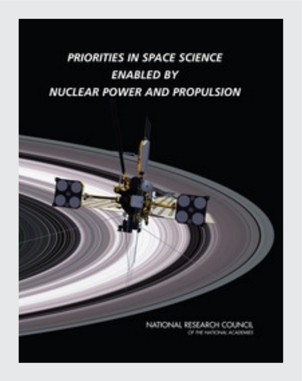

Priorities in Space Science Enabled by Nuclear Power and Propulsion

DETAILS

158 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-10011-3 | DOI 10.17226/11432

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PRIORITIES IN SPACE SCIENCE ENABLED BY NUCLEAR POWER AND PROPULSION

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Space Studies Board
Aeronautics and Space Engineering Board

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NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

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Support for this project was provided by Contracts NASW 96013 and 01001 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsor.

International Standard Book Number 0-309-10011-9

Cover design by Penny E. Margolskee. Images courtesy of the Jet Propulsion Laboratory and the National Aeronautics and Space Administration.

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Printed in the United States of America

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Preface

NASA's budget for fiscal year 2003 included funds to begin the Nuclear Systems Initiative focused on research into and development of enhanced capabilities in the general areas of spacecraft power and propulsion systems. The agency's fiscal year 2004 budget request renamed the activity Project Prometheus and proposed substantial funding for research and development activities for the next 5 years in the following areas:

- Energy generation (including radioisotope systems for the near term and fission reactor systems for the longer term);
- Conversion to electricity (including both static and dynamic system design concepts); and
- Electricity utilization (for nuclear-electric propulsion, scientific instruments, and communications).

According to NASA, Project Prometheus was initiated in response to identified limitations in the current paradigm for solar system exploration. In particular, photovoltaic arrays restrict a spacecraft's power budgets and are of limited use in the outer solar system. Similarly, chemical propulsion systems limit a spacecraft's maneuverability and the number of solar system destinations that can be readily reached. In early 2003, NASA selected the Jupiter Icy Moons Orbiter (JIMO)—a mission to study three of the Galilean satellites of Jupiter—as the first mission to use the new nuclear propulsion capabilities. But in early 2005, JIMO was deferred until beyond 2017 in favor of a less complex, but as yet undefined, nuclear-electric propulsion (NEP) mission designated Prometheus 1.

In late 2003, Edward J. Weiler, then NASA's associate administrator for space science, sought an independent assessment of whether, and if so, what, potentially highly meritorious space science missions beyond JIMO might be enabled if space nuclear power and propulsion systems could be developed and put into operation. In a letter dated October 14, 2003, Dr. Weiler requested that the Space Studies Board (SSB) and the Aeronautics and Space Engineering Board (ASEB) of the National Research Council (NRC) jointly organize a study to assist NASA in the following manner:

- Identify high-priority space science objectives that could be uniquely enabled or greatly enhanced by development of advanced nuclear power and propulsion systems for spacecraft; and
- Make recommendations for an advanced technology development program for long-term future space science mission nuclear power and propulsion capabilities.

In response to this request, the SSB and ASEB devised a plan to conduct a two-phase study sequentially addressing the two tasks identified in NASA's letter. The Phase I report (i.e., this report) identifies space science objectives and possible missions that could be enabled beyond 2015 by development of advanced spacecraft nuclear power and propulsion systems, as well as by nuclear power systems that might be used on planetary surfaces. This report draws on the strategic goals and priorities outlined in the recent NRC decadal survey reports in astronomy and astrophysics, in solar system exploration, and in solar and space physics as its scientific starting point, and considers potential directions in each field which go beyond the time span of the current strategies. The authoring Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion strongly emphasizes that the purpose of its Phase I study is not to reprioritize the science goals and missions endorsed in the decadal surveys or to establish priorities beyond the nominal time frames of the existing survey reports. Rather, this study's purpose is to define a series of unprioritized mission concepts to help identify where the availability of space nuclear power and propulsion systems can have a major impact. These conceptual missions can then be studied by NASA and the wider scientific community and, if found to have sufficient merit and potential, can be prioritized in the context of future decadal-survey activities.

Phase II of the study—originally scheduled to begin at a later date—will use the science mission concepts and associated mission requirements identified in this Phase I report as a set of reference missions enabled by nuclear systems. The Phase II study will consider the engineering requirements for such missions and make recommendations for an evolutionary technology development program for future space science missions utilizing nuclear power and propulsion capabilities.

In a subsequent letter, dated May 4, 2004, Dr. Weiler and Admiral Craig E. Steidel, the associate administrator of NASA's newly established Office of Exploration Systems, modified the scope of the Phase II study to account for developments in the establishment of NASA's new program of robotic and human exploration of the Moon and Mars. In particular, the committee was asked to address the following tasks during Phase II:

- Examine the gaps in technical capabilities needed to realize nuclear power systems for each of three classes—(1) instrumentation and propulsion for JIMO and follow-on science missions; (2) electrical power for spacecraft in transit or for operation on planetary surfaces; and (3) larger systems to energize thermal or electric propulsion systems for piloted spacecraft that would operate beyond the Earth-Moon system.
- Identify the major technology development areas where new work needs to be done to advance capabilities for each class.
- Compare the technical capabilities and development activities needed for each class, to identify common versus unique requirements.

Because of circumstances beyond the committee's control, the Phase II study was postponed indefinitely in mid-2005.

The Phase I study was undertaken by the Steering Group of the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion, supported by three panels focusing on science issues in solar and space physics, solar system exploration, and astronomy and astrophysics. The study was formally initiated when the Steering Group held its first meeting in Washington, D.C., April 7–9, 2004. Work continued at meetings held in Washington, D.C. (August 31–September 2, 2004), and in Irvine, California (November 15–16, 2004). In parallel with these meetings, the three science panels held their own information gathering and deliberative meetings: the Solar System Exploration Panel met in Washington, D.C. (May 5–7, 2004), and in Woods Hole, Massachusetts (June 21–23, 2004); the Solar and Space Physics Panel met in Washington, D.C. (August 9–11, 2004), and in Santa Fe, New Mexico (October 4–6, 2004); and the Astronomy and Astrophysics Panel met in Washington, D.C. (August 16–18, 2004), and in Pasadena, California (September 22–24, 2004). The three science panels completed drafts of their text in December 2004, and this material, suitably edited for consistent presentation, forms the basis of Chapters 3 through 8 of this Phase I report.

A fourth panel, focusing on engineering and technical issues, was supposed to have been appointed. Although intended to be active primarily in Phase II of this study, the fourth panel was to have supplied a limited amount of text relevant to this report. Due to the postponement of the Phase II study, this panel was not appointed and its role in this report was played by those members of the Steering Group with engineering expertise. The text they drafted can be found in Chapter 2.

The Steering Group assembled the first draft of the full report in late January 2005. The final draft of this report was completed in early April and sent to external reviewers for comment in mid-April. The text was extensively revised in May and June and approved for release by the NRC on July 22, 2005. The executive summary along with the front matter of this report was released in an unedited, prepublication format on August 30, 2005. This, the edited text of the full report of the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion, was prepared during the latter part of 2005 and finalized in January 2006. This version supersedes all other versions.

The Steering Group and its three supporting panels made a concerted effort to reach out to and engage the larger scientific and engineering community in this study. To this end, the following organizations were asked to make the study known to their respective constituencies: the International Astronautical Federation; the International Academy of Aeronautics and Astronautics; the American Institute of Aeronautics and Astronautics; the American Astronautical Society; the American Geophysical Union (the Planetary Sciences section and the Space Physics and Aeronomy section); and the American Astronomical Society (the Division for Planetary Sciences and the High-Energy Astrophysics Division). In addition, a Web site was established where material relevant to the study was posted. Although the committee did receive a small number of individual comments and suggestions via its Web site, the overall results of this outreach activity were mixed.

The work of the Steering Group and its panels was made easier thanks to the important help, advice, and comments provided by numerous individuals from a variety of public and private organizations. These include, in no particular order, the following: Marc Allen, Jay Bergstralh, Barry Geldzahler, Curt Niebur, John Rummel, and George Schmidt (NASA, Science Mission Directorate); Douglas Cooke, Leonard Dudzinski, Victoria Friedensen, Alan Newhouse, Raynor Taylor, and Carl Walz (NASA, Exploration Systems Mission Directorate); Keith Grogan, Torrence Johnson, Dayton Jones, and Robert Preston (NASA, Jet Propulsion Laboratory); Jason Dworkin, Sam Floyd, John Keller, and Robert MacDowall (NASA, Goddard Space Flight Center); Marianne Rudisill (NASA, Langley Research Center); Clark Chapman, Dan Durda, and S. Alan Stern (Southwest Research Institute); Francesco Bordi and Matt Hart (The Aerospace Corporation); Michael Brown and Richard Mewaldt (California Institute of Technology); J. Brad Dalton III (SETI Institute); Thomas K. Gaisser (Bartol Research Institute); Will Grundy (Lowell Observatory); Kevin Hurley (University of California, Berkeley); Edwin Kite (Massachusetts Institute of Technology); Jeffrey Linsky (University of Colorado); Michael Mendillo (Boston University); David Mildner (National Institute of Standards and Technology); Marcia Rieke (University of Arizona); Richard Rothschild (University of California, San Diego); Chris Shank (Committee on Science, U.S. House of Representatives); David A. Williams (Arizona State University); and Thomas Zurbuchen (University of Michigan).

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 NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC 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: John F. Ahearne (Sigma Xi, The Scientific Research Society), Robert D. Braun (Georgia Institute of Technology), Jon H. Bryson (The Aerospace Corporation), Freeman Dyson (Institute for Advanced Study), Eugene H. Levy (Rice University), Bruce D. Marcus (TRW Inc., retired), Frank B. McDonald (University of Maryland), and Christopher F. McKee (University of California, Berkeley).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J. Lanzerotti (New Jersey Institute of Technology). 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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APPENDIXES

Executive Summary

In 2002, NASA initiated a program to explore the use of nuclear power and propulsion systems for both human and robotic activities. By 2004, this activity, Project Prometheus, had acquired five tasks:

- Developing a new generation of radioisotope power systems (RPSs);
- Conducting advanced studies of nuclear power and propulsion systems;
- Initiating development of the first Prometheus flight program, the Jupiter Icy Moons Orbiter, and its nuclear-electric propulsion (NEP) system;
- Studying nuclear power systems as a means to supply auxiliary power for spacecraft in transit (i.e., to operate, for example, life-support and other spacecraft systems) and to supply power for surface activities on the Moon or Mars; and
- Exploring the use of much larger nuclear power systems to support thermal or NEP systems for human exploration activities beyond the Earth-Moon system.

ORIGIN AND ORGANIZATION OF THE STUDY

Against this backdrop, NASA asked the National Research Council (NRC) to undertake a two-task study. The first task was to identify high-priority space science objectives that could be uniquely enabled or greatly enhanced by the development of advanced spacecraft nuclear power and propulsion systems. The second was to make recommendations for an advanced technology development program for future space science missions employing nuclear power and propulsion capabilities.

In response to NASA's request, the Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion—consisting of a steering group and three science panels—was established to address the charge. This Phase I report addresses the first task only.

As a starting point for its scientific deliberations, the committee used the goals, priorities, and recommendations from the NRC's decadal surveys for solar system exploration (SSE),[1] solar and space physics (SSP),[2] and astronomy and astrophysics (AAp).[3] Although these reports predate the initiation of Project Prometheus, the community consensus they embody makes them compelling guides to the identification of high-priority science activities in their respective disciplines. Although none of the missions identified in these decadal survey reports as priorities for implementation in the coming decade explicitly require NEP, these reports are not entirely silent on the need for and uses of nuclear power and propulsion systems. In addition to calling for the reopening of RPS production lines, both the SSE and SSP decadal survey reports recommended that NASA assign a high priority to the development of advanced propulsion systems, including NEP.[4,5] The SSE decadal survey explicitly included NEP in its list of recommended technology developments, and it pointed to several missions that "are enabled or enhanced by NEP" and that naturally follow on from missions recommended as priorities for the decade 2003–2013.[6] The 2001 AAp decadal survey makes no recommendations concerning the use of nuclear power and propulsion systems.

It was specifically not the task of the committee to reprioritize the decadal surveys, to set priorities for the period beyond the time horizons of the respective surveys, or to draft a formal review of Project Prometheus. But because the committee was charged to identify *high-priority* objectives, it used selection criteria that are broadly consistent with those used by the three most recent decadal surveys. That is, priorities are determined by consideration of intrinsic scientific merit and a combination of other issues, including technical readiness, programmatic balance, availability of necessary infrastructure, and budgetary impact.[7]

In practice, this approach implied that the committee's primary task was the identification of a series of promising mission concepts to help define where the availability of space nuclear systems could have a major scientific impact. It also implied that a necessary secondary task was the identification of a variety of technological, programmatic, societal, and budgetary caveats that might impact the potential space science applications of nuclear power and propulsion systems. It is the committee's hope that, these caveats aside, the conceptual missions discussed in this Phase I report will be studied by NASA and the wider scientific community and, if found to have sufficient merit and potential, will then be considered for prioritization in future decadal surveys.

CONTRIBUTIONS OF NUCLEAR POWER AND PROPULSION TO THE SPACE SCIENCES

Solar and Space Physics and Solar System Exploration

The material presented in Chapters 4 and 6 clearly demonstrates that the availability of nuclear power and propulsion technologies has the potential to enable a rich variety of solar and space physics and solar system exploration missions. A particularly exciting prospect for the solar system exploration community is the likely availability of a new generation of RPSs that will enable missions ranging from long-lived surface landers to deep atmospheric probes. Similarly, the solar and space physics community is intrigued by the possible uses of nuclear power and propulsion systems to enable complex, multidisciplinary exploration activities in the outer solar system and the local interstellar medium.

Of the various nuclear technologies considered, RPSs directly enhance or are enabling for missions identified as priorities for the coming decade in the SSP and SSE survey reports. RPSs can also enhance and enable missions mentioned in the respective survey reports that are likely to be candidates for consideration as priorities in subsequent decades.

These and additional mission possibilities exist, but because of the lack of detailed studies, it is not possible at this time to say whether or not these missions are *uniquely* enabled or *greatly* enhanced by nuclear power and propulsion systems. Rather, the discussions in Chapters 4 and 6 center on the identification of a number of promising mission concepts that could plausibly be enhanced or enabled by RPS technologies and/or NEP. The mission concepts selected by the committee as particularly promising include the following (in heliocentric order):

- *Solar Coronal Cluster*—an NEP-class mission designed to deploy multiple RPS-powered subsatellites in the inner heliosphere to study the origins of space weather (see Box 4.2);
- *Long-Lived Venus Lander*—an RPS-powered lander designed to conduct seismic and other observations on the surface of Venus for at least 1 month (see Box 6.1);
- *Long-Lived Mars Network*—a network of RPS-powered probes designed to conduct seismic, meteorological, and other observations on the surface of Mars for an extended period (see Box 6.2);
- *Jupiter Magnetosphere Multiprobe Mission*—an NEP-class mission designed to deploy multiple RPS-powered subsatellites to study the global dynamics of the jovian magnetosphere (see Box 4.4);

- *Cryogenic Comet Sample-Return Mission*—an RPS-powered spacecraft designed to perform extensive remote-sensing and in situ observations of a cometary nucleus prior to collecting and returning a sample, maintained at cryogenic temperatures, to Earth (see Box 6.3);
- *Titan Express/Interstellar Pioneer*—an NEP-class mission designed to deploy an RPS-powered aerobot in Titan's atmosphere and then continue on to perform a secondary mission in the outer heliosphere (see Box 6.4);
- *Neptune-Triton System Explorer*—an NEP-class mission designed to perform a comprehensive study of Neptune and Triton by deploying atmospheric probes and landers (see Box 6.5);
- *Solar System Disk Explorer*—an NEP-class mission equipped with RPS-powered subsatellites designed to study the collisional evolution of the solar system by conducting complementary observations of dust and Kuiper Belt objects (see Box 4.3); and
- *Interstellar Observatory*—an NEP-class mission equipped with multiple RPS-powered subsatellites designed to conduct a comprehensive multidisciplinary study of the particles, fields, and dust environments encountered as it traverses the heliosphere and penetrates into interstellar space (see Box 4.1).

All these mission concepts and the others mentioned in Chapters 4 and 6 (and Appendix C) have to be studied in much more detail before their feasibility and priority can be determined. Exploiting the capabilities of nuclear power and propulsion systems will require ancillary technical developments in a variety of areas, including communications, radiation-hardened electronics, radiation-tolerant detectors, contamination mitigation procedures, and multispacecraft systems.

Astronomy and Astrophysics

The prospective contributions of nuclear technologies in astronomy, astrophysics, and fundamental physics are, as shown in Chapter 8, not very promising. Nuclear power and propulsion systems are not enhancing or enabling for any of the current high-priority goals of astronomy and astrophysics as defined in the decadal surveys or subsequent priority studies.[8] Most envisaged missions work as well at 1 AU from the Sun as anywhere and have power requirements of <10 kWe. Thus, their power and propulsion requirements can be met most readily with photovoltaic arrays and chemical (or, if needed, solar-electric) propulsion systems, respectively.

