible that such a mission may exceed the New Frontiers cost

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[57] *Jupiter System Observer*, *Mission Study: Final Report*, November 1, 2007, available at http://www.lpi.usra.edu/opag/JSO_Public_Report.pdf.

cap—the committee notes the results of the 2007 billion-dollar box study of missions to Titan and Enceladus which found that a Saturn orbiter with Enceladus flybys, analogous to a Jupiter orbiter with Io flybys, would probably cost well in excess of a billion dollars. Nevertheless, innovative approaches might be able to circumvent these problems and enable a capable New Frontiers Io mission.

GANYMEDE OBSERVER

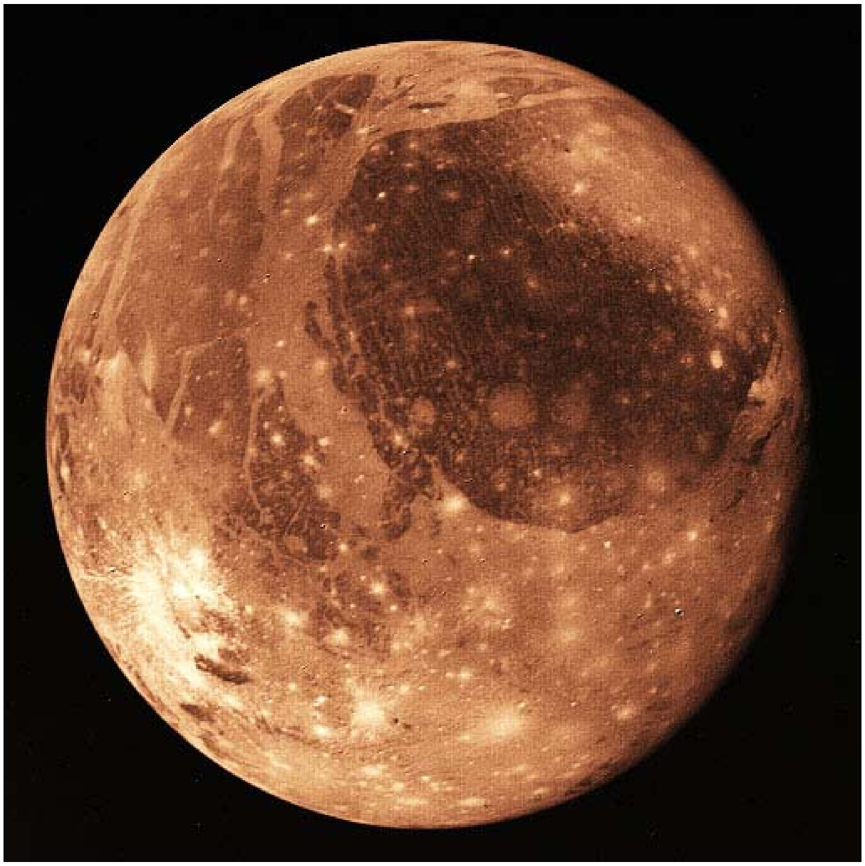

FIGURE 2.12 Ganymede, Jupiter's largest moon, which has a mean radius of 2,631.2 kilometers. Like Europa, which was the highest-rated outer planets priority in the decadal survey, Ganymede is also believed to have a large subsurface ocean. SOURCE: Courtesy of NASA.

The large icy satellites hold the key to answering many outstanding fundamental questions about the solar system, and Jupiter's largest moon Ganymede is of particular interest because of its unique internal magnetic field and its interaction with that of Jupiter.

Ganymede is the only icy body in the solar system known to generate its own magnetic field, thus providing a unique window into Ganymede's interior and, moreover, shedding light on the generation of internal magnetic fields elsewhere in the solar system. Ganymede also provides a laboratory for the study of plasma effects on satellite surfaces: the decadal survey notes "Ganymede's magnetic field is strong enough that it creates a mini-magnetosphere of its own in Jupiter's magnetosphere, partially shielding the satellite from plasma bombardment. The interaction between Ganymede's magnetosphere and Jupiter's magnetosphere is similar to the interaction between Earth's magnetosphere and the solar wind, in which magnetic reconnection plays a key role."[58]

Ganymede also exhibits evidence for a subsurface ocean. In contrast to the case of Europa, an ocean in Ganymede may be bounded both above and below by ice rather than rock; nonetheless, it is likely to illuminate processes that may produce habitable environments elsewhere in the solar system (or maybe on Ganymede itself).

Ganymede's surface illustrates a complex geological history (see Figure 2.12) with similarities to those of Miranda and Enceladus. Moreover, some of the geological terrains may be analogous to terrestrial features, thereby providing a bridge between silicate and icy bodies that could well provide fundamental information regarding the behavior of ice in geologic processes.

Ganymede's geologic activity and magnetic field are probably powered by tidal heating. The decadal survey states "Ganymede's differentiated interior and actively convecting core (required to generate its magnetic field) may be a consequence of its passage into resonance, while Callisto has not experienced this history." Thus, better understanding of Ganymede could provide information regarding the tidal history of the entire Jovian system.

Background

The decadal survey identified top-level, cross-cutting science themes contained within Table ES.1.[59] While the survey did not specifically address how these cross-cutting themes and key questions would be addressed by a Ganymede Observer mission, it is possible to map such a mission against many of these themes (numbering is taken from the decadal survey):

***New Frontiers in the Solar System* Table ES.1: Crosscutting Themes, Key Scientific Questions, Missions and Facilities**

The First Billion Years of Solar System History

1. What processes marked the initial stages of planet and satellite formation?
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?
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?

Volatiles and Organics: The Stuff of Life

4. What is the history of volatile compounds, especially water, across the solar system?
5. What global mechanisms affect the evolution of volatiles on planetary bodies?

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?

Processes: How Planetary Systems Work

1. How do the processes that shape the contemporary character of planetary bodies operate and interact?

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[58] *New Frontiers in the Solar System*, p. 129.
[59] *New Frontiers in the Solar System*, p. 3.