The one major exception where nuclear technologies appear to have some promise is in the area of infrared imaging. For this application, a case can be made between deploying a relatively large telescope in the high-zodiacal-light background at 1 AU versus deploying a smaller telescope in the lower-zodiacal-light background at ⩾3 AU. Nuclear power in the form of RPSs or a small reactor might be attractive for such a mission, but there are serious issues—e.g., the effect of high-energy particles, gamma rays, and waste heat from nuclear reactors on sensitive astronomical detectors—that would have to be addressed.

Other possibilities considered—e.g., the use of nuclear power to support astronomical facilities on the Moon—do not appear to offer clear advantages over other means of obtaining the same scientific observations. The lunar surface as an observatory site, for example, does not offer any enabling advantages over free space and has the disadvantages of gravity and, potentially, dust. Free space offers the same vacuum as the lunar surface does, and although the lunar polar craters are naturally very cold, passive cooling strategies—e.g., deployable sunshades—can achieve similarly low temperatures in free space. In addition, a nuclear-powered observatory on the lunar farside is not a uniquely enabling solution to the problem of terrestrial radio interference, because a free-flying fleet of solar-powered dipole receivers is likely to be easier to implement than is a similar array of dipoles deployed on the Moon's farside.

There do appear to be some more exotic astronomy and astrophysics mission possibilities that might be enhanced or enabled by the use of nuclear technologies—e.g., the Binary-Star Gravitational Telescope and the Solar Gravitational Telescope—but they do not uniquely address high-priority goals of the astronomy and astrophysics community. Similarly, there are a variety of interesting missions—e.g., the Gamma-Ray Burst Locator, the Infrared Background/Zodiacal Light Mapper, and the Microlensing Parallax Mapper—that also do not address major, high-priority questions in astronomy and astrophysics but that might be considered as cost-effective add-ons to missions to the outer solar system and interstellar space. Finally, missions such as the Interstellar Observatory or the Titan Express/Interstellar Pioneer may allow direct measurement of the properties of the local interstellar medium beyond the heliosphere. Although such measurements are of astronomical interest, they are not high-priority goals enunciated in either the latest AAp decadal survey or more recent priority studies.

Of particular concern to the astronomical community is the operation of nuclear reactors in Earth's magnetosphere. This practice is well documented as causing significant interference to balloon-borne and orbiting gamma-ray observatories. The effect that operating space reactors might have on other scientific activities should be carefully studied.

PRIMARY FINDINGS AND RECOMMENDATIONS

If nuclear propulsion is developed and demonstrated, then it can enable radically new missions capable of conducting activities of a scope never before contemplated by the space science community. Thus NASA and its partners in other federal agencies have taken some courageous and undoubtedly important first steps in what will be a long-term program to harness nuclear power and propulsion for the benefit of space exploration. Despite the promise of these technologies, however, it is essential to be clear about their positive and negative aspects. Nuclear propulsion systems will give researchers access to previously inaccessible objects and destinations and enable them to conduct comprehensive studies of a type and with a flexibility not previously contemplated in the history of space exploration. Yet spacecraft nuclear propulsion is in its infancy and will require a great deal of technological development. As described in Chapter 2, NASA's parametric studies of candidate NEP missions reveal a significant gap in performance (in terms of, for example, transit time) between what appears to be currently feasible and what is desirable from a scientific perspective. The committee is concerned that NASA's current nuclear propulsion research and development activities may be too narrowly focused on a single technology—NEP—and believes that NASA's efforts might benefit from a broader consideration of other technological approaches.

Spacecraft using nuclear propulsion systems, regardless of the exact technologies employed, will be very large, very heavy, very complex, and, almost certainly, very expensive. The development and deployment of such technologies may proscribe the diversity of space science missions. But it is difficult to imagine that space science goals for the period beyond 2015 will still be addressed with the power and propulsion technologies of the Mariners, Pioneers, and Voyagers. At the same time, though, it is equally difficult to imagine how it will be possible to transition smoothly from an era of Cassini, Mars Exploration Rovers, New Horizons, Discovery, and Explorers to a time when the mix of activities will be just as diverse but will also include super-flagship-class NEP missions.

> ***Finding:*** **Nuclear power and propulsion technologies appear, in general, to have great promise and may in some sense be essential for addressing important space science goals in future decades. This is particularly true for the fields of solar and space physics and solar system exploration, and especially so with respect to near- to mid-term applications of radioisotope power systems. Nevertheless, the committee has significant reservations about the scientific utility of some of NASA's current nuclear research and development activities, about NASA's current technological approach to the implementation of nuclear propulsion, and about the agency's ability to integrate a new class of large and potentially very expensive nuclear missions into its diverse and healthy mix of current missions.**

This finding is elaborated on below, and specific recommendations are offered.

Radioisotope Power Systems

> ***Finding:*** **Radioisotope power system technologies will enable varied and rich space science activities.**

RPSs have a long history of enabling science investigations. For maximum scientific utility, RPSs must be able to operate in a number of modes and settings (e.g., on orbiters, landers, and rovers) and environments (e.g., in extremes of hot and cold, in the vacuum of deep space, or in planetary atmospheres). RPSs may be useful on a variety of different classes of missions, and their use on small, principal-investigator-led missions, such as Mars Scout and Discovery, warrants serious consideration.

NASA and its partners in other federal agencies (e.g., the U.S. Department of Energy) are to be commended for supporting the future use of RPS technologies. Of particular interest to the space science community in the near term is the ongoing development of two new types of RPS—the so-called multi-mission radioisotope thermoelectric generator (MMRTG) and the Stirling radioisotope generator (SRG). The committee notes that both of these new RPSs are less efficient in terms of their specific mass (i.e., kg/kWe) than the devices they are replacing. Further, the SRG has moving parts that may limit its lifetime as well as cause vibrations and electromagnetic interference.

The committee is concerned that interruptions in the production, supply, or packaging of the plutonium isotope (^{238}Pu) fuel for RPSs could have an impact on future mission plans. A steady and reliable source of ^{238}Pu is required if the scientific potential of missions enhanced and enabled by RPS technologies is to be realized.

> ***Recommendation:*** **NASA should expand the development and application of radioisotope power system (RPS) technologies. Advances in these technologies should be pursued for such purposes as reducing specific mass, minimizing electromagnetic and other forms of contamination, and developing systems that can work in a variety of environments, from the surfaces of diverse planetary bodies to orbiters to the outer solar system. Attention should be given to the development of new types of RPSs that have smaller and, possibly, larger electrical power outputs than those currently in use or under development.**

Nuclear Propulsion Systems

> ***Finding:*** **Nuclear propulsion technologies will likely be used initially for moving relatively large scientific payloads (~1,000s kg) to destinations in the outer solar system and beyond and extremely large payloads (~10,000s kg) in support of human exploration activities in the inner solar system. But it is necessary to investigate nuclear propulsion technologies more thoroughly to determine if they can provide fast, affordable access to the outer solar system and beyond and can move large payloads in the inner solar system cost-effectively and efficiently.**

NASA's parametric studies of the potential applications of the NEP system being developed by Project Prometheus indicate that numerous desirable missions—e.g., a Neptune orbiter and an interstellar probe—will require a transit time of more than 10 years. Transit times of a decade or more create problems for sustaining continuous operation of systems, maintaining public support, and ensuring systems' reliability. Long transit times also mean that a scientific payload may be obsolete by the time it reaches its destination. The committee was not convinced that adequate work has been done to demonstrate that a viable NEP system with wide scientific applicability can be developed. Alternative technologies, such as nuclear-thermal propulsion (NTP) and bimodal systems, may provide a more cost-effective, faster means of transport to the outer solar system and beyond. Determining the benefits of nuclear propulsion requires level-playing-field trade-off studies that compare such metrics as the cost, initial mass in low Earth orbit, launch-vehicle requirements, and transit time of various propulsion options. Missions recommended for future study are described in the text boxes in Chapters 4 and 6. Other promising robotic mission candidates (e.g., those resulting from NASA's so-called Vision Missions competition), together with human missions to the Moon and Mars, should also be studied. Assessments of trade-offs among chemical propulsion, solar-electric propulsion, solar sail, NEP, NTP, and bimodal systems should be completed for missions with requirements for a wide range of velocity changes.

Trade-off studies should also consider the impact of system reliability when determining suitable space reactor system designs and operational profiles, especially for those systems designed to operate continuously without maintenance or repair for extended periods of time. For example, the current NEP concepts being considered for missions to the outer solar system are required to function without human intervention for durations between 10 and 20 years. However, no high-power-density reactor has ever been operated on Earth, without maintenance shutdowns, for any period longer than one order of magnitude or more below such a duration.

Recommendation: **NASA should commission detailed, comprehensive studies—supported by external independent reviews and the broad participation of the space science and space technology communities—to examine the feasibility of developing space nuclear propulsion systems with reduced transit times and costs, in order to determine which nuclear propulsion technologies should be pursued at this time, and to ensure that investments in advanced propulsion technologies yield the greatest benefit for the NASA community.**

SECONDARY FINDINGS AND RECOMMENDATIONS

The Decadal Surveys and Program Balance

Finding: **Program balance is critical to the long-term health of the space science enterprise. An important aspect of a balanced program is a flight program encompassing a range of flagship missions combined with moderate and small missions.**

The most recent decadal surveys have placed high importance on overall program balance and have reiterated the need for a mix of more frequent, principal-investigator-led small- and medium-class missions combined with less frequent, more costly, larger missions. This overall program balance is considered practical, given the size of NASA budgets, and is necessary for nurturing a healthy scientific and engineering community; it promotes the achievement of progress and discovery on a broad front. The development of nuclear propulsion systems is seen as offering many possible advantages for future science missions. However, the cost associated with their development may have a dramatic impact on near-term mission capability. If NASA's science program is required to cover the development of nuclear power and propulsion systems, the result will be a substantial decline in the diversity and scope of space science activities. Recovery from such a decline will not occur quickly.

Recommendation: **The cost of developing advanced power and propulsion technologies, and of implementing missions employing such technologies, must not be allowed to compromise the diversity of the space science missions recommended by the decadal surveys, because these missions address the most important scientific questions in solar and space physics, solar system exploration, and astronomy and astrophysics and are thus essential to maintaining the long-term health and vitality of the entire space science enterprise. Given the level of resources required to implement NEP-class missions, these super-flagship endeavors will have to be extraordinarily capable of addressing a broad-based, cross-cutting range of truly interdisciplinary scientific activities, if such missions are to provide a science return commensurate with the investment made in them.**

Public Acceptance and Launch Approval

Finding: **Previous launches of nuclear-powered spacecraft have raised concerns among members of the public. If such concerns were to intensify, it could seriously affect any planned use of nuclear technology on space science missions.**

The perceived risk of nuclear power plants and the associated hazards posed by the disposal of long-lived radioactive waste have led to a significant fraction of the U.S. public resisting the development of new nuclear systems. The experience with space nuclear systems has been somewhat different. Opposition to the launch of RPS-powered spacecraft has been visible and vocal, but not necessarily widespread, and not ultimately successful in preventing the launch of these systems. Nevertheless, the potential for public opposition to nuclear power development exists and must be considered by NASA in planning the development of nuclear space power and propulsion systems. Denial of risk and neglect of possible impacts have led to the demise of otherwise potentially beneficial nuclear technologies, such as nuclear power generation for civilian uses. Nuclear space reactor technology has seen very limited development and undoubtedly poses a number of reliability and safety questions that have to be fully understood and addressed by the technical and scientific community, and made comprehensible to the public at large.

> ***Recommendation:*** **It is essential that NASA communicate clearly and openly with the public regarding the potential benefits of and challenges posed by the use of space nuclear power and propulsion systems. The agency and its partners must avoid the denial of risks and neglect of impacts, as well as the perception thereof. NASA should adopt a very proactive stance and role in the management and integration of current (e.g., National Environmental Policy Act and interagency launch-approval procedures) and future foreseeable processes of assessment and decision making that will undoubtedly influence public opinion about the general environmental and safety risks associated with the use of nuclear power and propulsion systems in space.**

Human Exploration Activities

> ***Finding:*** **Fission reactors are likely to be useful in providing long-term power for human activities on the surface of the Moon and Mars. Surface power systems are, in practice, likely to be very different from shipboard reactors and will require separate development programs.**

Nuclear systems could provide the large amounts of electricity necessary to power astronauts' life-support systems and to support surface science and exploration activities. Surface and space power systems are likely to be different, and it is not clear whether the NEP-class reactor currently under study by Project Prometheus is adequate for either application. NTP systems may be better able to provide the thrust needed to send astronauts to Mars. Nuclear reactor power and propulsion systems for human exploration missions, however, must be qualified to a level of reliability much higher than that for power and propulsion systems for robotic missions, and will have to be validated for reliable operation at full power and mission lifetime.

> ***Recommendation:*** **NASA should reexamine the technology goals of Project Prometheus to assess the benefits (in terms of cost, schedule, and performance) of using a technology that can support the propulsion requirements of both human and robotic missions.**

Heavy-Lift Launch Vehicles

> ***Finding:*** **NEP-class spacecraft are inherently massive and, as such, will require either in-space assembly following multiple launches of components on the largest launch vehicles currently available, or a single launch on a new heavy-lift booster.**
>
> A heavy-lift launch capability would potentially enable new classes of space science missions.
>
> ***Recommendation:*** **Studies of trade-offs comparing propulsion options should take into account the complexities and cost of launching NEP-class missions.**

Technical, Programmatic, and Infrastructure Issues

> ***Finding:*** **Attention has to be paid to a variety of technical and programmatic issues that can affect the scientific utilization of NEP-class missions. These issues include the fraction of a spacecraft's launch mass dedicated to the science payload; high-bandwidth communications; onboard data processing; the capacity of the Deep Space Network, Planetary Data System, and research and analysis programs to handle increasing volumes of data; the availability of radiation-hardened components and radiation-tolerant detectors; and mitigation of contamination. Failure to make allowance for some or all of these factors can lead to hidden costs that will impact the implementation of NEP-class missions.**

Considerations relating to these technical and programmatic issues include the following:

- *Fraction of launch mass for science*—On typical planetary missions flown over the last 30 years, the ratio of science payload mass to total mass has varied between 0.09 and 0.17. The science payload mass ratios for Cassini and JIMO are ≥0.1 and ≤0.06, respectively. The much larger masses necessitated by large NEP systems should offer the opportunity for much larger science payloads.
- *The Deep Space Network and the Planetary Data System*—The ability to accommodate the extremely large volume of data returned by NEP missions will require some combination of advanced onboard data processing, high-bandwidth communications, and improvements in the Deep Space Network. The Planetary Data System and other data repositories will have to be expanded, and data-analysis programs will have to be established and/or augmented to meet the needs of future missions and ensure that the data returned are fully analyzed.
- *Radiation-hardened components and radiation-tolerant detectors*—The development of new, more capable, radiation-hardened electronic components, together with new detector materials and detection concepts, will enhance measurement capabilities.
- *Contamination mitigation for instruments*—To enhance or enable scientific measurements from spacecraft equipped with nuclear reactors, power and propulsion systems must be “clean” and “stable” in terms of transient magnetic and electric fields, chemical contamination, radiation and charged-particle levels, and vibration. In addition, nuclear reactors should not be operated within Earth’s magnetosphere unless it can be demonstrated that interference to other spacecraft caused by primary and secondary gamma rays, electron bremsstrahlung, and positron-annihilation radiation will not occur.

> ***Recommendation:*** **Determination of the cost of NEP-class missions should take into account the cost of necessary associated technologies and programs. Particular emphasis should be placed on studies of the means to maintain or, if possible, increase the fraction of launch mass allotted to science payloads above that typical for current space science missions.**

REFERENCES

1. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, Space Studies Board, The National Academies Press, Washington, D.C., 2003, pp. 202–205.
2. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, Space Studies Board, The National Academies Press, Washington, D.C., 2003.
3. National Research Council, *Astronomy and Astrophysics in the New Millennium*, Board on Physics and Astronomy–Space Studies Board, National Academy Press, Washington, D.C., 2001.
4. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, Space Studies Board, The National Academies Press, Washington, D.C., 2003, pp. 202–205.
5. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, Space Studies Board, The National Academies Press, Washington, D.C., 2003, pp. 10–11 and 85.
6. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, Space Studies Board, The National Academies Press, Washington, D.C., 2003, p. 205.
7. See, for example, National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, Space Studies Board, The National Academies Press, Washington, D.C., 2003, pp. 176–177 and 189.
8. See, for example, National Research Council, *Connecting Quarks with the Cosmos—Eleven Science Questions for the New Century*, Board on Physics and Astronomy, The National Academies Press, Washington, D.C., 2003.

1

Introduction and Background

Two of the most constrained resources on all spacecraft are propulsion power and electrical power. Chemical systems have been used to propel spacecraft since the dawn of the Space Age. Similarly, photovoltaic arrays, batteries, and fuel cells have been the principal source of electric power in space. The increasing demands for higher power, shorter trip times, and greater maneuverability at the target destination have led to numerous suggestions and recommendations calling for the development of nuclear reactors for space-based power and propulsion systems.[1]

Chemical rockets have been the only available option for launch into Earth orbit or for any other task requiring large amounts of thrust. Even if powerful nuclear propulsion systems are developed in the future, safety and environmental considerations will prevent them from being operated until they are in space, which means that spacecraft will have to be launched using a chemical propulsion system.

Photovoltaic and other potential solar-power systems are well suited to long-duration applications because they eliminate the need for large stores of chemical fuels and associated spacecraft structures. However, solar-power systems are not generally suitable for high-power applications, and photovoltaic systems in particular suffer from other drawbacks such as degradation caused by solar particles and ultraviolet radiation. Moreover, the output capacity of all types of solar-power systems drops off dramatically as the distance between the spacecraft and the Sun increases. On the other hand, photovoltaics are technologically mature and unit cost ($/watt of electrical power) is well understood (Figure 1.1).

Radioisotope thermoelectric generators (RTGs) and other radioisotope power systems (RPSs)[a] are the systems of choice when low levels of electric or thermal power are needed for extended durations. RPSs are also ideally suited for use by spacecraft far from the Sun, or in locations where solar energy is available only intermittently (e.g., on the lunar surface) or not at all (e.g., at the lunar poles).

Except for one short-lived experimental reactor—the SNAP-10A—launched in 1965, no U.S. space mission has used a nuclear reactor as a source of electric power, and none has used a reactor-based propulsion system.[b] Instead, space exploration missions have been designed within the power and energy envelope defined by the capabilities of chemical, solar, and radioisotope power and propulsion systems (see Figure 1.2). This is not a

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[a] The RTG is a particular technological implementation of a more generic class of devices, the RPS. Thus, this report uses the latter term unless the specific RTG technology is implied.

[b] Details of past U.S. space nuclear power and propulsion systems can be found in Appendix A.

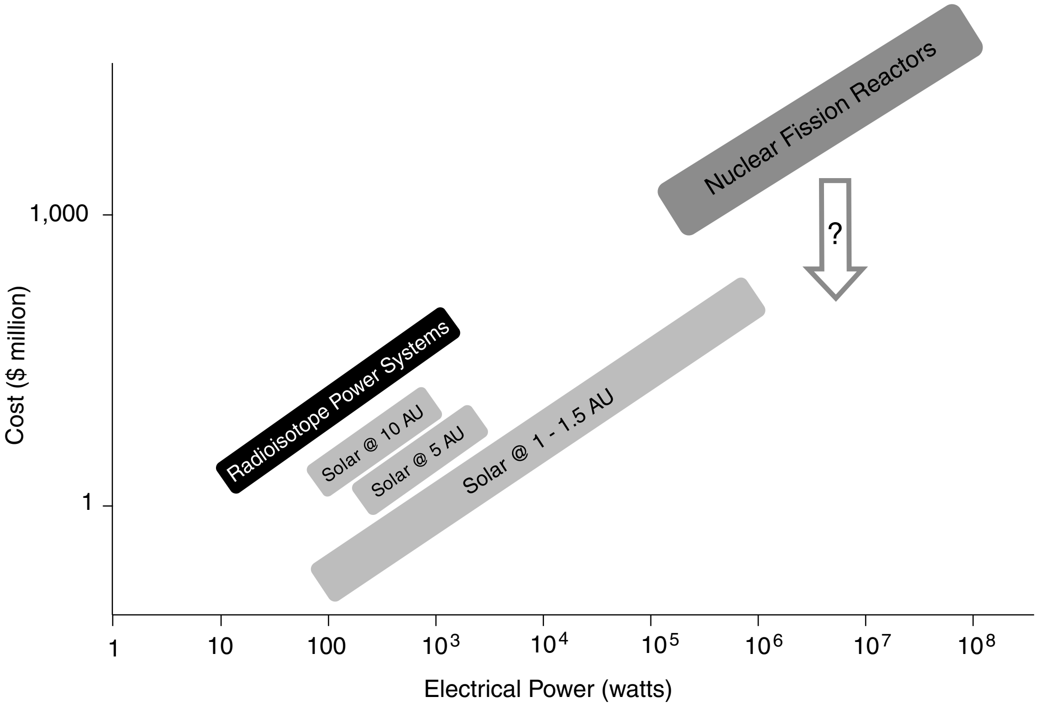

FIGURE 1.1 A schematic showing the approximate cost ($) per watt of electrical power (We) required for radioisotope power systems (RPSs), photovoltaic systems at various distances from the Sun, and fission reactors of the type that might be used in nuclear-electric propulsion (NEP) systems. Most current space science missions have relatively modest power requirements, typically in the range of 0.1 to 1 kilowatts of electricity (kWe). For spacecraft operating at or near 1 AU from the Sun, photovoltaic systems have the advantages of cost-effectiveness and reliability. At greater distances from the Sun, RPSs become the favored option for satisfying modest power requirements. Fission reactors may fill a niche for supplying the large amounts of electrical power required by NEP systems and new types of power-hungry scientific instruments or to support human exploration activities. The plot is based on data supplied by the Boeing Company and is courtesy of Michael Kaplan.

serious handicap for space missions limited to Earth orbit, short visits to the Moon, or robotic missions to Mars. But the capability of missions to the outer planets (Jupiter, Saturn, Uranus, Neptune, and Pluto) and their moons is restricted if they must rely on only chemical, solar, and/or radioisotope systems for electric power and propulsion. While RPSs are inherently low-power systems, most space science experiments have only low power demands. Thus, highly capable missions such as Cassini, which is equipped with a dozen instruments, can manage sufficiently on some 800 watts of electricity. The outer planets are so far from the Sun, however, that the output of solar-power systems at such distances is minuscule. Also, the duration of missions to the outer planets is so long that the average power available to a spacecraft over its lifetime from a chemical power system would also be minuscule, and the total energy available from a chemical system would be limited by the need to carry along the requisite fuel.

Low power and energy limits are problems because power is needed to operate science instruments, communications systems, and propulsion systems. Nuclear reactor systems, which can provide relatively high power over long periods, make it possible to design missions with more numerous and more capable science instruments, high-bandwidth communications systems, shorter transit times, and greater flexibility to change the course and speed of spacecraft enough to:

- Conduct extended investigations (rather than brief flybys) of bodies of interest;

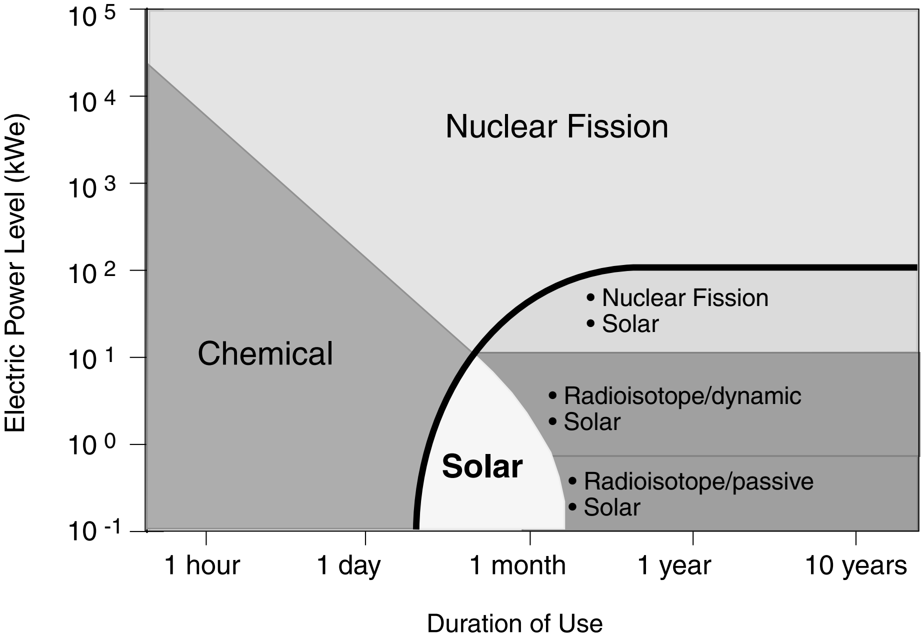

FIGURE 1.2 A schematic showing the relative applicability of various space-based sources of electrical power. Courtesy of George Schmidt, Project Prometheus, NASA.

- Visit multiple bodies much more easily; and
- Significantly alter a spacecraft's trajectory in response to information collected during a particular mission.

Nuclear reactors have the potential to overcome limitations associated with low energy and power. They do this by providing electricity and propulsion over a wide range of power levels for extended periods (years to decades), including during both transit and surface operations, without regard to the availability of either solar energy or large quantities of chemical fuel. Nuclear reactor systems, however, are expensive to develop, and their potential will be realized only if key technology issues can be overcome.

PROJECT PROMETHEUS

In 2002, NASA initiated the Nuclear Systems Initiative, within the Office of Space Science (now the Science Missions Directorate), to explore the use of nuclear power and propulsion systems for both human and robotic activities. According to NASA, the initiative was begun in response to identified limitations of the current paradigm for solar system exploration missions. In particular, solar power constrains power budgets and is of limited use in the outer solar system, and chemical propulsion limits spacecraft maneuverability and mission destinations.

The following year, the Nuclear Systems Initiative was renamed Project Prometheus and given three tasks:

1. To develop a new generation of RPSs;
2. To conduct advanced studies of nuclear power and propulsion systems; and
3. To initiate development of the first Prometheus flight program, the Jupiter Icy Moons Orbiter (JIMO).

In February 2004, responsibility for Project Prometheus was transferred to NASA's newly established Office of Explorations Systems (now the Explorations Systems Mission Directorate). The Office of Space Science, however, retained managerial control of the development of RPSs and the science requirements for JIMO. The initiation, at about the same time, of the Vision for Space Exploration—NASA's new program of coordinated robotic and human exploration of the Moon, Mars, and beyond (Box 1.1)—greatly expanded the scope of the type of nuclear power and propulsion systems under consideration by Project Prometheus. In addition to RPS technology and the fission reactor to power JIMO's NEP system and high-powered instruments, Prometheus was now responsible for research and development of the following:

- Nuclear power systems to supply auxiliary power for spacecraft in transit (i.e., to operate, for example, life-support and other spacecraft systems) and to supply power for surface activities on the Moon or Mars; and
- Much larger nuclear power systems to support thermal or NEP systems for human exploration activities beyond the Earth-Moon system.

BOX 1.1
The Vision for Space Exploration

The major activity that now focuses many if not all of NASA's programs, including Project Prometheus, is the human and robotic exploration initiative known as the Vision for Space Exploration.

On January 14, 2004, President George W. Bush announced a new civil space policy that was soon named the Vision for Space Exploration.[1] Not only did NASA quickly start several new projects as part of this new policy, but the agency also began a major restructuring of its organization. Significantly, NASA was one of only a few non-defense agencies to receive a budget increase in the 2005 fiscal year, and the reason for this was the Vision for Space Exploration.

Origins of the Vision for Space Exploration

The new space policy owes its origins to the Columbia accident in February 2003. Prior to that, NASA's overall policy goals—as outlined in the national space policy annunciated by the Clinton administration in 1996—included completing the International Space Station (ISS), maintaining a continuous robotic presence on Mars, undertaking a concerted effort to search for and characterize extrasolar planets, and conducting a long-term program of Earth remote sensing.[2] But NASA's leadership had explicitly declared that the agency would pursue space technology development to enable future efforts, rather than establish a specific destination to explore, and lunar exploration was not part of the agency's future plans. At the beginning of 2003, NASA also had no plans to retire the Space Shuttle in the foreseeable future. The Columbia disaster in February 2003 changed everything.

The Columbia Accident Investigation Board (CAIB) declared in August 2003 that if the Space Shuttle were to continue to operate past 2010 (the planned completion date for the core version of the ISS), the space agency should "recertify" it.[3] The CAIB also declared that one of NASA's institutional problems was the lack of a clear programmatic focus, which led to constantly changing plans for the Shuttle fleet.

As the CAIB conducted its investigation in the spring and summer of 2003, staffers in the White House, including the National Security Council and the Office of Science and Technology Policy, began discussing

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

[2] National Science and Technology Council, National Space Policy Fact Sheet, September 19, 1996, Executive Office of the President, Washington, D.C., 1996, available online at <http://history.nasa.gov/appf2.pdf>.

[3] Columbia Accident Investigation Board, *Report*, Volume 1, August 2003. Available online at <http://www.nasa.gov/columbia/home/CAIB_Voll.html>.

The basic characteristics of the nuclear systems relevant to Project Prometheus are shown in Table 1.1, and NASA's notional timeline for the development of these technologies is indicated in Figure 1.3.

In August 2004, NASA and the Department of Energy's (DOE's) Office of Naval Reactors signed a memorandum of understanding relating to the development, design, delivery, and operational support of civilian space nuclear reactors within NASA's Project Prometheus. The following month, the Jet Propulsion Laboratory (JPL) selected Northrop Grumman Space Technology as the prime contractor for developing a preliminary design for the JIMO spacecraft. The contract, valued at approximately $400 million and relating to activities through mid-2008, also covers the development of hardware, software, and test activities for the design of the non-nuclear portion of the spacecraft, and the interfaces for the spacecraft, reactor, and science instruments.

the future of the civilian space agency.[4] These discussions gained momentum after the August release of the CAIB report, which contained a scathing critique of NASA. The internal deliberations continued through the autumn, gaining increased momentum from the CAIB report. Discussions on the future of NASA were not confined to the White House. In the waning days of 2003, Congress, the Space Studies Board (SSB),[5] the media, and other interested parties all began to pay more attention to the goals of, and prospects for, human spaceflight activities. Then, in January 14, 2004, President Bush announced the new policy at NASA Headquarters.

Scope of the Vision for Space Exploration

The Vision established exploration as the primary goal for the space agency. President Bush called for humans to return to the Moon no later than 2020, leading to the eventual human exploration of Mars. The Vision for Space Exploration also called for greater use of robotic probes "to maximize our understanding of the solar system and pave the way for more ambitious manned missions." The new policy also addressed several existing programs. Under the new plans, the Space Shuttle would be retired by 2010, after the completion of the ISS. NASA would develop a new human exploration vehicle to explore "beyond our orbit to other worlds" and replace the Space Shuttle. This new craft would be known as the Crew Exploration Vehicle (CEV). Later, the CEV was declared to be part of a broader human exploration effort called Project Constellation. Project Prometheus, the effort to develop space nuclear power and related technologies for various missions, predated the Vision for Space Exploration, but was incorporated into it.

Budgetary Impact

An important aspect of the Vision for Space Exploration was that it would not require substantial increases in the NASA budget over the next 15 years. Retiring the Space Shuttle in 2010 and curtailing operations on the ISS around 2016 should free up substantial amounts of money that could be applied to the new initiative. These savings will not, however, be realized until early in the next decade, creating a potential cash shortage in the latter part of this decade. Compounding NASA's near-term budgetary situation are a number of non-Vision-related issues, including the cost of returning the Space Shuttle to flight status, a Hubble Space Telescope servicing mission, and an ever-growing number of congressional earmarks in the agency's budget.

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[4] C. Stadd and J. Bingham, "The U.S. Civil Space Sector: Alternate Futures," *Space Policy* 20: 241–252, 2004.

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

TABLE 1.1 Characteristics of Nuclear Systems of Relevance to Project Prometheus

Type	Approximate Power Range (kWe)	Approximate Mass Range (kg)	Shielding Issues	Launch Approval Issues
Radioisotope power systems	<0.3	<50 to 100	Alpha particles, gamma rays	On-pad accident with solid rocket boosters; reentry
NEP reactor system	100 to 500	4,000 to 15,000	Neutrons, gamma rays	No inadvertent criticality[a]
Auxiliary power reactor system	10 to 100	400 to 4,000	Neutrons, gamma rays	No inadvertent criticality[a]
NTP reactor system	20,000 to 4,000,000	1,000 to 8,000	Neutrons, gamma rays	No inadvertent criticality[a]
NEP human transport reactor system	6,000 to 20,000	60,000 to >200,000	Neutrons, gamma rays	No inadvertent criticality[a]
Moon/Mars surface reactor system	20 to 100	800 to 6,000	Neutrons, gamma rays, regolith activation, scatter	No inadvertent criticality[a]

[a] Release of radioactive material from launch or reentry accidents involving a reactor is relatively minor if the reactor is not powered and accidental criticality is prevented by design. Adaptation of current National Environmental Policy Act and launch-approval risk assessment processes may be adequate to validate/verify system safety characteristics and assumptions.

NOTE: NEP, nuclear-electric propulsion; NTP, nuclear-thermal propulsion; kWe, kilowatts of electric power.
SOURCE: A. Newhouse, Project Prometheus, NASA.

RADIOISOTOPE POWER SYSTEMS

RPSs have been used extensively on solar system exploration missions and to a somewhat lesser extent on space physics missions. The continued availability of these devices has been of great concern to the space science community. Plutonium-238, whose decay provides the RPSs' thermal power, is no longer manufactured in the United States and supplies have to be purchased from Russia. DOE has, however, recently announced its intention to open a new ^{238}Pu production facility at the Idaho National Laboratory.[2,3] The solar system exploration (SSE) decadal survey completed in 2002 was drafted in part under the assumption that there was a significant possibility that no additional RPSs would be available for use on planetary exploration missions other than the spare Cassini RTG now allocated to the New Horizons mission to Pluto and the Kuiper Belt.[4] The commitment of NASA and its partners at DOE to development of new RPS technologies is welcome.