The following excerpts from the decadal survey indicate questions that would be addressed by a Ganymede Observer, as delineated in Table 5.2 of the decadal survey:[60]

Questions a Ganymede Orbiter could offer a breakthrough-level advance

A. Origin and Evolution of Satellite Systems

1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?
   —Characterization of magnetic fields in satellites
5. What does the magnetic field of Ganymede tell us about its thermal evolution, and is Ganymede unique?
   —Internal magnetic fields

B. Origin and Evolution of Water-Rich Environments in Icy Satellites

3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?
   —Intrinsic magnetic field (past/present)

D. Understanding Dynamic Planetary Processes

1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?
   —Secular variations of magnetic field
3. What are the complex processes and interactions on the surfaces and in volcanic or geyserlike plumes, atmospheres, exospheres, and magnetospheres?
   —Atmospheric loss (fields and particles)

Questions a Ganymede Orbiter could offer a major advance

A. Origin and Evolution of Satellite Systems

2. What affects differentiation, outgassing, and the formation of a thick atmosphere? (Why is Titan unique?)
   —Production/loss rates
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?
   —Geologic processes/ history (including impacts)
   —Tectonics/volcanism
   —Map surface composition
   —Subsurface sounding

B. Origin and Evolution of Water-Rich Environments in Icy Satellites

1. What is the chemical composition of the water-rich phase?
   —Remote and in situ composition observations
2. What is the distribution of internal water, in space and in time?
   —Geology/stratigraphy
   —Subsurface sounding
   —Internal structure
3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?
   —Composition
   —Internal Structure

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[60] *New Frontiers in the Solar System*, pp. 140-143.

4. Can and does life exist in the internal ocean of an icy satellite?
   —Characterization of surface radiation environment
   —Characterization of chemistry of surface and ocean
   —Life in extreme environments (Earth analogues)
   —Transport processes

C. Exploring Organic-Rich Environments

1. What is the nature of organics on large satellites?
   —Composition (elemental, isotopic, and molecular), remote and in situ

D. Understanding Dynamic Planetary Processes

1. What are the active interior processes and their relations to tidal heating, heat flow, and global patterns of volcanism and tectonism?
   —Interior structure
   —Heat flow and tidal heating
   —Global volcanism and tectonism

Questions a Ganymede Orbiter can offer a significant advance

A. Origin and Evolution of Satellite Systems

1. How do conditions in the protoplanetary nebula influence the compositions, orbits, and sizes of the resulting satellites?
   —Interior structure and composition of (major) satellites
   —Secular variation of orbital parameters
2. What affects differentiation, outgassing, and the formation of a thick atmosphere? (Why is Titan unique?)
   —Atmospheric composition
   —Interior structure and composition
   —Characterization of internal heat sources
3. To what extent are the surfaces of icy satellites coupled to their interiors (chemically and physically)?
   —Transport processes
4. How has the impactor population in the outer solar system evolved through time, and how is it different from the inner solar system?
   —Observation of craters (on many different bodies)
   —Geology/modification
5. What does the magnetic field of Ganymede tell us about its thermal evolution, and is Ganymede unique?
   —Plasma/ionospheric observation of external field
   —Transport processes

B. Origin and Evolution of Water-Rich Environments in Icy Satellites

2. What is the distribution of internal water, in space and in time?
   —Elemental and isotopic composition
3. What combination of size, energy sources, composition, and history produce long-lived internal oceans?
   —Geology
4. Can and does life exist in the internal ocean of an icy satellite?
   —Search for evidence of biology and organic compounds at surface and in the deeper interior

C. Exploring Organic-Rich Environments

1. What is the nature of organics on large satellites?
   —Production/loss (radiation, degassing, escape, lightning, and exogenic/endogenic)
   —Physical state
   —Optical properties

—Reaction rates/kinetic information

2. What are the processes currently affecting organic-rich surfaces?
   —Impact processes
   —Tectonic processes
   —Chemical (and radiation) processes

D. Understanding Dynamic Planetary Processes

2. What are the currently active endogenic geologic processes (volcanism, tectonism, diapirism) and what can we learn about such processes in general from these active worlds?
   —Observations of dynamic processes with high spatial and temporal resolution
   —Composition of recent surface deposits, plumes or geysers, and atmospheres
   —Search and discovery of new types of activity
3. What are the complex processes and interactions on the surfaces and in volcanic or geyserlike plumes, atmospheres, exospheres, and magnetospheres?
   —Dynamic of plumes, geysers, atmospheres, exospheres, and magnetospheres
   —History of volatiles

Developments Since the Decadal Survey

There was no Ganymede white paper submitted for the decadal survey; however, the science definition team for the Jupiter Icy Moons Orbiter mission (which was canceled in 2005), which included a long stay in Ganymede orbit, discussed Ganymede science goals in some detail.

More recently, an extensive review of the science that could be accomplished at Ganymede by a flagship-class Ganymede orbiter has been published in the 2007 NASA flagship mission study: Jupiter System Observer Science Definition Team 2007 report.[61] That report established several goals relevant to a Ganymede Observer mission:

Goal, Magnetospheres: Understand the magnetospheric environments of Jupiter, its moons and their interactions

- Objective A. Moon Interior Structure. Establish internal structure of icy moons including presence and properties of putative conducting layers, measurement of higher harmonics and secular variations of Ganymede's magnetic field and set limits on intrinsic magnetic fields for Europa and Callisto
- Objective B. Ganymede's Intrinsic Magnetosphere. Investigate the magnetic field, particle populations, and dynamics of Ganymede's magnetosphere.
- Objective C. Moon-Magnetosphere Interactions. Determine the effect of the Jovian magnetosphere on the icy moons. Understand effects of the moons on the magnetosphere and Jupiter's auroral ionosphere.

Goal, Satellites: Understand the mechanisms responsible for formation of surface features and implications for geological history, evolution, and levels of current activity

- Understand geologic history, potential for current activity, and the implications for Jupiter's satellite system
- Understand the processes responsible for the observed geologic features
- Understand heat balance and tidal dissipation

Goal, Satellites: Determine the surface compositions and implications for the origin, evolution and transport of surface materials

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[61] *Jupiter System Observer*, *Mission Study: Final Report*, November 1, 2007, available at http://www.lpi.usra.edu/opag/JSO_Public_Report.pdf.