NASA's current RPS activities are focusing on the development of two alternative technologies: the multi-mission radioisotope thermoelectric generator (MMRTG)—baselined for use by the Mars Science Laboratory in 2009—and the Stirling radioisotope generator (SRG). Although both are designed to supply approximately 110 to 120 watts of electrical power (We), the former makes use of eight ^{238}Pu general-purpose heat sources (GPHSs), whereas the latter's more efficient power-conversion system requires only 2 GPHSs. Unlike the RPSs used on Cassini and Galileo, the MMRTG and SRG can function equally well in a vacuum or in a planetary atmosphere. It is important to note, however, that when compared in terms of their mass per unit of electrical power output, the MMRTG and SRG are significantly less efficient than the Cassini-class GPHS-RTG. The characteristics of both new systems and the Cassini-class RPS are shown in Table 1.2

A related development of great potential interest to the space science community involves the nascent activities by NASA and DOE to develop RPSs much smaller than the devices discussed above. These activities are

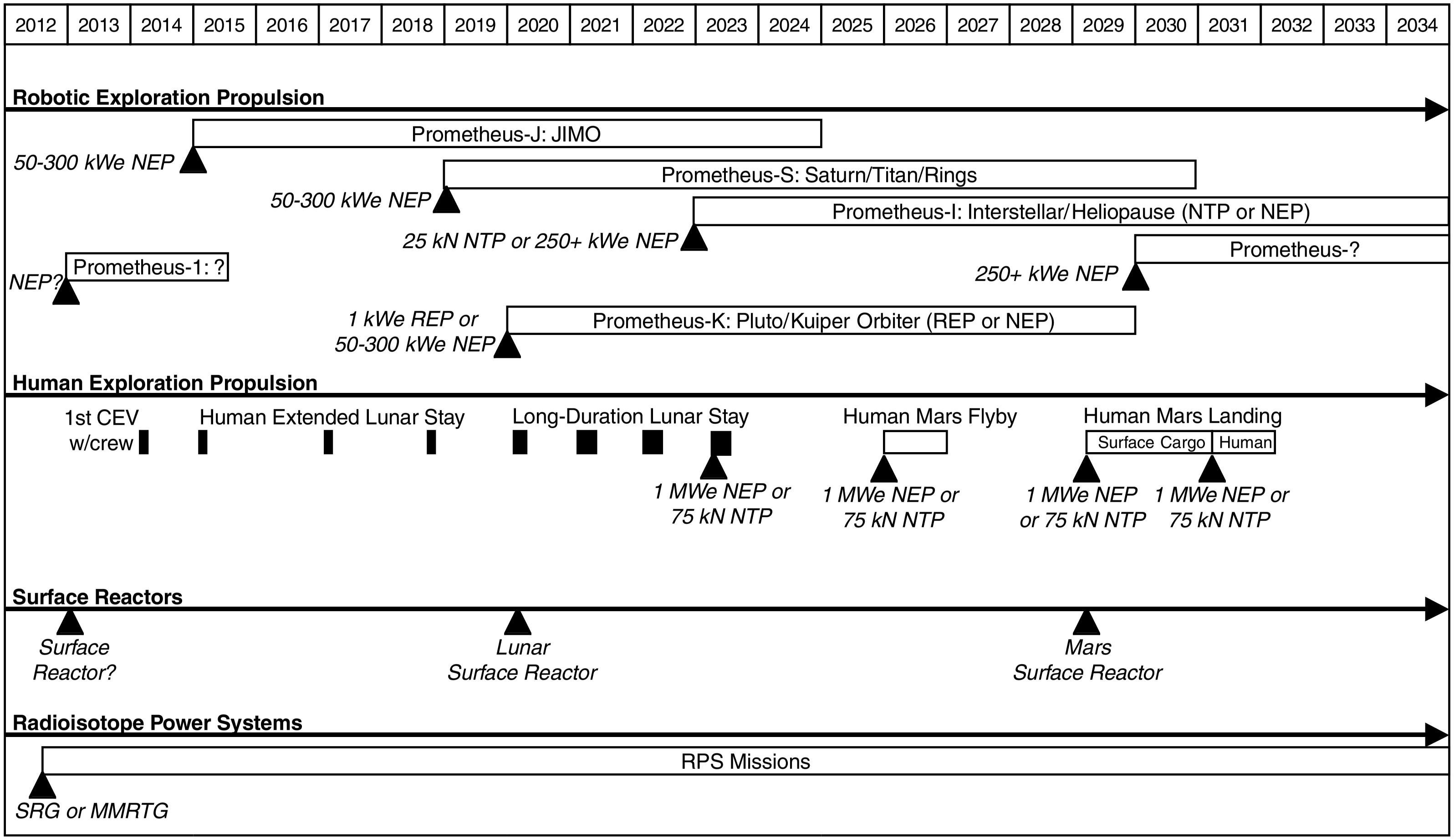

FIGURE 1.3 The potential applications of the various technologies of interest to Project Prometheus are outlined in a notional progression. The chart is intended to indicate the evolutionary relationship between the technologies being developed for the JIMO propulsion system and more advanced nuclear systems that would be applicable to human exploration or space science missions. The chart was generated by NASA to guide internal studies and reflects the agency's thinking as of November 2004. Since then, there have been significant changes in NASA's plans, including the deferment of JIMO until beyond 2017. Note that the 75-kilonewton NTP system mentioned would require a fission reactor with a thermal power output of approximately 330 megawatts. Courtesy of Project Prometheus.

TABLE 1.2 Characteristics of Different Radioisotope Power System Technologies

	Power (We)			Specific Mass (kg/kWe)			
RPS Type	Beginning of Mission	End of Mission	Mass (kg)	Beginning of Mission	End of Mission	^{238}Pu Usage	Notes
MMRTG	123 121	~100—deep space ~100—Mars	40	325 331	400—deep space 400—Mars	~5 kg 8 GPHSs	Developed from SNAP-19 RTG used on Viking and Pioneer 10 and 11
SRG	112 110	~94—deep space ~90—Mars	34	303 309	361—deep space 378—Mars	~1 kg 2 GPHSs	Stirling-cycle power converter is four times as efficient as the MMRTG's thermocouples
GPHS-RTG	290	~250—deep space	55.5	191	222—deep space	~11 kg 18 GPHSs	Used on Galileo, Ulysses, Cassini, and New Horizons; design incompatible with operation in the martian atmosphere

NOTE: MMRTG, multi-mission radioisotope thermoelectric generator; SRG, Stirling radioisotope generator; GPHS-RTG, general-purpose heat source radioisotope thermoelectric generator. End of mission is arbitrarily defined as 10 years after launch.
SOURCE: G.R. Schmidt, R.L. Wiley, R.L. Richardson, and R.R. Furlong, "NASA's Program for Radioisotope Power System Research and Development," *Space Technology and Applications International Forum—STAIF-2005,* M.S. El-Genk, ed., American Institute of Physics, Melville, N.Y., 2005.

focusing on developing an RPS whose heat source is either one GPHS, a fraction of a GPHS, or multiple radiosotope heater units (RHUs).[5] The potential characteristics of such systems are indicated in Table 1.3.

An area not actively pursued currently is the development of either a replacement for the GPHS-RTG or something with an even larger power output. In other words, it is possible to conceive of missions needing ~1 kWe—e.g., spacecraft using a radioisotope-electric propulsion system—but the only way to provide such power at the moment is to gang ~10 MMRTGs or SRGs.

TABLE 1.3 Characteristics of Possible Small Radioisotope Power Systems

Small-RPS Class	Approximate Power (We)	Approximate Mass (kg)	Specific Mass (kg/kWe)	^{238}Pu Packaging	Example of Possible Use
Large	10 to 20	~5	~250 to ~500	1 GPHS	Europa Surface Science Package
Medium	0.1 to <10	~0.5 to 1.5	⩾150 to ~15,000	Multiple RHUs	Magnetospheric Microsatellite Constellation
Small	>0.01	⩽0.5	⩽50,000	1 RHU	Mars Meteorological Network

NOTE: RHU, radioisotope heater unit; GPHS, general-purpose heat source.
SOURCE: R.D. Abelson, ed., *Enabling Exploration with Small Radioisotope Power Systems* (JPL-Publication 04-10), Jet Propulsion Laboratory, Pasadena, Calif., 2004.

THE JUPITER ICY MOONS ORBITER

JIMO was conceived as an ambitious mission designed to send a spacecraft to orbit three of the Galilean moons: Callisto, Ganymede, and Europa. The spacecraft would explore the moons and investigate their makeup, their history, and their potential for sustaining life in the vast subterranean oceans believed to exist under these moons' icy surfaces. It was intended to serve as the flight test of a fission reactor power system, an advanced ion propulsion system, and a new generation of high-power scientific instruments.

Science Goals

The Galileo spacecraft that orbited Jupiter during the latter 1990s discovered evidence that Europa had an icy surface that probably covers a huge liquid water ocean up to 100 kilometers thick. The SSE decadal survey, *New Frontiers in the Solar System*, ranked the scientific exploration of Europa as a top priority for NASA's planetary exploration program and recommended the development of a Europa Geophysical Explorer. It is worth noting that although the Europa Geophysical Explorer is envisaged as an RPS-powered spacecraft with a limited instrument complement,[6] the report's authors did consider the possibility of a nuclear-electric mission that would sequentially orbit the three outer Galilean satellites. This possibility was, however, deemed inappropriate until after there was confirmation of a subsurface ocean on one of the Galilean satellites.[7]

At the same time that the NRC was conducting its review of solar system exploration, NASA was actively considering a demonstration mission for Prometheus that would orbit Jupiter and its large Galilean moons. In 2003, NASA formally established the JIMO project to explore not only Europa but also Ganymede and Callisto, all of which are believed to exhibit evidence of subterranean liquid water. The initiation of JIMO was essentially concurrent with the SSE decadal survey, rather than, strictly speaking, flowing from its recommendations. Funding for JIMO was first included in NASA's budget for fiscal year 2003.[c]

The goals of the JIMO mission are as follows:

- To determine the evolution and present state of the Galilean satellite surfaces and subsurfaces and the processes affecting them;
- To determine the interior structures of the icy satellites and the potential "habitability" of the moons;
- To search for signs of past and current life; and
- To determine how the components of the jovian system operate and interact.

JIMO was, however, intended to be a technology-demonstration mission as well as a mission of scientific exploration.

Spacecraft Design

As conceived by NASA, the basic JIMO spacecraft would weigh ~25,000+ kilograms and would consist of three main components (Figure 1.4): the reactor and power-conversion systems, a long boom equipped with radiators to disperse waste heat, and the propulsion module and science instrument platform.

The reactor—probably a fast, moderator-less design equipped with external neutron reflectors to control criticality and using a gas, heat-pipe, or liquid-metal cooling system—is capable of generating ~500 kilowatts of thermal energy (kWth). It is mounted several tens of meters from the propulsion module to protect the avionics and the scientific payload from radiation.[d] The reactor's thermal energy is converted into ~100+ kWe using an as-yet-to-be-determined power-conversion system; possibilities under consideration include thermoelectric, Stirling-

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[c] JIMO was first proposed in NASA's budget request for fiscal year 2004. But the first funding was actually included in NASA's budget for fiscal year 2003, which was not finally approved by Congress until after the 2004 request had been announced.

[d] NASA's so-called TB2.5 design for JIMO stretched some 36 meters (m) from the leading edge of the reactor to the trailing edge of the ion thrusters. The design proposed by the Northrop Grumman Corporation was some 75 m long.

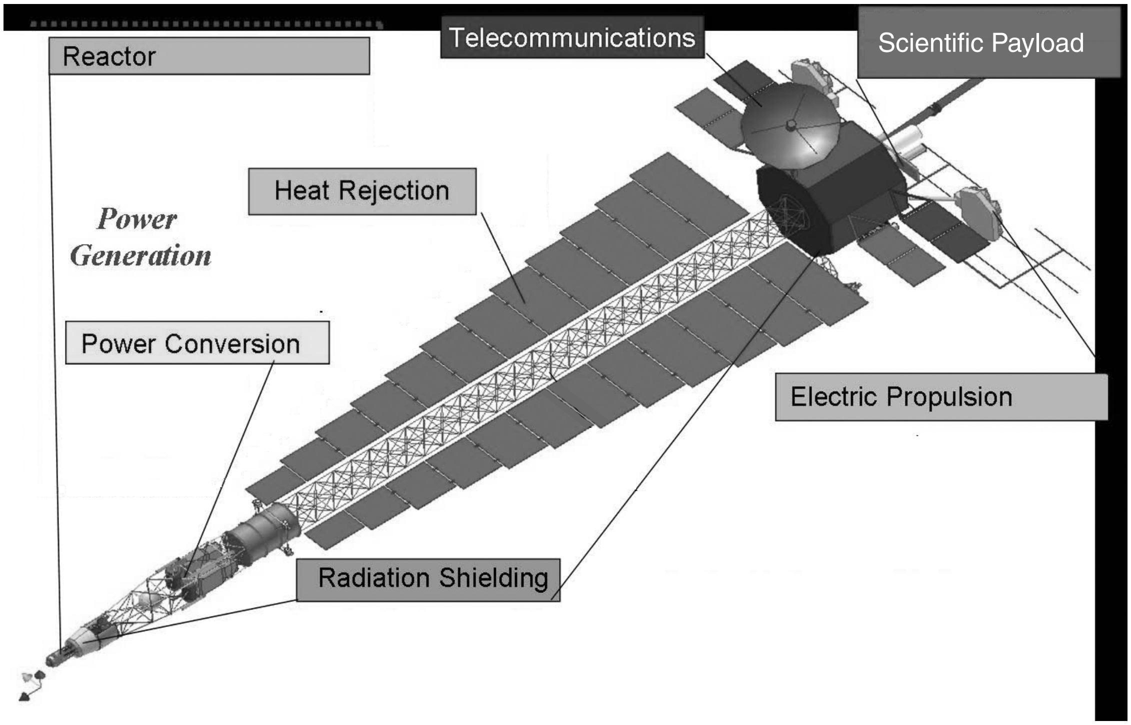

FIGURE 1.4 A schematic of one possible configuration for the Jupiter Icy Moons Orbiter. Also indicated are the various technologies that are under consideration for its various major subsystems. Courtesy of NASA/Jet Propulsion Laboratory.

cycle, and Brayton-cycle systems. The electricity from the reactor would be used to power an ion propulsion system much larger than that employed on previous spacecraft such as NASA's Deep Space 1, the European Space Agency's SMART 1, or the Japan Aerospace Exploration Agency's Hayabusa.

Although the exact details are highly subject to assumptions made, a notional JIMO mission would involve a 5- to 8-year transit time from Earth to Jupiter and a 4- to 6-year-duration tour of the outer three Galilean satellites.[8] On arrival at Jupiter, JIMO would sequentially go into high-inclination (>70°) orbits about Callisto, Ganymede, and finally Europa. The sequence is dictated by the spacecraft's propulsion capabilities and the hazards posed by the jovian radiation environment. It is worth noting that the Earth-Jupiter flight time of the Europa Orbiter mission, studied by NASA in the late 1990s, was a little over 3 years, followed by an additional 2 years or so of maneuvering into orbit about Europa.[9]

Following the selection of Northrop Grumman Corporation (NGC) as JIMO's prime contractor in October 2004, elements of NASA's TB2.5 design for JIMO were merged with elements of the NGC design to create the so-called Prometheus Baseline (PB) 1 concept (Figure 1.5). This basic spacecraft design would be descoped or augmented as necessary to undertake a variety of missions in the outer solar system.

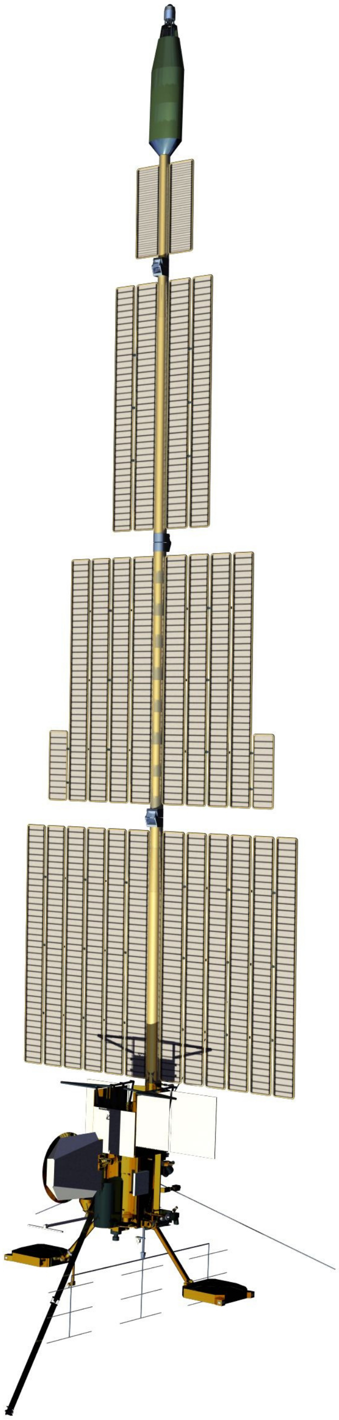

FIGURE 1.5 Artist's impression of the so-called Prometheus Baseline 1 spacecraft proposed by NASA and the Northrop Grumman Corporation as the basic design to be used for the Jupiter Icy Moons Orbiter and, in descoped and enhanced versions respectively, for Prometheus 1 and possible JIMO follow-on missions to Saturn and other destinations in the outer solar system. The proposed spacecraft would stretch some 58 m from the tip of the nuclear reactor (top) to the end of the boom (bottom). Courtesy of NASA.

Launch Issues

JIMO would be the largest robotic spacecraft ever launched (for comparison, the launch mass of the Cassini-Huygens spacecraft was some 5,800 kg). The size of the spacecraft presents special challenges for launch. Its mass is close to, or exceeds, the launch capability of the largest rocket in the current U.S. inventory. Mission designers have stated a strong desire to boost the entire spacecraft onto an Earth-escape trajectory prior to turning on its reactor and engaging its ion propulsion system. This stems from several considerations, including the following:

- Operating the reactor in low Earth orbit (LEO) will build up an inventory of fission products, which would present a hazard in the event of an unplanned reentry into Earth's atmosphere.
- The radiation from the reactor could interfere with other spacecraft. This is particularly problematic for reactors located inside Earth's magnetosphere because they generate charged particles that remain trapped in the geomagnetic field for relatively long periods (up to several minutes).
- Using the ion propulsion system to spiral out from LEO would likely add several years to the flight time.
- Protracted immersion in Earth's Van Allen belts during the spiral out will expose the spacecraft's sensitive instruments and avionics to a significant radiation dose.

As a result, the spacecraft has to be boosted to escape velocity with a chemical propulsion system. Lifting both the spacecraft and this propulsion system into space would require either a single launch of a new heavy-lift launch vehicle or two or more separate launches of large, existing launch vehicles, followed by their rendezvous and mating in Earth orbit. Neither capability currently exists.

Scientific Payload

In 2004, the JIMO Science Definition Team strongly recommended increasing the spacecraft's science payload from a nominal 600 kg to 1,500 kg (including scan platforms, booms, etc.).[10] For comparison, Cassini's total science payload (including Huygens and booms) is approximately 600 kg. The team also recommended that JIMO include a Europa Surface Science Package—a relatively simple lander designed to conduct a limited set of geophysical, geochemical, geological, and astrobiological studies. The lander would make a soft landing on the surface and would have to weigh approximately 375 kg, or roughly 25 percent of the science payload mass.

The electrical power available to JIMO's scientific instruments would far exceed that available on any previous scientific spacecraft. Instruments such as high-power, ground-penetrating, and synthetic-aperture radar systems; laser-ablation spectrometers; and active plasma sounders could in principle be accommodated.[11] To begin development of such instruments, NASA initiated the High Capability Instruments for Planetary Exploration grants program.

JIMO Deferred

Because of its size and complexity, JIMO would be significantly more expensive than any previous planetary exploration mission. In late 2004, NASA began to investigate a simpler, less expensive mission, designated Prometheus 1 (see next section), which could be implemented more rapidly than JIMO. The agency also evaluated the application of the baseline JIMO spacecraft to a variety of follow-on missions.

In February 2005, the President's proposed budget for the 2006 fiscal year deferred additional work on JIMO until after 2017 at the earliest, and Project Prometheus focused its flight-development efforts on a less complex NEP mission designated Prometheus 1 (see next section).

PROMETHEUS 1

The ambitious scope of JIMO, its advanced technology, and its considerable size make it an expensive spacecraft.[12] In the second half of 2004, NASA's Prometheus program office at JPL began the so-called Analysis of Alternatives (AoA) process to identify a less ambitious, nearer-term mission that could demonstrate the capabilities of NEP, high-power instrumentation, and high-capacity communications systems.

By fall 2004, NASA personnel were actively seeking an NEP technology demonstration mission that could meet several key criteria, including the following:

- Launch using a single, existing expendable launch vehicle (or a derivative thereof) by approximately 2014;
- A 3-year mission duration;
- Operation in a more benign environment than JIMO; and
- Significantly less complexity than JIMO, but still using the JIMO-class reactor (possibly at a lower mission power level).

The goal was to demonstrate technology as soon as possible that could be used later on a JIMO-class mission. Concepts suggested for this so-called Prometheus 1 mission were as follows:

- A technology-demonstration mission would carry a minimum of science instruments and would be intended primarily to demonstrate successful operation of the fission power system in deep space.
- A lunar geophysical orbiter would be placed in a high-inclination, low-altitude orbit about the Moon. Its instrument complement would include a topographic mapping radar, a scanning lidar system, and a high-resolution imager.
- A next-generation Mars telecommunications station would test high-power communications systems in Mars orbit, to support very-high-data-volume Mars missions.
- A near-Earth-object mission would sequentially rendezvous with and study several near-Earth objects.
- A Venus orbiter would be designed to produce very-high-resolution radar maps of the planet’s surface.
- There would be an unspecified astrophysics mission.

In addition, JPL scientists began to reconsider the possibility of launching an RPS mission to Europa in 2012. This mission would be somewhat akin to the SSE decadal survey’s Europa Geophysical Explorer or to the somewhat simpler Europa Orbiter that NASA was considering in the late 1990s. A detailed study of such a mission would not only be relevant to achieving the primary science goal of any Europa mission—i.e., conclusively demonstrating whether or not the satellite has a liquid-water layer beneath its icy surface—but it would also serve as a technological baseline against which other programmatic options could be compared. It would also be a means of focusing the development of technology for, and subsequent demonstration of, the radiation-hardened avionics and sensors that would be required for an eventual JIMO-class mission.

By early 2005, NASA had significantly expanded the AoA process to define possible mission options for Prometheus 1 and other nuclear-electric vehicle concepts. Presentations to the NASA Nuclear Systems Strategic Roadmap Team in April 2005 made passing reference to AoA concepts with names such as Heliostorm and Solar Polar, but without providing any specific details of what any of these concepts entailed. Without having access to details of any of the missions considered in the AoA process, it is not possible for the committee to say if any of these missions are uniquely or even plausibly enabled by nuclear power and propulsion technologies.

At about the same time the AoA process was under way, NASA’s planning for the Prometheus 1 mission was being subjected to close congressional scrutiny.[13]

NUCLEAR POWER AND PROPULSION IN THE DECADAL SURVEYS AND THE INITIATION OF THIS STUDY

Although the NRC decadal strategies exist to guide NASA on scientific priorities in space science,[14-16] all of them were drafted prior to the start of Project Prometheus. This does not mean, however, that the decadal surveys were silent on the need for and uses of nuclear power and propulsion systems. In addition to calling for reopening the RPS production lines, the solar and space physics (SSP) survey also recommended that NASA assign a high priority to the development of advanced propulsion systems, including NEP.[17] The solar system exploration (SSE) survey echoed the need for a ready supply of RPSs and also included NEP systems in its list of recommended technology developments.[18] Moreover, the latter report pointed to several missions "which are enabled or enhanced by NEP" and which naturally follow on from missions recommended as priorities for the decade 2003–2013.[19] These missions include a Neptune orbiter, the Titan Explorer, and the Saturn Ring Observer.

Against this backdrop, NASA asked the NRC in late 2003 to identify high-priority space science objectives that could be either uniquely enabled or greatly enhanced by development of advanced spacecraft nuclear power and propulsion systems of the type being developed under the aegis of Project Prometheus.[20]

In response to NASA's request, the Space Studies Board (SSB) and the Aeronautics and Space Engineering Board (ASEB) jointly organized a study that was formally initiated in the spring of 2004. The study committee, divided into a steering group and three science panels, focused on the task of identifying space science objectives and possible missions that could be enabled in the time frame beyond 2015 by the development of advanced spacecraft nuclear power and propulsion systems. It was not the task of the committee to reprioritize the decadal surveys, to set priorities for the period beyond the time horizons of the respective surveys, or to draft a formal review of Project Prometheus. The committee was, however, specifically charged to identify *high-priority* space science objectives. As such, it is important to be specific about the criteria used to select the priorities.

In the absence of specific instructions to do otherwise, the committee chose criteria broadly consistent with those used in the three most recent space science decadal surveys. In other words, the priorities are determined by consideration of intrinsic scientific merit and a combination of more practical issues, including technical readiness, programmatic balance, availability of necessary infrastructure, and budgetary impact.[21] In practice, this meant that the committee saw its primary task as identifying a series of promising mission concepts to help define where the availability of space nuclear systems could have a major scientific impact. The practical aspects of the prioritization criteria imply that consideration of scientific issues alone is insufficient to be fully responsive to the charge from NASA. Thus, the committee saw its secondary task as including some minimal discussion of technological, programmatic, societal, and budgetary caveats that might impact potential space science applications of nuclear power and propulsion. It is the committee's hope that, these caveats notwithstanding, the conceptual missions will be studied by NASA and the wider scientific community and, if found to have sufficient merit and potential, will then be prioritized in the context of future decadal survey activities.

ORGANIZATION AND APPROACH OF THIS REPORT

Chapter 2 is based on material drafted, in part, by a subset of members of the committee's Steering Group and is designed to fill three roles: (1) to be the focus of the discussion on the applications of nuclear power and propulsion to human exploration activities; (2) to discuss the performance characteristics of the NEP system on which Project Prometheus is currently focusing its attention; and (3) to preview the specific technical issues to be discussed in Phase 2 of this study. The bulk of the remainder of the report (Chapters 3 through 8) was drafted based on material supplied by the committee's three science panels. Chapters 3, 5, and 7 summarize the existing science and mission priorities from the decadal surveys conducted by the solar and space physics, solar system exploration, and astronomy and astrophysics communities, respectively. These chapters also discuss important scientific developments since the surveys were issued and provide important background information on how these different scientific communities address their priority goals. Chapters 4, 6, and 8 discuss possible areas where nuclear power and propulsion systems may have an impact in solar and space physics, solar system exploration, and astronomy and astrophysics, respectively. These chapters also, where appropriate, outline promising mission concepts and briefly discuss important community-specific technology issues. The final chapter was drafted by the Steering Group and outlines the report's conclusions and recommendations.

Basic Assumptions

The Steering Group and its panels worked under several assumptions. These can be summarized as follows:

- The starting point for the scientific deliberations in this study are the goals, priorities, and recommendations in the NRC's decadal surveys for solar system exploration (SSE), solar and space physics (SSP), and astronomy and astrophysics (AAp). NASA's exploration initiative—the Vision for Space Exploration—has caused significant changes in the structure of NASA, and in some cases, scientific priorities and strategies of the subdisciplines have been reexamined.[22-24] Some observers might argue that the use of the science priorities in the decadal surveys is nothing more than maintaining the status quo or protecting entrenched interests. Nothing could be further from the case. The three decadal surveys represent the community consensus that emerged from extensive consultations with, and deliberations among, hundreds of individuals in the respective communities. The committee believes strongly that this consensus is compelling. Thus, it is an exercise in due diligence to require that the science objectives and high-priority missions within those surveys retain their priority unless new scientific priorities have emerged with community-wide consensus in the time since the decadal surveys were completed.
- Important issues relating to the launch from Earth, or assembly in low Earth orbit, of massive JIMO-class spacecraft are assumed to be solvable, or will be addressed by another and more appropriately constituted committee.
- Project Prometheus is a moving target. When the committee held its first meetings in spring of 2004, JIMO, for example, was a priority activity and NASA was actively studying follow-on missions. Six months later, however, when the committee held its final meeting, JIMO was being deferred in favor of an undefined, simpler, and less expensive NEP mission, Prometheus 1.

Initial Concerns

Although the committee was specifically charged to identify high-priority space science objectives that might be enabled or enhanced by nuclear technologies, it could not, as indicated above, do this in a vacuum. From its very first briefings on Project Prometheus, the committee was highly concerned about a variety of practical issues, including the possible impact of expensive, long-lived, data-rich missions—as exemplified by the now-deferred JIMO—both on the critical infrastructure supporting NASA's space science activities and, indeed, on the rest of NASA. In other words, missions deriving from Project Prometheus, whether Prometheus 1, JIMO, or possible follow-ons, will coexist with other NASA programs and activities. The question is whether this coexistence, complicated by possible launch-approval and public-acceptance issues, is feasible within any plausible budgetary and implementation scenario. These concerns, in no specific order, include the following:

- Are issues relating to the safety of and the launch-approval process for radioactive materials, whether packaged as RPSs or fission reactors, sufficiently well understood so that they do not present insuperable obstacles to the expanded use of such devices?
- Is a new class of super-flagship, NEP-enabled missions programmatically conceivable while preserving a balance of mission classes and targets?
- Can the existing Deep Space Network handle the data-return rates from missions such as JIMO?
- Can existing data archives, such as the Planetary Data System, accommodate the large volumes of data returned by NEP-class missions and ensure that the wider scientific community has ready access to these?
- To what extent will data analysis programs and other related activities have to be augmented to meet the needs of JIMO-type missions and to ensure that the research base for follow-on activities has a sound foundation?

Additional concerns of the committee relating to the capabilities of nuclear power and propulsion systems included the following:

- Are the decadal surveys an appropriate starting point for deliberations on the scientific opportunities opened up by nuclear technologies, given that these reports were drafted on the basis of particular sets of assumptions concerning the likely power and propulsion technologies available to support priority missions? In other words, are the priorities in the decadal surveys still valid if their technological assumptions are significantly perturbed by the introduction of radically new capabilities such as nuclear power and propulsion?

- Has there been sufficient foundational work in the form of mission and trade-off studies so that a quantitatively informed assessment can be made of what scientific opportunities are or are not enhanced or enabled by nuclear technologies?

These issues are considered in subsequent chapters of the report.

REFERENCES

1. See, for example, National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 202–203.
2. W.J. Broad, "U.S. Has Plans to Again Make Own Plutonium," *The New York Times*, June 27, 2005, pp. A1 and A13.
3. See, for example, Office of Nuclear Energy, Science, and Technology, U.S. Department of Energy, *Draft Environmental Impact Statement for the Proposed Consolidation of Nuclear Operations Related to Production of Radioisotope Power Systems*, DOE/EIS-0373D, U.S. Department of Energy, Washington, D.C., June, 2005. Available at <www.consolidationeis.doe.gov/>, accessed February 2, 2006.
4. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 203.
5. G.R. Schmidt, R.L. Wiley, R.L. Richardson, and R.R. Furlong, "NASA's Program for Radioisotope Power System Research and Development," *Space Technology and Applications International Forum—STAIF-2005,* M.S. El-Genk, ed., American Institute of Physics, Melville, N.Y., 2005
6. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 196.
7. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 204.
8. R. Greeley, T.V. Johnson, et al., *Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO)*, National Aeronautics and Space Administration, Washington, D.C., 2004.
9. See, for example, National Research Council, *A Science Strategy for the Exploration of Europa*, National Academy Press, Washington, D.C., 1999, pp. 11–12.
10. R. Greeley, T.V. Johnson, et al., *Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO)*, National Aeronautics and Space Administration, Washington, D.C., 2004, p. 49.
11. M.J. Hart, *Jupiter Icy Moons Orbiter High Capability Instrument Feasibility Study*, Aerospace Report No. TOR-2004(2172)-3231, The Aerospace Corporation, El Segundo, Calif., 2004.
12. See, for example, Congressional Budget Office, *A Budgetary Analysis of NASA's New Vision for Space Exploration*, Congress of the United States, Washington, D.C., 2004, p. 22.
13. United States Government Accountability Office, *NASA's Space Vision: Business Case for Prometheus 1 Needed to Ensure Requirements Match Available Resources*, GAO-05-242, Congress of the United States, Washington, D.C., 2005.
14. National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.
15. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.
16. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.
17. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003, pp. 10–11 and 85.
18. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 202–205.
19. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 205.
20. Letter from Edward J. Weiler, Associate Administrator of Space Science, to Lennard Fisk, Chair of the Space Studies Board, October 14, 2003.
21. See, for example, National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 176–177 and 189.
22. National Research Council, *Solar and Space Physics and Its Role in Space Exploration*, The National Academies Press, Washington, D.C., 2004.
23. National Research Council, "Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision: Letter Report," The National Academies Press, Washington, D.C., 2005.
24. National Research Council, *Science in NASA's Vision for Space Exploration*, The National Academies Press, Washington, D.C., 2005.

2

Engineering and Technical Issues

NUCLEAR REACTORS AND HUMAN EXPLORATION

Propulsion

Several studies over the past few decades have recognized the need for advanced propulsion to support human exploration. As early as the 1960s, Wernher von Braun and others recognized the value of a nuclear rocket for sending humans to Mars. The great distances, harmful cosmic radiation, and physiological response to zero gravity all supported the concept of using a nuclear rocket to decrease mission time. These same needs have been recognized in later studies.[1-5]

Exploration missions by humans beyond the Moon must cope with radiation levels between 1 and 2 centi-Sievert (cSV) per week from galactic cosmic rays.[6,7] Astronauts will also face the substantial decalcification of bone that occurs in a zero-gravity environment. A high-thrust nuclear propulsion system with a high specific impulse would mitigate these threats by reducing exposure time.

Power

Nuclear reactor power systems can support human exploration at surface outposts and onboard spacecraft. A nuclear reactor on the surface of the Moon or Mars can be a source of reliable power to provide life support, to replenish fuel cells for mobile systems, and to supply the large power demands of facilities processing materials. A continuous source of power is needed for life support onboard a spacecraft. Power levels for surface and shipboard life support systems are approximately equivalent. However, the environments in the two applications can vary dramatically. Shipboard systems will need to radiate all waste heat to the vacuum and will need to have a low specific mass (i.e., kg/kW), which calls for operation at higher temperatures and the use of more exotic materials. Specific mass is typically less important for surface systems—as opposed to actual mass, which must be minimized for ease of transportation—and so more common materials can be used, and it will be easier to address radiation shielding issues. However, in the case of Mars or other surfaces possessing an atmosphere, the materials used may be dictated by the chemical interactions between, for example, hot radiators and atmospheric gases. In addition, radiators designed for shipboard use—i.e., to function most efficiently in the vacuum of space—will need to be modified to function efficiently in an atmosphere. Thus, surface power systems are, in practice, likely to be very different from shipboard reactors.