- Understand composition, physical characteristics, distribution, and evolution of surface materials

Goal, Satellites: Determine the compositions, origins, and evolution of the atmosphere, including transport of material throughout the Jovian system

- Understand the sources (sublimation, surface sputtering) and sinks (freezing out, plasma pickup/sputtering, thermal escape) of atmospheric components
- Understand the temporal, spatial, and compositional variability of the atmosphere

Goal, Interiors: Determine the interior structures and processes operating in the Galilean Satellites in relation to the formation and history of the Jupiter system and potential habitability of the moons.

- The study also established several goals at the investigation level for the interiors section:

—Characterize the formation and chemical evolution of the Jupiter system
    Place bounds on the orbital evolution of the satellites
    Determine the sizes and states of the cores of the moons.
—Determine the presence and location of water within these moons.
    Determine the extent of differentiation of the three icy satellites
    Establish the presence of oceans
—Characterize the extent and location of water (including brines) in 3D within Europa, Ganymede and Callisto
—Determine the thickness of the ice layer for all Icy Satellites
—Characterize the operation of magnetic dynamo processes in the Jovian system and their interaction with the surrounding magnetic field
—Globally characterize Ganymede's intrinsic magnetic field and search for temporal variability in the field
—Characterize the interaction of Ganymede's magnetosphere with Jupiter's magnetosphere
—Identify the dynamical processes that cause internal evolution and near-surface tectonics of all four moons
—Determine the extent of differentiation of all four satellites
—Characterize the near-surface tectonic and volcanic processes and their relation to interior processes

The committee notes that there have also been technological developments since the decadal survey that may make such a mission more feasible now than it was only five years ago. In particular, radiation-hardened electronics have been developed which would be vital to a Ganymede mission and the radiation environment in the Jovian system is much better understood, now that there's been sufficient time to fully analyze Galileo data. The Juno mission also demonstrates the feasibility of using a solar powered satellite at Jupiter's distance from the Sun and NASA's development of a Stirling engine could also help enable this mission.

Conclusions

The Galileo mission to Jupiter provided relatively limited information on Ganymede for several reasons: it had very limited ability to provide high-resolution spatial coverage of Ganymede due to the low data rate; its instrumentation was limited; it was limited to several Ganymede flybys, not nearly enough to characterize Ganymede's internal structure and magnetic field. Numerous fundamental questions about Ganymede remain, questions that bear upon essential scientific objectives identified in the decadal survey. Thus, a mission to explore Ganymede in depth has great potential for substantial science return. Furthermore, Galileo's results regarding radiation levels and the Jupiter System Orbiter study demonstrate the longevity possible at Ganymede's distance from Jupiter; therefore a platform located at Ganymede could also provide potential for long-term monitoring of other high-priority targets in the Jovian system. Finally, the committee notes that the selection of the New Frontiers Juno mission illustrates the feasibility of solar power at Jupiter.

A Ganymede orbiter was identified as a potential medium-class mission in the decadal survey which stated: "No detailed studies are yet available, and the assumption that this mission could achieve the stated goals within this cost category rests partially on assuming that the lesser radiation environment and heritage from the Europa Geophysical Explorer mission would allow significantly reduced costs."[62] The development of the Juno mission and the more recent NASA Science Definition Team investigation of the flagship-class Jupiter System Observer produced a mission that ultimately would achieve orbit around Ganymede, characterizing its surface in detail as well as its gravity and magnetic fields, thereby accomplishing a multitude of science objectives. However, the committee is concerned whether a spacecraft orbiting Ganymede would be feasible under New Frontiers budgetary constraints given the results of NASA's "Billion-Dollar-Box" study in 2007.[63]

Nonetheless, such a rich array of fundamental science questions can be addressed at Ganymede that a New Frontiers-class mission that focuses on answering a subset of these questions would be a very worthwhile consideration. The committee concluded that a spacecraft going into Ganymede orbit may not be required. If a significant number of such questions can be achieved without the spacecraft going into Ganymede orbit, significant cost savings may ensue, which would more easily accommodate the New Frontiers cost caps. In addition, such a mission would enable broader goals within the Jovian system.

Mission-Specific Recommendations

A Ganymede Observer mission that addresses fundamental goals for solar system exploration may be possible, and would also enable broader goals within the Jovian system. Consequently, such a mission should be included in the suite of possible missions included in the next New Frontiers announcement of opportunity. Because the Ganymede Observer was not described in significant detail in the decadal survey, the committee chose to list science questions that such a mission could address, but stresses that this list should not be exclusive, and other science questions may also be considered for Ganymede. In no case should these science questions be considered to be mission requirements, merely options for such a mission. The committee recognizes that the list it has produced includes far more science than can be included in a single New Frontiers mission and stresses that it fully expects those proposing such a mission to pick and choose among these science objectives. It will be up to the proposers to make the case as to why some science objectives are more important than others. These questions, which are not prioritized, include:

- Understand Ganymede's intrinsic and induced magnetic fields and how they're generated, and characterize their interaction with Jupiter's magnetic field.
- Determine Ganymede's internal structure, especially the depths to and sizes or thicknesses of the probable metallic core and deep liquid water ocean, and the implications for current and past tidal heating and the evolution of the Galilean satellite system as well as ocean chemistry.
- Understand Ganymede's endogenic geologic processes, e.g., the extent and role(s) of cryovolcanism, the driving mechanism for the formation of the younger, grooved terrain, and the extent to which Ganymede's tectonic processes are analogs for tectonics on other planetary bodies (both icy and silicate).

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[62] *New Frontiers in the Solar System*, p. 133.

[63] See K. Reh, J. Elliott, T. Spilker, E. Jorgensen, J. Spencer, and R. Lorenz, *Titan and Enceladus $1B Mission Feasibility Study Report*, JPL D-37401 B, Jet Propulsion Laboratory, Pasadena, Calif., January 30, 2007.