Testing and Reliability

Nuclear reactor power and propulsion systems for human exploration missions must be qualified to a much higher level of reliability than power and propulsion systems that are intended for use by robotic missions. In the past, chemical systems such as the Space Shuttle Main Engines were tested more than 400 times on 30 engine systems to establish operational safety margins. These tests included operation at full power or greater, and for full lifetime duration or greater.

Nuclear systems will likewise need to be validated for reliable operation at full power and for mission lifetime. The latter factor is especially important because some potential applications—e.g., missions using nuclear-electric propulsion (NEP) to the outer solar system—require continuous operation without maintenance or repair for periods as long as 10 to 20 years. No high-power-density reactor has, however, ever been operated on Earth, without maintenance shutdowns, for any period longer than one order of magnitude or more below such a duration.

CANDIDATE SOURCES OF ELECTRICAL POWER AND PROPULSION

Nuclear-Electric Propulsion

Currently, NASA's Project Prometheus is pursuing the development of NEP systems. In these systems, the heat from the reactor is carried away by a coolant in a closed loop to a power-conversion system, where it is used to generate electricity. The electricity then powers one of a variety of different electric propulsion technologies that accelerate ions and eject them from the thrusters at high velocities. JPL has demonstrated ion thrusters with a specific impulse of some 3,100 seconds in space on the Deep Space 1 mission and more than 6,000 seconds in the laboratory, which greatly reduces the amount of propellant required for the mission as compared to chemical propulsion systems. The electric power from an NEP system is also available for spacecraft instrumentation. Typically the power requirements for the mission may range from ~100 kWe, the nominal requirement for JIMO, to many megawatts of electricity (MWe) that might be required for human and cargo missions to Mars and beyond.

The leading reactor concepts employ liquid-metal coolants (either actively pumped or circulated in heat pipes), liquid-metal-to-gas heat exchangers, and Brayton-cycle conversion systems. An inherent difficulty with NEP systems is that only 10 to 20 percent of the thermal energy generated in the reactor is converted into thrust. Thus, massive radiators are required to reject the waste heat into space. In addition, electric propulsion systems provide low thrust, so NEP systems must operate at near 100 percent duty for long durations to provide high delta-V. The low thrust also complicates navigation, maneuvering the spacecraft and trimming its orbit in a complex gravitational field (e.g., when orbiting a satellite of one of the giant planets). In addition, the NEP systems currently under development for robotic missions may not scale up to provide the tens of megawatts necessary for expedited human missions to Mars.

In 2004, NASA conducted a limited set of parametric studies to examine the utility of the basic JIMO spacecraft design for other missions. The results of such studies are highly dependent on the assumptions made about the system and mission performance, which are, in turn, tightly linked. Figure 2.1 shows the results of a typical set of calculations to determine how the flight time and launch mass for a Neptune mission vary for different power values for the NEP system and the specific impulse of its ion thrusters. Representative solutions from such calculations can be combined and plotted to show the scaling relationships between mission metrics such as transit time, total launch mass, reactor power, propellant mass, and delta-V (Figure 2.2).[a]

These parametric studies had mixed results. The JIMO design envisioned when these calculations were performed in 2004 did appear suitable for some missions—e.g., a multiasteroid sample-return mission and a Saturn-Titan mission. But missions to other important solar system destinations—e.g., Neptune—did not appear feasible because the transit times were excessively long and launch masses excessively large. Studies performed in

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[a] The committee cannot verify the results of these calculations because specific assumptions—e.g., mass-to-thrust ratio, spacecraft mass, power-conversion efficiencies, and payload mass—were not provided.

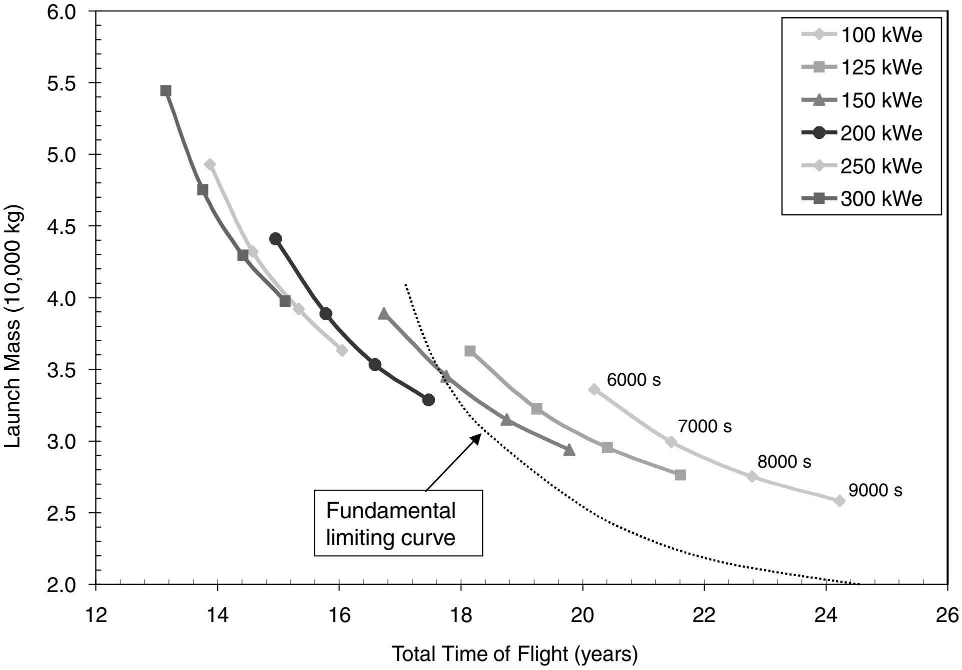
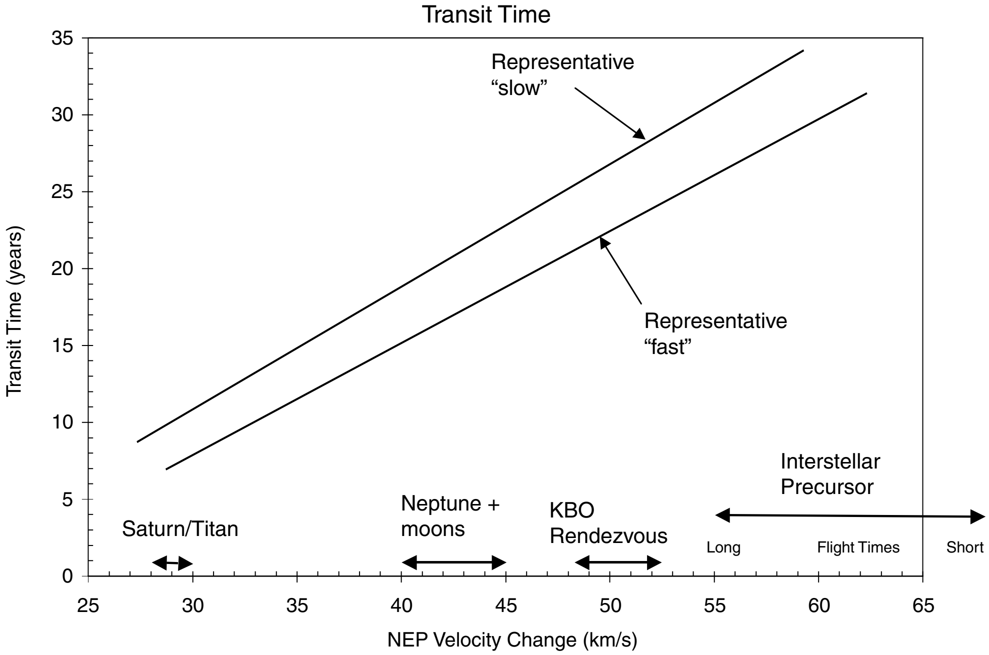


FIGURE 2.1 Calculations showing how the flight time and launch mass for a Neptune mission vary for different values for the power of the nuclear-electric propulsion (NEP) system and the specific impulse of its ion thrusters. Thus, for example, to achieve a transit time of 13 years requires a 300-kWe NEP system powering ion thrusters with a specific impulse of 6,000 seconds, and the resulting spacecraft has a launch mass of almost 55,000 kg (i.e., almost 10 times the mass of Cassini). The results of such calculations are highly dependent on assumptions made about the design characteristics of the spacecraft, its propulsion system, and its mission. Thus, the assumptions inherent in these particular calculations appear to be incompatible with a transit time of less than 12 years or a launch mass of less than 20,000 kg. The results plotted here assume performance characteristics derived from a particular design for the Jupiter Icy Moons Orbiter spacecraft, and they assume that the spacecraft is launched from Earth with a C3 = 0 km^2s^{-2}. Solutions to the right of the fundamental limiting curve are consistent with the technology under consideration for JIMO. No allowance is made for performance enhancements such as planetary gravity-assist maneuvers. Representative solutions from families of such calculations can be combined and plotted to show the scaling relationships between important mission metrics, such as launch mass, for a broad variety of missions, as indicated in Figure 2.2. Illustration courtesy of Lennard Dudzinski, NASA.

2005, which were based on the expected performance of the Prometheus Baseline (PB) 1 spacecraft design and included performance enhancements (e.g., Jupiter gravity assists) not previously considered, revealed a somewhat better performance. This performance is, however, still below that of conventional chemical propulsion systems (Table 2.1).

Roughly speaking, the performance of a nuclear propulsion system can be measured by the ratio α of the initial mass in orbit to the power embodied in the outgoing propellant. For the NEP system proposed for JIMO and follow-on mission, α is between ~250 and 300 kg/kW. For a long mission to the outer solar system, the transit time varies roughly as the cube root of α.[8] The effects of this relationship can be demonstrated by looking at three examples:

1. To reduce the transit time to Neptune from 13–15 years to 10 years (as required for the Neptune-Triton System Explorer mission described in Box 6.5) will require reducing α from ~250–300 to ~75–140. This improvement in efficiency is probably achievable with current technology.[9]



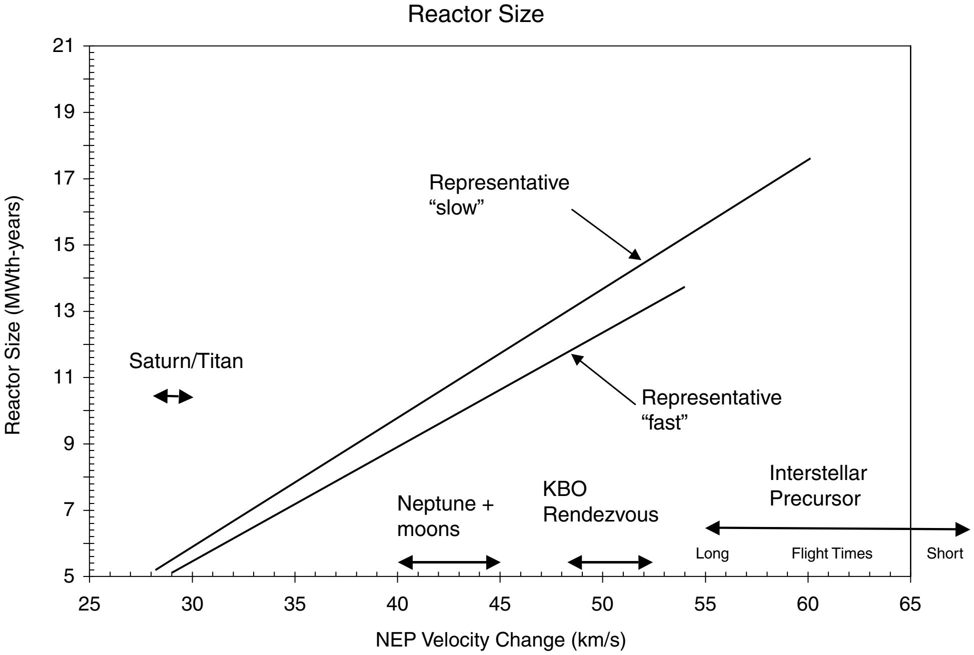
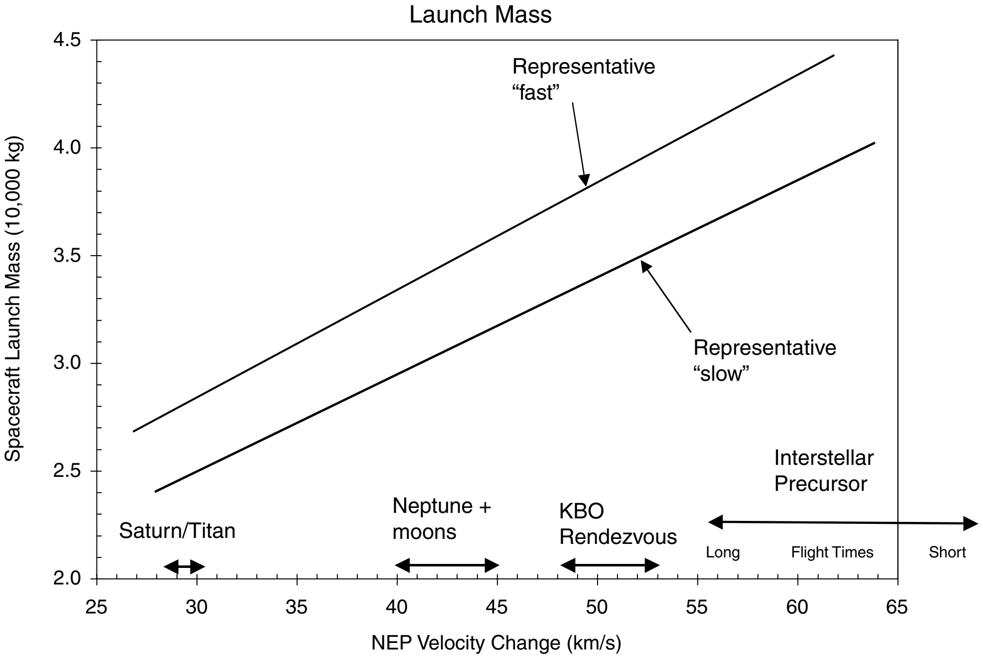


FIGURE 2.2 Results of parametric studies (such as those shown in Figure 2.1) can be combined and plotted to understand how the velocity change (delta-V) needed to undertake four representative missions to the outer solar system scales with important mission metrics such as *(clockwise from upper left)* transit time, launch mass, propellant mass, and reactor size. The solid lines circumscribe solutions characterized by representative fast and slow transit times. These plots clearly show that the particular spacecraft design characteristics embodied in these calculations are not well suited to distant outer solar system missions because of excessively large launch masses, long transit times, etc. The illustrations are simplified versions of plots supplied by Lennard Dudzinski, NASA.


Launch Mass
Spacecraft Launch Mass (10,000 kg)
4.5
4.0
3.5
3.0
2.5
2.0
Representative "fast"
Representative "slow"
Interstellar Precursor
Neptune + moons
KBO Rendezvous
Saturn/Titan
Long
Flight Times
Short
25
30
35
40
45
50
55
60
65
NEP Velocity Change (km/s)

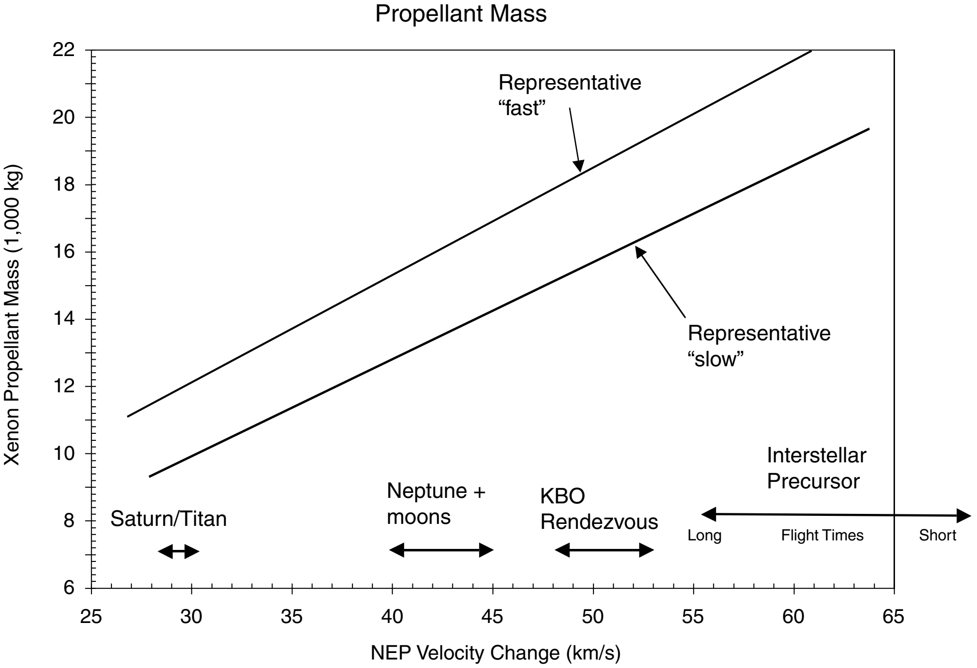

Propellant Mass
Xenon Propellant Mass (1,000 kg)
22
20
18
16
14
12
10
8
6
Representative "fast"
Representative "slow"
Interstellar Precursor
Neptune + moons
KBO Rendezvous
Saturn/Titan
Long
Flight Times
Short
25
30
35
40
45
50
55
60
65
NEP Velocity Change (km/s)

TABLE 2.1 Transit Times of NEP Spacecraft to Representative Objects in the Outer Solar System

Objective	NEP Transit Time 2004 Study (years)	NEP Transit Time 2005 Study (years)	Minimum/Maximum Transit Times Achieved So Far Using Conventional Propulsion Systems (years)
Jupiter	7–8	5–6	1.6 (Voyager 1)/6.3 (Galileo)
Saturn	9–10	7–8	3.3 (Voyager 1)/6.5 (Pioneer 11)
Neptune	18–20	13–15	12.0 (Voyager 2)
Kuiper Belt object	22–24	17–19	[9.5 to 15.0 (New Horizons)][a]
200 AU	~30	n/a[b]	n/a

[a] Assuming a successful Jupiter flyby in February 2007 and a Pluto flyby in July 2015.