- Document the non-ice materials on Ganymede's surface and characterize in detail the connection between Ganymede's magnetosphere and its surface composition (e.g., polar caps).
- Document the composition and structure of the atmosphere, identifying the sources and sinks of the atmospheric components and the extent of variability (spatial and/or temporal).

Under a New Frontiers budget it is likely that the most feasible way to address these questions is by a Jupiter-orbiting spacecraft with multiple Ganymede flybys—in other words, the spacecraft may not have to enter Ganymede orbit. It is possible that such a mission may exceed the New Frontiers cost cap—the committee notes the results of the 2007 billion-dollar box study of missions to Titan and Enceladus which found that a Saturn orbiter with Enceladus flybys, analogous to a Jupiter orbiter with satellite flybys, would probably cost well in excess of a billion dollars. Nevertheless, innovative approaches might be able to circumvent these problems and enable fundamental Ganymede science under New Frontiers constraints.

INNOVATIVE MISSION OPTIONS

During the course of this study, the committee was impressed with the abilities of those competing in both the Discovery and New Frontiers programs to develop innovative ideas about how to accomplish their missions. Missions that were considered nearly impossible less than two decades ago—like a solar-powered spacecraft at Jupiter, or a Mercury orbiter—can now be done due to the clever solutions developed by principal investigators. The committee believes that this is a strength of the competitive process, and sought to utilize this strength to increase the probability that NASA will receive New Frontiers proposals that are realistic and doable considering the constraints of the program.

The committee was also impressed with arguments it heard about the importance of innovation not only in individual missions, but in the overall New Frontiers Program, and the risks of being overly specific on how to accomplish the goals of the decadal survey. Thus, in addition to the eight identified missions, the committee concluded that NASA should offer an additional option for other missions in the same size class that may offer compelling answers to high-priority science questions from the decadal survey.

The committee heard of several proposals for missions in the New Frontiers class that were not explicitly drawn from the decadal survey. Although the committee did not recommend any of these specifically for the next New Frontiers announcement of opportunity, it was unwilling to explicitly rule them out. In order for the New Frontiers Program to remain healthy over the long run, it must maintain an influx of new ideas, and growing the applicant pool for new missions.

Finally, as the previous sections on the eight missions demonstrate, scientific understanding of the solar system has continued to advance since the decadal survey. Thus, there may be new science to be explored that was not included in the survey and may be viable as the basis for a New Frontiers mission. Thus, the committee concluded that NASA's next New Frontiers announcement of opportunity should not be strictly limited to the eight mission options discussed in detail above, but should also be open to proposals of extraordinary justification and inventiveness. This was the foundation for the committee's third recommendation mentioned earlier:

Recommendation 3: NASA should consider mission options that are outside the 3 remaining and 5 additional medium-size missions from the decadal survey but are spurred by major scientific and technological developments made since the decadal survey. As with any New Frontiers mission, these proposals must offer the potential to dramatically advance fundamental scientific goals of the decadal survey, and should accomplish scientific investigations well beyond the scope of the smaller Discovery program. Both mission-enabling technological advances or novel applications of current technology could be considered. However, NASA should give priority to the eight specific candidate missions unless a highly compelling argument can be made for an outside proposal.

3
Mission-Specific Recommendations Summary

Chapter 1 established three recommendations that the committee considered to be relevant to the entire New Frontiers Program, whereas Chapter 2 addressed each of the eight specific mission options, as well as the innovative mission category that the committee believes should form the core of the next New Frontiers announcement of opportunity. The committee expects that NASA and the scientific community will use this report in slightly different ways. NASA will be more interested in the science goals for each mission, which it will use to formulate the science goals of the missions included in the next announcement of opportunity. Members of the science community who expect to propose missions will be primarily interested in specific mission options rather than the goals of all the options, and will therefore focus on the mission sections individually. Nevertheless, the committee determined that it would be useful to separate out the mission-specific recommendations for each mission option and to reprint them below for easy reference. The committee has not prioritized its list of eight missions.

SOUTH POLE-AITKEN BASIN SAMPLE RETURN

The committee has identified no changes to recommend for the scientific objectives or engineering implementation of this mission from the decadal survey. However, the committee recommends that NASA not overly prescribe specific approaches to address the scientific objectives. Instead, NASA should allow proposers to develop their own innovative approaches.

The committee believes that the following science goals, not in priority order, should be established for this mission:

- Elucidate the nature of the Moon's lower crust and/or mantle by direct measurements of its composition and of sample ages;
- Determine the chronology of basin-forming impacts and constrain the period of late, heavy bombardment in the inner solar system, and thus, address fundamental questions of inner solar system impact processes and chronology;
- Characterize a large lunar impact basin through "ground truth" validation of global, regional, and local remotely sensed data of the sampled site;
- Elucidate the sources of thorium and other heat-producing elements in order to understand lunar differentiation and thermal evolution; and
- Determine ages and compositions of far-side basalts to determine how mantle source regions on the far side of the Moon differ from regions sampled by Apollo and Luna basalts

VENUS IN SITU EXPLORER

The committee concluded that several of the VEXAG goals should be included with the goals established in the decadal survey, particularly the VEXAG goals concerning understanding the thermal balance of the atmosphere and gathering global mineralogic data.

The New Frontiers announcement of opportunity should not preclude a mission that addresses the major goals for chemical sampling of the mid- to lower atmosphere on Venus and for characterizing atmospheric dynamics, but that lacks a surface sampling component.

The science goals for this mission, which are not in priority order, should be:

- Understand the physics and chemistry of Venus' atmosphere through measurement of its composition, especially the abundances of sulfur, trace gases, light stable isotopes, and noble gas isotopes;
- Constrain the coupling of thermochemical, photochemical and dynamical processes in Venus' atmosphere and between the surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles;
- Understand the physics and chemistry of Venus' crust, for example through analysis of near-IR descent images from below the clouds to the surface and through measurements of elemental abundances and mineralogy from a surface sample;
- Understand the properties of Venus' atmosphere down to the surface through meteorological measurements and improve our understanding of Venus' zonal cloud-level winds through temporal measurements over several Earth days;
- Understand the weathering environment of the crust of Venus in the context of the dynamics of the atmosphere of Venus and the composition and texture of its surface materials; and
- Map the mineralogy and chemical composition of Venus' surface on the planetary scale for evidence of past hydrological cycles, oceans, and life and constraints on the evolution of Venus' atmosphere.

COMET SURFACE SAMPLE RETURN

For this mission candidate the committee recommends that the science goals should be as they were originally stated in the decadal survey, seeking to answer the following scientific questions:

These science goals are not in priority order, and not all of them must be answered. Such a mission should seek to answer the following scientific questions:[1]

- What is the elemental, isotopic, organic, and mineralogical composition of cometary materials?
- How is cometary activity driven?
- How do small bodies accrete?
- What are the scales of physical and compositional heterogeneity?
- How are the particles on a cometary nucleus bound together?
- What are the macroscopic mineralogical and crystalline structure and isotopic ratios in cometary solids?

The committee further recommends that the New Frontiers announcement of opportunity should leave the choice of target comet to the proposer and that the choice of target should be a major evaluation factor.

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[1] This text is taken from several sections in the decadal survey. *New Frontiers in the Solar System*, pp. 25, 180, 182-183, and 195.

NETWORK SCIENCE

The committee recommends a network science mission be included in the forthcoming NASA New Frontiers announcement of opportunity. The decadal survey identifies a network mission's primary objective as geophysics. For Mars, atmospheric measurements near the surface are a valuable supplement to the geophysics measurements, but cannot be a substitute for them.

In light of the decadal survey's recognition of the importance of network science on all the terrestrial planets and the Moon, the committee recommends that network missions to the Moon, Venus and Mercury also be considered as candidate missions for the New Frontiers announcement of opportunity in addition to a Mars mission.

The scientific objectives of such a mission should be drawn from a subset of the objectives (not in priority order) described in the decadal survey:[2]

For the Interior

- Determine the internal structure including horizontal and vertical variations in the properties of the crust and mantle, and evaluate implications for how the core, mantle and crust evolved.
- Determine the characteristics of the metallic core (e.g., size, density, and presence and distribution of liquid) and explain the strength or absence of a present day magnetic field.
- Determine the heat flow and the distribution of heat-producing elements in the crust and mantle.
- Determine interior composition and compositional variations to elucidate differentiation, crust-mantle evolution (plate tectonics, basin formation by impacts, conditions for life), and how the bulk composition relates to that of the Earth and other terrestrial planets and how planetary compositions are related to nebular condensation and accretion processes.

For the Surface/Atmosphere

- Measure the surface winds and their time variability and the near surface global circulation.
- Measure the temperature, pressure, humidity, and radiative flux.
- Measure the atmospheric, elemental and isotopic compositions.
- Understand the relationship between the near-surface general circulation and the physical processes that force it.
- Determine how the near-surface general circulation controls the exchange of dust, water, CO_2, etc., between the atmosphere and surface.
- Begin to establish a weather monitoring infrastructure to support future robotic and manned missions.
- Provide an enhanced assessment of year-to-year atmospheric mass exchange between the atmosphere and polar caps and regolith.
- Determine the mineralogic composition of the surface and its thermophysical properties.

TROJAN/CENTAUR RECONNAISSANCE

The mission originally described in the decadal survey should be modified so that NASA informs potential proposers of the kind of science questions that should be answered and does not prescribe how

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[2] This list is culled from several places in the decadal survey. See *New Frontiers in the Solar System*, pp. 7, 42, and 62.

the mission should actually be accomplished. The mission requirements should also permit orbital encounters, and state that main belt asteroid flyby is not considered critical to this mission.

Such a mission should have the following science objectives (not in priority order):

- Determine the physical properties (e.g., mass, size, density) of a Trojan and a Centaur.
- Map the color, albedo, and surface geology of a Trojan and a Centaur at a resolution sufficient to distinguish important features for deciphering the history of the object (e.g., craters, fractures, lithologic units).

Each of these objectives can be addressed by appropriate imagers and/or spectrometers/spectrographs that resolve the target. For example, spacecraft tracking could obtain a mass, so that a density can be determined. If the target Centaur has suspected cometary or quasi-cometary activity, then in situ instrumentation capable of addressing such activity and its constituents should be considered.

ASTEROID ROVER/SAMPLE RETURN

The committee recommends that although the Asteroid Rover/Sample Return mission should be included as a possible mission for the New Frontiers Program, the mission objectives should be changed to reflect new scientific information acquired since the decadal survey. Specifically, the unique scientific value of organic-rich targets may elevate them for consideration when compared to the type of asteroid visited by the Near Earth Asteroid Rendezvous mission emphasized by the decadal survey.

Such a mission should have the following science objectives, which are not prioritized:

- Map the surface texture, spectral properties (e.g., color, albedo) and geochemistry of the surface of an asteroid at sufficient spatial resolution to resolve geological features (e.g., craters, fractures, lithologic units) necessary to decipher the geologic history of the asteroid and provide context for returned samples.
- Document the regolith at the sampling site in situ with emphasis on, e.g., lateral and vertical textural, mineralogical and geochemical heterogeneity at scales down to the sub-millimeter.
- Return a sample to Earth in amount sufficient for molecular (or organic) and mineralogical analyses, including documentation of possible sources of contamination throughout the collection, return and curation phases of the mission.

The committee considers sample return an essential component of this mission, and the inclusion of global mineralogical, geochemical and textural and in situ imaging/analyses of the regolith differentiate this mission from Discovery-class missions. However, the committee acknowledges that it may not be possible to include both global mapping and in situ regolith characterization within the New Frontiers cost cap.

IO OBSERVER

An Io Observer mission that addresses fundamental goals for solar system exploration may be possible. Consequently, an Io Observer mission should be included in the suite of possible missions included in the next New Frontiers announcement of opportunity.