[b] The 20+ year transit time exceeds the PB 1 design lifetime, and the mission's delta-V requirements may demand that the spacecraft be redesigned to increase the size of the xenon tank and/or the ion thruster's throughput capacity.

2. To reduce the transit time for a mission to the outer heliosphere from 30 years to 15 years will require reducing α from ~250–300 to ~30–40. Although such a specific mass is below levels offered by current technologies (~70 kg/kW), such a reduction might be achievable.[10,11]

3. To reduce the heliospheric flight time still further to 10 years will require a propulsion system with an α of ~10. This is probably beyond the bounds of existing technology and may well require a radically new technical approach.

Nuclear-Thermal Propulsion

Nuclear-thermal propulsion (NTP) systems produce propulsion by exhausting reactor coolant directly through a nozzle. These systems typically employ cryogenic hydrogen as the propellant and must be designed to operate at an exhaust gas temperature >2,200 K. However, NTP systems typically have short operation times (under 2 hours for human missions to Mars, for example). NTP systems have higher temperature requirements for fuel and structural materials than do NEP systems, but they have the potential to provide the high thrust needed for faster human missions to Mars.[12,13] NTP systems may also be suitable for some robotic missions, but few studies of the relevant trade-offs have been performed comparing NTP to NEP for robotic missions, and development efforts for robotic missions are focused on NEP systems.

Roughly 95 percent of the thermal energy generated in the reactor of an NTP system is vented in the exhaust, which eliminates the need for large radiators. The United States built and ground-tested several NTP systems during the NERVA/Rover program in the 1960s (see Appendix A for details). More than 23 engine tests were performed at the Nevada Test Site demonstrating a specific impulse of 850 seconds (Figure 2.3), peak temperatures of 2,550 K, operation for more than 1 hour, multiple restarts, and the safety of various accidental failure modes. It should be noted that the open-air testing of an NTP system and the associated venting of radioactive materials are no longer permissible.

An NTP variant is an indirect system that employs a heat exchanger to transfer thermal energy from the reactor primary coolant to the hydrogen propellant. A potential advantage of such a system is that the exhaust plume is far less likely to be contaminated with fission products, which is an issue with a direct system.

Bimodal Systems

Bimodal systems produce both propulsion via the normal direct hydrogen exhaust method and electricity via a separate power-conversion loop. The engines tested in the Rover/NERVA programs had design features allowing a secondary closed-loop, electric power production system, although electric power was never generated in the tests. Compared with either a pure NTP or NEP system, the bimodal concept places the greatest demand on the nuclear fuel, because the fuel in a bimodal system must operate in a high-temperature mode for a short duration for

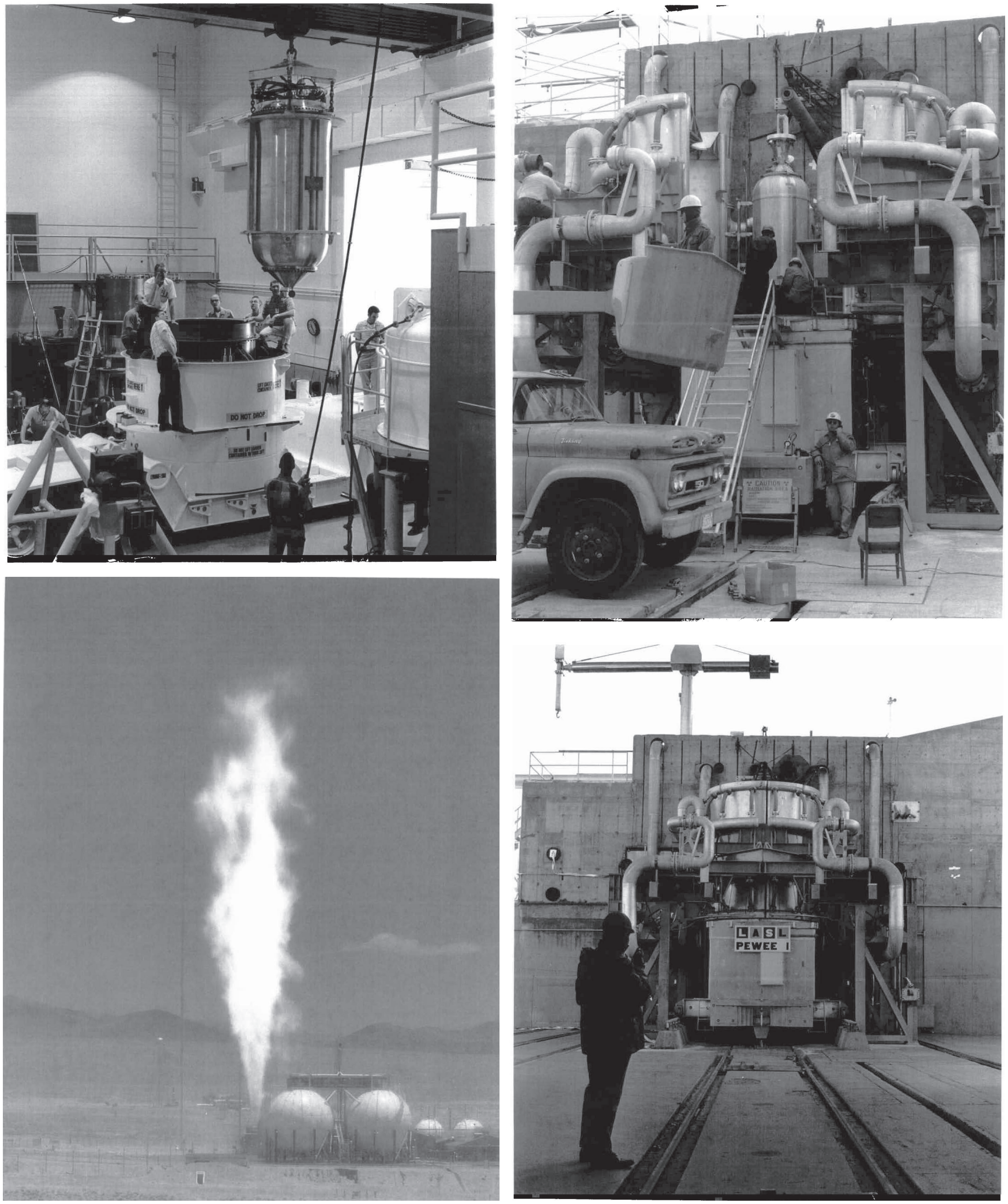


FIGURE 2.3 This sequence shows *(clockwise from top left)* the assembly and test firing of the Pewee nuclear-thermal rocket engine in 1968. The Pewee had 500-MW thermal power and would have had a thrust of 15,000 pounds at a specific impulse of 850 seconds. The Pewee engine was intended for use on a tug that would ferry supplies between Earth orbit and lunar orbit to support a lunar base. Courtesy of Stephen Howe, Los Alamos National Laboratory.

"rocket" thrusting, and then in a low-temperature mode for a long duration for "NEP" thrusting and/or while supplying power for the avionics, communications, and life-support systems. The bimodal operation offers the fastest trip times for high delta-V missions but will require significant testing and demonstration to validate fuel performance.

Surface Power Systems

Surface power systems are those designed to produce electricity for use on the Moon and Mars. Electrical power requirements may range from a low of between several kilowatts and tens of kilowatts for robotic missions, to between 50 kilowatts and 100 kilowatts for human outposts. Surface power systems may share much technology with NEP systems but must be designed to undergo entry, descent, and landing and to withstand gravitational, chemical, atmospheric, and thermal environments very different from those to which in-space systems are exposed. Power-conversion concepts include thermoelectric, Stirling, Brayton, Rankine, and a variety of other options that are more technologically advanced, but less mature.

THE IMPORTANCE OF STUDIES OF TRADE-OFFS

NASA missions enabled by nuclear propulsion will, in general, require high delta-V, fast transit times, or large amounts of electric power at the destination. To determine the benefits of nuclear propulsion for such missions requires that trade-off studies be conducted on a "level playing field." Various propulsion options need to be compared using metrics such as initial mass in low Earth orbit, launch requirements, or transit time to primary destination. Without such a series of comprehensive studies of trade-offs, it is not possible to demonstrate quantitatively where nuclear systems would be most enabling. Trade-offs between chemical systems, NEP systems, NTP systems, and bimodal systems are needed for missions requiring a wide range of delta-V. These studies should consider both robotic missions to the outer planets and human missions to the Moon or Mars. Furthermore, these studies should incorporate the impact on the systems of requiring risk mitigation through the use of redundant subsystems and extensive ground testing.

The estimated fiscal cost of developing a nuclear propulsion system is viewed as significant and could impact currently planned science missions.[b] However, nuclear propulsion will clearly enable missions in the future that cannot even be considered now. The identification of the benefit versus cost and the best technology development path to follow requires "apples to apples" comparisons among different technologies.

POTENTIAL TECHNOLOGY ISSUES TO BE ADDRESSED IN A PHASE II STUDY

The committee intends to investigate many potential technology issues associated with space nuclear reactors during Phase II of its study, including the following:

- *Testing and validation.* Reactors will be expected to operate as designed with a significant margin of safety and reliability. Although NTP and NEP systems would be operated only after they are launched into a safe orbit, the reactors must be ground-tested at full operational parameters (e.g., power and lifetime) to establish reliability. Existing concepts allow NTP systems, which will operate intermittently for short periods of time during an operational mission, to be tested for their full operational lifetime. In addition, NEP systems can be tested at full power. However, because NEP systems will operate continuously during multiyear missions, cost and schedule considerations will require that some type of accelerated life tests be developed, validated, and approved.

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[b] Despite repeated requests to NASA for information on projected costs for JIMO and other Prometheus-related activities, none were forthcoming. One estimate places the cost of JIMO at $10 billion. During testimony to the House Science Committee on June 29, 2005, NASA Administrator Michael Griffin commented that JIMO was "at $11 billion and counting for cost estimates before we got off the drawing board. . . ." For details see, for example, <www.spaceref.com/news/viewsr.html?pid=17157>, last accessed December 16, 2005. The committee cannot confirm or refute these estimates.

- *Reliability and unattended operation.* Reactors must operate under conditions in which communications are delayed from minutes to several hours, and be appropriately engineered for reliability and long-term drift in instruments.
- *Testing and evaluation.* There are potential gaps in the U.S. infrastructure for research, manufacture, and testing of space reactor systems. Areas of concern include the following:

—Fabrication process facilities for highly enriched uranium fuel and for lithium hydride components for the radiation shield subsystem;
—Irradiation facilities that can adequately simulate the fast neutron energy spectrum of space reactors;
—Facilities for integrated ground tests of space reactors; and
—Liquid metal facilities for component development and testing.

In addition, the presence of a nuclear reactor may introduce new issues in relation to the assembly, test, and launch operation processes that NASA currently uses:

- *High-temperature materials.* Mission requirements for higher performance and lower vehicle mass can be met only by high-temperature (>1,200 K) materials such as refractory alloys. These types of materials are not used in commercial nuclear power plants or research reactors. The database to support the design and qualification of these materials is only partially complete.
- *Availability of radioisotope power systems.* The long-term availability of plutonium-238 for radioisotope power systems for base electric power is assumed for mission planning but may become an issue if a proposed new production facility at the Idaho National Laboratory is not realized.[14,15]
- *Radiation shielding.* The protection of spacecraft electronics from the neutron and gamma-ray emissions of the reactor requires a complex radiation shield subsystem consisting of hundreds of components fabricated from lithium hydride, depleted uranium, and tungsten. The ease of component fabrication and the engineering design of the shield are issues to be addressed. Studies undertaken in the context of the SP-100 program (see Appendix A) suggest that the shield design was rather straightforward, but that misrepresents the actual situation.
- *Nuclear fuel development.* Development of the specialized nuclear fuels required for space reactors may be expected to require long time periods, and the research and development facilities and human expertise infrastructure will have to be rebuilt.
- *Launch considerations.* Reactor systems must be capable of being accommodated within the volume of launch-vehicle shrouds and must withstand the vibrations and acceleration forces associated with launch. Reactors must also be designed to mitigate the effects of severe accidents such as launch-pad explosions or events such as reentry into Earth's atmosphere.
- *Lunar and planetary entry and surface operations.* Issues with lunar and planetary entry might include heat management and rejection (for planets with an atmosphere) and ambient radiation from Van Allen belts (Jupiter), as well as gravity issues. Mars's oxidizing atmosphere may preclude the use of the refractory alloys currently under study for reactor systems for propulsion and lunar applications. The environment for lunar or planetary surface operations may also involve large variations in temperature and ubiquitous dust.
- *Systems integration.* Much more than with previous space nuclear power and propulsion development programs, the effective integration of systems will be a fundamental aspect of accomplishing a comprehensive program of robotic and human exploration. Issues that must be addressed include integration between and among the following:

—Reactor, power conversion, and propulsion systems;
—All spacecraft systems;
—Hardware and software systems;
—Astronauts and other human operators;
—The totality of individual missions; and
—Related missions.

REFERENCES

1. W. Mendel, ed., *Manned Mars Mission*, NASA M001, NASA, Washington, D.C., 1986.
2. T. Paine et al., *Pioneering the Space Frontier: The Report of the National Commission on Space*, Bantam Books, May 1986.
3. A. Cohen, *Report of the 90-Day Study on Human Exploration of the Moon and Mars,* NASA, Washington, D.C., November 1989.
4. T.P. Stafford, *America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative,* U.S. Government Printing Office, Washington, D.C., 1991.
5. D. Cooke et al., *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*, NASA Special Publication 6107, NASA Johnson Space Center, Houston, Tex., March 1997.
6. T.P. Stafford, *America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative*, U.S. Government Printing Office, Washington, D.C., 1991.
7. Radiation limits for human exploration outside low Earth orbit have not yet been established. Radiation limits for astronauts in low Earth orbit for blood-forming organs are 25 cSv per month, 50 cSv per year, and 40 to 300 cSv per career (depending on age and gender). See, for example, National Council on Radiation Protection and Measurement, *Radiation Protection Guidance for Activities in Low-Earth Orbit*, NCRP Report No. 132, NCRP, Bethesda, Md., 2001.
8. See, for example, P. Dimotakis, F. Dyson, D. Eardley, R. Garwin, J. Goodman, D. Hammer, W. Happer, J. Katz, C. Max, and J. Vesecky, "Interplanetary Travel: Nuclear Propulsion Prospects," presentation based on JASON-01-752 Summer Study for the NASA Office of Space Science, JASON Program, The Mitre Corp., McLean, Va., 2001, p. 8.
9. L.S. Mason, "A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts," NASA-TM 2001-210593, NASA Glenn Research Center, Cleveland, Ohio, 2001.
10. See, for example, P. Dimotakis, F. Dyson, D. Eardley, R. Garwin, J. Goodman, D. Hammer, W. Happer, J. Katz, C. Max, and J. Vesecky, "Interplanetary Travel: Nuclear Propulsion Prospects," presentation based on JASON-01-752 Summer Study for the NASA Office of Space Science, JASON Program, The Mitre Corp., McLean, Va., 2001, p. 8.
11. L.S. Mason, "A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts," NASA-TM 2001-210593, NASA Glenn Research Center, Cleveland, Ohio, 2001.
12. S.K. Borowski et al., "Nuclear Thermal Rocket/Vehicle Design Options for Future Missions to the Moon and Mars," AIAA-93-4170, American Institute of Aeronautics and Astronautics, Reston, Va., 1993.
13. S.D. Howe, B. Travis, and D.K. Zerkle, "SAFE Testing Nuclear Rockets Economically," *Proceedings of the 20th Space Technology and Applications International Forum (STAIF-2003),* M.S. El-Genk, ed., American Institute of Physics, Melville, N.Y., 2003.
14. W.J. Broad, "U.S. Has Plans to Again Make Own Plutonium," *The New York Times,* June 27, 2005, pp. A1 and A13.
15. See, for example, Office of Nuclear Energy, Science and Technology, U.S. Department of Energy, *Draft Environmental Impact Statement for the Proposed Consolidation of Nuclear Operations Related to Production of Radioisotope Power Systems*, DOE/EIS-0373D, U.S. Department of Energy, Washington, D.C., June 2005. Available at <http://www.consolidationeis.doe.gov/>, last accessed February 2, 2006.