These science questions that could be addressed for an Io Observer mission can include (not in priority order):

- Determine the magnitude, spatial distribution, temporal variability, and dissipation mechanisms of Io’s tidal heating.
- Determine Io’s interior structure, e.g., does it have a magma ocean?
- Determine whether Io has a magnetic field.
- Understand the eruption mechanisms for Io’s lavas and plumes and their implications for volcanic processes on Earth, especially early in Earth’s history when its heat flow was similar to Io’s, and elsewhere in the solar system.
- Investigate the processes that form Io’s mountains and the implications for tectonics under high-heat-flow conditions that may have existed early in the history of other planets.
- Understand Io’s surface chemistry, volatile and silicate, and derive magma compositions (and ranges thereof), crustal and mantle compositions and implications for the extent of differentiation, and contributions to the atmosphere, magnetosphere and torus.
- Understand the composition, structure, and thermal structure of Io’s atmosphere and ionosphere, the dominant mechanisms of mass loss, and the connection to Io’s volcanism.

GANYMEDE OBSERVER

Because the Ganymede Observer was not described in significant detail in the decadal survey, the committee chose to list science questions that such a mission could address, but stresses that this list should not be exclusive, and other science questions may also be considered for Ganymede. In no case should these science questions be considered to be mission requirements, merely options for such a mission. These questions, which are not prioritized, include:

- Understand Ganymede’s intrinsic and induced magnetic fields and how they’re generated, and characterize their interaction with Jupiter’s magnetic field.
- Determine Ganymede’s internal structure, especially the depths to and sizes or thicknesses of the probable metallic core and deep liquid water ocean, and the implications for current and past tidal heating and the evolution of the Galilean satellite system as well as ocean chemistry.
- Understand Ganymede’s endogenic geologic processes, e.g., the extent and role(s) of cryovolcanism, the driving mechanism for the formation of the younger, grooved terrain, and the extent to which Ganymede’s tectonic processes are analogs for tectonics on other planetary bodies (both icy and silicate).
- Document the non-ice materials on Ganymede’s surface and characterize in detail the connection between Ganymede’s magnetosphere and its surface composition (e.g., polar caps).
- Document the composition and structure of the atmosphere, identifying the sources and sinks of the atmospheric components and the extent of variability (spatial and/or temporal).

INNOVATIVE MISSION OPTIONS

See recommendation three for guidance on this option. However, the committee stresses that the recommendation states that any such mission option should “offer the potential to dramatically advance fundamental scientific goals of the decadal survey, and should accomplish scientific investigations well beyond the scope of the smaller Discovery program.”

As the committee stated at the beginning of this report, the New Frontiers Program is valuable and a vital part of NASA’s solar system exploration program. It combines the strengths of both flagship and Discovery class missions—the strategic direction of the flagship missions which take their direction from the decadal survey with the competition and innovation of the Discovery missions. The committee’s ultimate goal was to provide NASA with sufficient options, and to provide potential proposers with sufficient flexibility in their proposals to enable NASA to select a mission that can be done within the constraints of the New Frontiers Program, particularly the cost cap.

The committee believes that as long as NASA provides the scientific community with the flexibility it requires, the next round of New Frontiers competition can produce the world class science that has so far typified this program.

A
Speakers Before the Committee

AUGUST 6-8, 2007, WASHINGTON, D.C.

Michael A'Hearn, University of Maryland
Comet Science and the New Frontiers Program

Fran Bagenal, Laboratory of Atmospheric and Space Physics, University of Colorado
OPAG Perspectives on the New Frontiers Program

Richard P. Binzel, Massachusetts Institute of Technology
New Horizon Competition Experience

Scott Bolton, Southwest Research Institute
Juno and the First Announcement of Opportunity

Glen Fountain, Applied Physics Laboratory
Programmatic and Managerial Lessons

Jim Green, NASA
NASA Perspectives on the New Frontiers Program

Janet Luhman, University of California, Berkley and Jim Cutts, Jet Propulsion Laboratory*
VEXAG Perspectives on the New Frontiers Program

John Mustard, Brown University
MEPAG Perspectives on the New Frontiers Program

Paul Spudis, Applied Physics Laboratory
Lunar Science in the New Frontiers Program

Greg Vane, Jet Propulsion Laboratory
JPL Perspective on New Frontiers Based on First Pluto Announcement of Opportunity and First New Frontiers Announcement of Opportunity Experience

Joseph F. Veverka, Cornell University
COMPLEX Perspective on the New Frontiers Program

Rich Vondrak, NASA Goddard Space Flight Center
Center Perspectives on the New Frontiers Program

OCTOBER 1-3, 2007, IRVINE, CALIFORNIA

Ray Arvidson, Washington University, St. Louis*
Adding Mars to the New Frontiers Program

Bruce Banerdt, Jet Propulsion Laboratory
Planetary Networks and New Frontiers

John Elliott, Jet Propulsion Laboratory
Flight System Options and Descriptions

Larry Esposito, Laboratory of Atmospheric and Space Physics, University of Colorado
Venus in the New Frontiers Program

Kimberly Lichtenberg, Washington University, St. Louis
Venus Missions and the Planetary Science Summer School

Doug McCuistion, NASA*
NASA Mars Plans for New Frontiers

Curt Niebur, NASA*
Outer Solar System Flagship Study Overview

John Niehoff, SAIC
Cost Issues for the New Frontiers Program

Kim Reh, Jet Propulsion Laboratory*
Billion Dollar Mission Study Overview

Thomas Spilker, Jet Propulsion Laboratory
Science Objectives and Science Definition Team Procedures
Saturn Shallow Probe Missions

NOVEMBER 14-16, 2007, LUNAR AND PLANETARY INSTITUTE, HOUSTON, TEXAS

Sushil Atreya, University of Michigan*
Science of Shallow Probe Missions

Dave Crisp, Jet Propulsion Laboratory
Science Objectives for Venus Missions

Mike Drake, University of Arizona
Asteroid Sample Return

Carle Pieters, Brown University*
Lunar Science and the New Frontiers Program

Bruce Runnegar, University of California at Los Angeles*
Astrobiology Objectives of the New Frontiers Program

Tom Spilker, Jet Propulsion Laboratory, and Heidi Hammel, Space Science Institute
Neptune and the New Frontiers Program

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[*] Addressed the committee via teleconference.

B
Biographical Sketches of Committee Members and Staff

RETA BEEBE, *Co-chair,* is a professor in the Astronomy Department at New Mexico State University, Las Cruces. Dr. Beebe's research activities cover the study of the atmospheres of Jupiter and Saturn and, in particular, studies of cloud motions and evolution in Jupiter's atmosphere. She is the author of several books and articles concerning telescopic observations of the giant planets, including *Jupiter: The Giant Planet.* Dr. Beebe manages the Atmospheres Discipline Node of NASA's Planetary Data System. She was also a member of the Galileo imaging team and lead scientist for the team using the Hubble Space Telescope to provide context images for the Galileo project. She is the former chair of the American Astronomical Society's (AAS's) Division for Planetary Sciences. Dr. Beebe has served as chair of several NRC committees including the committee for the study "Review of the Next Decade Mars Architecture," the Committee on Planetary and Lunar Exploration; and she was a member of the Committee on an Assessment of Balance in NASA's Science Programs and the Space Studies Board. She also served on the solar system decadal survey.

WARREN W. BUCK, *Co-chair,* is an internationally known theoretical physicist. He is chancellor emeritus and professor at the University of Washington, Bothell (UWB). He is also an adjunct professor of physics at the University of Washington, Seattle. Prior to joining UWB, Dr. Buck was a professor of physics and director of the Nuclear/High Energy Physics Research Center of Excellence at Hampton University. He was also a member of a team that established the scientific program at the Department of Energy's Jefferson Laboratory in Newport News, Virginia. He is a fellow of the American Physical Society (APS) and has served on a variety of national and international physics and educational committees, including the Board of Directors of the Thomas Jefferson National Accelerator Facility's Users Group, the American Institute of Physics' Advisory Committee for Statistics and Education Division, and as chair of the APS Committee on Education. He is on the board of the Pacific Science Center.

DOUGLAS P. BLANCHARD retired as NASA Johnson Space Center (JSC) senior executive in January 2007, after serving for a year as executive on loan to the Bay Area Houston Economic Partnership. Dr. Blanchard, who has over 30 years of science and leadership experience at JSC, began his career as a principal investigator in the NASA Planetary Materials and Geochemistry Program in 1973. He has served in numerous positions, including Lunar Sample curator and chief of the Planetary Materials Branch, chief of the Planetary Science Branch, vice-chair of the Mars Science Working Group, JSC study scientist, Mars Rover Sample Return mission, chief of the Earth Science and Solar System Exploration Division, JSC project scientist for the Alpha Magnetic Spectrometer, deputy director of the JSC Public Affairs Office, and assistant director of the Space Life and Life Sciences Directorate. Dr. Blanchard is the recipient of the 1983 NASA Group Achievement Award for Planetary Materials Curation and the 1997 NASA Outstanding Leadership Medal.

ROBERT D. BRAUN is the David and Andrew Lewis Associate Professor of Space Technology in the Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology (Georgia Tech). As director of Georgia Tech's Space Systems Design Laboratory, he leads a research and education program focused on the design of advanced flight systems and technologies for planetary exploration. Prior to joining the Georgia Tech faculty, Dr. Braun was on the technical staff of the NASA Langley Research Center. While at NASA he contributed to the design and flight operations of the Mars Pathfinder and Mars Microprobe flight projects, performing analyses pertaining to Mars entry, descent and landing. Dr. Braun has received the 1999 American Institute of Aeronautics and Astronautics (AIAA) Lawrence Sperry Award, two NASA Exceptional Achievement Medals and seven NASA Group Achievement Awards. Dr. Braun is an AIAA fellow and the author or co-author of more than 150 technical publications in the fields of atmospheric flight dynamics, planetary exploration systems, multidisciplinary design optimization and systems engineering.

BERNARD F. BURKE is the William A.M. Burden Professor of Astrophysics, emeritus, at the Massachusetts Institute of Technology (MIT). He is also a principal investigator at the MIT Kavli Institute for Astrophysics and Space Research. His research career has covered a wide-range of activities including the co-discovery of Jupiter radio bursts and the discovery of the first "Einstein Ring," a manifestation of the warping of space-time by matter that was predicted by Albert Einstein in his general theory of relativity. Dr. Burke was president of the AAS (1986-1988) and served as a member of the National Science Board (1990-1996). He is a member of the National Academy of Sciences, American Academy of Arts and Sciences, a fellow of the American Association for the Advancement of Science (AAAS), and the recipient of the NASA Group Achievement Award for Very-Long-Baseline Interferometry. Dr. Burke has served on numerous NRC committees, including the U.S. National Committee for the International Astronomical Union and the International Space Year Planning Committee. He currently serves on the Committee to Assess Solar System Exploration.

ALAN DELAMERE is a retired senior engineer and program manager at Ball Aerospace and Technology Corporation. He is currently involved as co-investigator on the Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Instrument (HIRISE) and on the Deep Impact mission to Comet Tempel 1. Mr. Delamere has been involved in the Mars program since the 1980s. His expertise focuses on instrument building and mission design. He was a member of the NRC Committee on Preventing the Forward Contamination of Mars.

ROSALY M. LOPES is a principal scientist at the Jet Propulsion Laboratory, where she is also the group supervisor for Geophysics and Planetary Geosciences. Her expertise is on planetary geology and volcanology. Her current research involves analysis of geologic features on Titan using the Cassini Radar Mapper, with specific emphasis on cryovolcanic features. Dr. Lopes joined JPL in 1979 to pursue planetary studies and work on flight projects. At JPL, she joined the Galileo Flight Project as part of the science team for the Near Infrared Mapping Spectrometer (NIMS), one of the major instruments in the spacecraft. She was responsible for planning all of the observations of Jupiter's volcanic moon Io using NIMS, leading the data analysis and the collaborations with other teams. She is currently investigation scientist for the radar instrument on Cassini. Dr. Lopes is a fellow of the AAAS and has been awarded the Carl Sagan Medal from the AAS and the NASA Exceptional Service Medal.

STEPHEN MACKWELL is the director of the Lunar and Planetary Institute. Prior to his 2002 appointment to the Lunar and Planetary Institute, Dr. Mackwell served as the director of the Bayerisches Geoinstitut at the University of Bayreuth, Germany. Under his guidance, the Geoinstitut strengthened its position as one of the preeminent experimental geosciences facilities in the world, and broadened its research programs to more fully address deep-Earth issues. Dr. Mackwell has or is serving as program director for geophysics at the National Science Foundation's (NSF's) Division of Earth Sciences (1993-1994), expert reviewer for the Department of Energy's Geosciences Research Program (1993), member of the Review Panel for NASA's Planetary Geology and Geophysics Program (1994-1998; 2002-2006), and expert consultant for NSF's Division of Earth Sciences (1995). Dr. Mackwell conducts laboratory-based research into the physical, chemical, and mechanical properties of geological materials under conditions relevant to the mantle and crust of Earth and other terrestrial planets.

TIMOTHY J. McCOY is a curator with the Department of Mineral Sciences at the National Museum of Natural History of the Smithsonian Institution. His research is focused on examinations of the mineralogy, chemistry, and texture of meteorites as a tool to understand the origin and evolution of their parent bodies, specifically asteroids and Mars. He has served as a participating scientist on the Near Earth Asteroid Rendezvous mission, the Mars Exploration Rover mission and the MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) mission to Mercury. Dr. McCoy served as chair of the NRC Panel on In Situ Resource Utilization of the Committee for the Review of NASA's Capability Roadmaps, and as a member of the Committee for the Review of the Next Decade Mars Architecture. He is currently serving on the Committee on Planetary and Lunar Exploration.

RALPH 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 PLS and LECP 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 VLF 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). He currently serves on the Committee to Assess Solar System Exploration.

SANDRA PIZZARELLO is research professor and professor emeritus in the Department of Chemistry and Biochemistry at Arizona State University. Dr. Pizzarello's research activity for the last 24 years has focused on the study of organic components of carbonaceous chondrites. Her work has aided progress toward the recognition, identification, and molecular and isotopic characterization of their main extractable organic constituents. She was the lead member of a team of scientists that assessed the organic composition of the Tagish Lake meteorite, a carbonaceous chondrite that fell in Canada in 2000. Dr. Pizzarello is currently principal investigator for three NASA studies, "Meteorite organics: Tracers of molecular asymmetry in cosmochemistry," "Non racemic amino acids in meteorites: A gauge of water processes in early solar system planetesimals," and "Molecular asymmetry in prebiotic chemistry: A study guide from meteorites." She was a member of the NRC Committee on the Astrophysical Context of Life and the Committee on the Origins and Evolution of Life.

GERALD SCHUBERT is a professor in the Department of Earth and Space Sciences and in the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles and Distinguished Professor of Geophysics and Planetary Physics. Dr. Schubert's research interests center on theoretical studies of the internal structures of the giant planets and their major satellites and the dynamics of planetary atmospheres. He has been associated with many spacecraft missions, including serving as an interdisciplinary scientist and co-investigator for the Atmospheric Structure Experiment on Galileo; member of the Magellan Radar Investigation Group; interdisciplinary scientist for Pioneer Venus; co-investigator for Apollo 16's Lunar Surface Magnetometer; and co-investigator for Apollo 15 and 16's subsatellite magnetometers. Dr. Schubert has served as a member of the NASA Planetary Geology and Geophysics Management Operations Working Group; the Lunar and Planetary Geoscience Review Panel and Geophysics Group chief; and the Planetary Atmospheres Review Panel and Dynamics Group chief (1995). He is a former member of the NRC Committee on Planetary and Lunar Exploration and also served on the solar system decadal survey.

DONNA L. SHIRLEY is president of Managing Creativity, a management consulting, speaking and training firm. During a 32 year career at the Jet Propulsion Laboratory (JPL), she managed the NASA Mars Exploration Program and oversaw the Pathfinder and Mars Global Surveyor missions and the Sojourner Rover project. After retiring from JPL she served as assistant dean of engineering for advanced program development and as an instructor in aerospace mechanical engineering at the University of Oklahoma. Ms. Shirley has experience in aerospace engineering, space science, government technical program management, and systems engineering. She served on the NRC Committee on the National Aerospace Initiative and the Task Group on the Availability and Usefulness of NASA's Space Mission Data. She is a former director of the Science Fiction Museum in Seattle.

JOHN SPENCER is a staff scientist at Southwest Research Institute's Department of Space Studies. He specializes in studies of the moons of the outer planets, particularly the four large Galilean satellites of Jupiter, using theoretical models, Earth-based telescopes, close-up spacecraft observations, and the Hubble Space Telescope. He was responsible for temperature mapping of Jupiter's moons with the photopolarimeter-radiometer instrument on the Galileo mission, and is now mapping the temperatures on Saturn's moons as a science team member on the composite infrared spectrometer instrument on Cassini. He is a science team member on the New Horizons mission to Pluto and the Kuiper Belt. He is particularly interested in the active volcanos and atmosphere of Jupiter's moon Io, and more recently in the active ice eruptions of Saturn's moon Enceladus. He has also published research on Mars, asteroids, Pluto, and Neptune's moon Triton.

ELIZABETH P. TURTLE is a planetary scientist at the Johns Hopkins University Applied Physics Laboratory (APL). Prior to joining APL she was an assistant research scientist in the Lunar and Planetary Laboratory at the University of Arizona. Dr. Turtle studies geological processes and impact cratering on icy satellites, Io, and terrestrial planets through the combination of remote sensing observations and numerical modeling. She has worked with the imaging teams of the Galileo and Cassini missions, planning observations of Io and Titan, respectively. She is also a co-investigator on the Lunar Reconnaissance Orbiter Camera.

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 Concrete*, 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).

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 Microgravity Research 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 7 years of experience in event management.

VICTORIA SWISHER joined the Space Studies Board in December 2006 as a research associate. She recently received a B.A. in astronomy from Swarthmore College. She has presented the results of her research at the 2005 and 2006 AAS meetings and at various Keck Northeast Astronomy Consortium (KNAC) undergraduate research conferences. Her most recent research focused on laboratory astrophysics and involved studying the x-rays of plasma, culminating in a senior thesis entitled “Modeling UV and X-ray Spectra from the Swarthmore Spheromak Experiment.”