3

Applications of Nuclear Power and Propulsion in Solar and Space Physics: Background

SCIENTIFIC AND PROGRAMMATIC CONTEXT

The Goals of Solar and Space Physics

What causes the complex and often violent activity on the nearest star, the Sun? What are the effects of solar activity on Earth and other planetary bodies, the interplanetary environment, and the local interstellar medium? How do the phenomena observed on the Sun and in the complex of plasma, energetic particles, and magnetic fields that fill the solar system relate to those seen in more distant astrophysical environments? These are some of the fundamental questions motivating research in solar and space physics. And although this research reflects the deep-seated human impulse to know and understand the workings of nature, the lessons learned also promise to yield important practical benefits in areas such as understanding the effects of global climate change and the impact of the solar-terrestrial environment on human technology.

As explained in the solar and space physics (SSP) decadal survey released in 2003, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*,[1] the scientific challenges to be addressed by the solar and space physics community in the coming decade are as follows:

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

High-Priority Missions in the SSP Decadal Survey

Overcoming these challenges will, as described in the SSP decadal survey, require a systems approach to theoretical, ground-based, and space-based research that encompasses the flight programs and focused campaigns of NASA, the ground-based and basic research programs of the National Science Foundation (NSF), and the complementary operational programs of other agencies such as the Department of Defense, the Department of Energy, and the National Oceanic and Atmospheric Administration. Elements of this program consist of large (>$400 million), medium (between $250 million and $400 million), and small (<$250 million) space- and ground-based projects backed up by theoretical, computational, and modeling activities and related research and data-analysis programs.

The SSP decadal survey identified only one large (>$400 million) program, the Solar Probe, a spacecraft intended to study the heating and acceleration of the solar wind. It will do this through in situ measurements and some remote-sensing observations during one or two passes through the innermost region of the heliosphere (i.e., the region from ~0.3 AU to as close as 3 solar radii above the Sun's surface).

In addition, the SSP decadal survey selected nine moderate-cost ($250 million to $400 million) projects as being especially important. These are as follows, in priority order:

1. *Magnetospheric Multiscale.* A four-spacecraft cluster to investigate magnetic reconnection, particle acceleration, and turbulence in magnetospheric boundary regions.
2. *Geospace Network.* Two radiation-belt mapping spacecraft and two ionospheric mapping spacecraft to determine the global response of the geospace environment to solar storms.
3. *Jupiter Polar Mission.* Polar-orbiting spacecraft to image the aurora, determine the electrodynamic properties of the Io flux tube, and identify magnetosphere-ionosphere coupling processes.
4. *Multispacecraft Heliospheric Mission.* Four or more spacecraft with large separations in the ecliptic plane to determine the spatial structure and temporal evolution of coronal mass ejections and other solar-wind disturbances in the inner heliosphere.
5. *Geospace Electrodynamic Connections.* Three to four spacecraft with propulsion for low-altitude excursions to investigate the coupling among the magnetosphere, the ionosphere, and the upper atmosphere.
6. *Suborbital Program.* Sounding rockets, balloons, and aircraft, equipped with advanced instrumentation, to perform targeted studies of solar and space physics phenomena.
7. *Magnetospheric Constellation.* Fifty to 100 nanosatellites to create dynamic images of magnetic fields and charged particles in the near magnetic tail of Earth.
8. *Solar Wind Sentinels.* Three spacecraft with solar sails positioned at 0.98 AU to provide earlier warning than L1 monitors and to measure the spatial and temporal structure of coronal mass ejections, shocks, and solar-wind streams.
9. *Stereo Magnetospheric Imager.* Two spacecraft providing stereo imaging of the plasmasphere, ring current, and radiation belts, along with multispectral imaging of the aurora.

The small, space-based projects identified by the SSP decadal survey were as follows, in priority order:

1. *L1 Monitor.* Continuation of solar-wind and interplanetary magnetic field monitoring, in support of Earth-orbiting space physics missions;
2. *Solar Orbiter.* Instrument contributions to a European Space Agency spacecraft that periodically corotates with the Sun at 45 solar radii to investigate the magnetic structure and evolution of the solar corona; and
3. *University-Class Explorer.* Revitalization of the so-called UnEx line of PI-led missions designed to provide frequent access to space for focused research projects.

Recent Scientific Developments

Major discoveries and significant trends since the release of the SSP decadal survey in 2003 can be summarized under the following headings:

- The Sun, the inner heliosphere, and space weather;
- The outer heliosphere;
- Planetary magnetospheres; and
- Basic physical processes.

The Sun, the Inner Heliosphere, and Space Weather

In October–November 2003, the most intense solar flares ever detected by spacecraft occurred, saturating the Geostationary Operational Environmental Satellite (GOES) soft x-ray detectors. The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), a Small Explorer mission, imaged, for the first time, flare gamma-ray line emissions produced by energetic ions at the Sun. The fast coronal mass ejections (CMEs) and shock waves associated with these flares accelerated solar energetic particles (SEPs) to relativistic energies in the inner heliosphere. The numbers of SEPs observed at 1 AU by the Advanced Composition Explorer are surprisingly similar to the numbers inferred by RHESSI for energetic particles at the Sun. These CMEs and shock waves then propagated outward and were observed by all operating spacecraft in the heliosphere, including Cassini, Ulysses, and Voyager. In late July 2004, Earth's radiation belts were pumped up to the highest levels ever observed, with relativistic (>2 MeV) electron fluxes, several times the maximum fluxes recorded during the last >18 years. These new observations provided a severe test of researchers' understanding of the interconnections of space weather and how solar effects are manifested throughout the heliosphere and in Earth's magnetosphere.

Missions currently under development, including the Solar Dynamics Observatory and the Solar Terrestrial Relations Observatory, promise to provide more important vantage points for understanding this complex system. The ultimate proof that solar effects can be accurately modeled throughout the global heliosphere will come from consideration of conditions at the inner boundary (obtained from the data collected by Solar Probe, which will also provide ground truth for remote solar observations), and propagating these effects to an interstellar probe in the outer heliosphere and the local interstellar medium. In 2004, NASA's Living with a Star program established a science and technology definition team for the Solar Sentinels mission that will explore how space weather is influenced by events on the Sun and conditions in the inner heliosphere. The long-term goal is to reach a level of understanding sufficient to accurately model solar effects throughout the global heliosphere.

The Outer Heliosphere

Observations by the Voyager spacecraft since the 2003 SSP decadal survey may be consistent with multiple observations of the termination shock of the solar wind. Although particle spectra and composition appear consistent with a crossing into the shocked solar wind, the lack of magnetic and plasma wave signatures has led to controversy about how the observations should be interpreted. These new observations have shown that:

- Scientists are likely on the verge of definitively determining the size of the unshocked solar wind cavity; and
- The dynamics of the outer heliosphere remain a mystery and reinforce the SSP decadal survey's emphasis on characterizing this region far from the Sun and understanding how the heliosphere interacts with the very local interstellar medium (i.e., the region within some 2,000 AU of the Sun). These goals are further explored in the report of a recent NRC workshop.[2]

Planetary Magnetospheres

The space environment of Jupiter has been probed with separate but simultaneous measurements by the Galileo and the Cassini spacecraft during the latter's flyby of that planet in late 2000. In showing that interplanetary shocks drive magnetospheric dynamics, these measurements have reemphasized the need for multiple-point space physics measurements at the outer planets. In addition, combining auroral imaging with in situ measurements has yielded new information on how shocks affect auroral emissions. Finally, the new technique of neutral atom imaging for obtaining global views of space physics environments—which was pioneered on Imager for Magnetopause-to-Aurora Global Exploration (the first Midsize Explorer mission) spacecraft at Earth—provided new insight on the jovian system structure (as seen from Cassini during its flyby) and promises even more insight into the complexities of the Saturn system as the Cassini orbital tour evolves. The continuing observations of Sun-grazing comets are changing perceptions of the importance of the origins and evolution of dust in the inner heliosphere, a topic that is being reviewed during the development of the Solar Probe.

Basic Physical Processes

Recently, the Polar and the Wind spacecraft made the first observations inside the magnetic reconnection regions at the dayside magnetopause and in the distant magnetotail, allowing for in situ study of the fundamental plasma process, which controls the dynamics of the magnetosphere (and, by extension, solar flares and other astrophysical phenomena). These spacecraft penetrated the ion diffusion region (and possibly the electron diffusion region) and detected the Hall fields that are predicted by theory and simulation. Multispacecraft observations with much higher temporal resolution and accuracy, such as those planned for the Magnetospheric Multiscale mission, are required to understand the microphysics controlling this process.

Programmatic Context

The scientific goals of the solar and space physics community, as articulated in the SSP decadal survey, remain essentially unchanged by the recent discoveries just outlined. There has, however, been a major change in the direction of U.S. space activities as a result of policy responses to President Bush's Vision for Space Exploration, announced on January 14, 2004.[3,4] This new exploration initiative comes at a time when the solar and space physics community is rapidly developing a connected view of deep-space radiation systems. Researchers are working to understand the network of space radiation environments, to develop capabilities to warn of radiation hazards, to understand how space radiation has affected Earth's climate and biosphere in the past, and to project the effects of these radiation environments on future global sustainability.

Solar and space physicists are striving to understand how steady and punctuated ejections of matter and energy from the Sun propagate through the solar system and in many cases form shocks that cause large transient changes in the radiation environments at Earth and other planets. Researchers are also learning how the conditions in the local interstellar medium control the radiation environment in the solar system and may change the solar system's radiation environment in the future. This development will be critical for understanding not only the radiation environment of interplanetary space, but also the radiation system of Earth and its impact on global sustainability. Key to all of these developments are spacecraft observations of solar phenomena and their effects both at Earth and at many other locations throughout the solar system.

Some researchers would even argue that an inability to monitor the solar system's space environment significantly threatens the viability of the President's exploration initiative. Indeed, without the ability to assess, monitor, and develop advanced warning capabilities for space radiation hazards, extended voyages by crews beyond low Earth orbit may not be realizable.[5] A substantial improvement in understanding of the interconnectivity of the solar system radiation environment will enhance the ability to provide advanced warning of radiation hazards, and will provide more detailed knowledge of the radiation environments near the surfaces of the Moon, Mars, and other planets in the solar system. Because of the essential role that solar and space physics is likely to play in supporting the exploration initiative, the discipline's scientific priorities are being reexamined and a strategy is being developed for the solar and space physics community to engage fully in this initiative.[6]

At issue in this report are the new space science territories that will be opened up by the availability of nuclear power and propulsion systems. Space physicists are familiar with radioisotope power systems (RPSs) from their use on spacecraft—e.g., Pioneer 10 and 11, Voyager 1 and 2, and Ulysses—and will likely make use of RPSs again on future missions such as the Solar Probe and the Interstellar Probe (see Chapter 4). In contrast, the use of fission reactors for power and propulsion is something new to the space science community. Although technologies such as nuclear-electric propulsion will likely open up new capabilities and enable types of missions not previously envisaged, this is likely to entail a programmatic cost. Given the budgetary pressures facing the solar and space physics community, advanced nuclear systems are likely to enhance research capabilities only if they do not displace the small and medium-sized missions that are so important both to the health and the vitality of the community and to the implementation of the exploration initiative.

IMPLEMENTATION AND TECHNIQUES

A variety of implementation features common to many solar and space physics missions are rather different from those typical of astronomical or planetary missions. The characteristics and requirements detailed below influence the application of fission reactors and RPSs to space physics missions as well as to many other aspects of mission design. Mission concepts highlighting some of these characteristics are described in Chapter 4. Features important for the implementation of solar and space physics goals include the following:

- *In situ observations are important.* Space physics has traditionally been dominated by in situ observation of solar, heliospheric, and magnetospheric phenomena. As the discipline has matured, the ability to access new environments near the Sun and in the solar system and beyond will become increasingly important. Nuclear propulsion systems clearly have a role to play in enabling access to observing locations not easily accessible using existing chemical propulsion systems. Another trend seen in recent years has been the development and increasing importance of remote-sensing techniques—for example, energetic neutral atom (ENA) imaging—as opposed to the in situ techniques that have traditionally dominated space physics. Space physics instruments do not, in general, require fine pointing accuracy or knowledge; generally a pointing knowledge of ~0.1° to 1° will suffice. In situ and remote-sensing instruments are prominent features of most, if not all, of the space physics mission concepts described in Chapter 4.
- *Mass, power, and data rates are modest.* There is considerable flexibility in the design of in situ sensors, and in many circumstances considerable progress can be made using instruments with modest mass and power requirements—generally less than ~10 kg and 10W, depending on the instrument—delivered to suitable orbits in the heliosphere. Although it is true that some investigations of microphysics occurring on short timescales demand high instantaneous data rates, the use of onboard data storage means that only low-to-moderate average data rates—say 10 kilobits per second (kbps)—have traditionally been used. On the other hand, processes such as cosmic ray modulation can be studied using data averaged over periods of days or longer, and require modest telemetry rates. Abundant electrical power from nuclear systems potentially opens up the possibility of using new types of instruments, such as those that actively probe extraterrestrial particle and field environments by the use of such techniques as incoherent scatter radar. The use of these and related approaches has, to date, generally been limited to terrestrial applications because the relevant instruments have very large power requirements. The availability of abundant power can also enable larger datasets to be returned to Earth than have typically been used in space physics experiments. One possible benefit of such improved data transmission rates is the ability to routinely sample all three electric and magnetic components of plasma waves, together with three-dimensional plasma distribution functions, rather than limited data subsets as is now typical. This complete set of measurements allows for direct determination of the source and the nature of wave-particle interactions such as sources of free energy for the waves or pitch-angle scattering of the charged particles by the waves. The ability to return complete datasets of this type and/or the inclusion of active instruments would likely be features of concepts such as the Neptune-Triton System Explorer mission (see Box 6.5).
- *Space physics experiments as secondary payloads.* The modest power, mass, and data rate requirements of most space physics instruments make them ideally suited for inclusion as secondary payloads on solar system exploration missions. Because many space physics investigations address interplanetary phenomena, the ability to conduct cruise-phase investigations on planetary missions has been particularly important for the development of this discipline. The ability of nuclear propulsion systems to transport comprehensive scientific payloads to diverse planetary environments (see Chapter 6) will necessarily increase the available opportunities to include secondary space physics instruments. Moreover, the potential development of a new generation of small RPSs (see Table 1.3) creates additional opportunities since they could, for example, be used to power small, deployable subsatellites.[7]

The Titan Express/Interstellar Pioneer concept (see Box 6.4) is an example of a mission in which an elaborate, secondary payload addressing space physics goals is piggybacked onto what is primarily a solar system exploration mission.

- *Diverse locations must be accessed.* Space physics instruments have to be delivered to widely separated and diverse locations, including the corona within a few solar radii of the Sun's surface, high heliographic latitudes, planetary magnetospheres, regions of interaction of the solar-wind plasma with planets and their satellites, regions of interplanetary space far removed from any planet, and the distant boundary of the heliosphere and beyond. Nuclear propulsion systems clearly have an important role to play in enabling access to observing locations that may be too difficult, if not impossible, to access using more conventional propulsion systems. The Interstellar Observatory (see Box 4.1), the Solar Coronal Cluster (see Box 4.2) and the Solar System Disk Explorer (see Box 4.3) are examples of missions using nuclear-electric propulsion systems to place scientific payloads in locations—e.g., the outermost and innermost regions of the heliosphere—that might be inaccessible otherwise.
- *Simultaneous multipoint measurements are advantageous.* It is commonly the case that simultaneous measurements at different locations are needed to resolve basic physical processes. Using similar instrumentation on multiple spacecraft to conduct simultaneous observations is enabling because it allows for the resolution of space-time ambiguities that are characteristic of single-point measurements, and it provides stereoscopic viewing for understanding inherently three-dimensional structure and dynamics. The results from the Cluster 2 mission indicate that the use of four probes can provide fundamentally new information through global views of large dynamical systems. For example, to resolve microphysical processes such as turbulence and reconnection requires measurements from multiple spacecraft separated by short distances in what typically are relatively compact three-dimensional regions. The Jupiter Magnetosphere Multiprobe Mission (see Box 4.4) is an example of a concept that combines the propulsive capacities of nuclear-electric propulsion with the capabilities of RPSs to enable multipoint observations of the global structure of the jovian magnetosphere.
- *Observing timescales are extensive.* Solar and space physics missions address phenomena that vary on a wide range of timescales from sub-millisecond plasma processes through decade-long variations in solar, heliospheric, and magnetospheric environments driven by the Sun's 22-year magnetic cycle. In general, a statistically significant description of such phenomena requires long-term observations with relatively few data gaps. These observations have most often been achieved using dedicated space physics missions—e.g., Interplanetary Monitoring Platform 8—and by cruise-phase operation of space physics payloads on planetary spacecraft such as Voyager 1 and 2. The demonstrated multidecade lifetimes of RPSs and the potentially long life of reactor-based power systems are ideally suited to support extended-duration observations.
- *Environmental factors must be controlled.* In situ measurements generally depend on sensitive instruments requiring careful control of interference and background. This has important implications for spacecraft design in areas such as control of spacecraft charging and protection from stray magnetic fields, electromagnetic emissions, and ionizing radiation. A nuclear-powered spacecraft may have requirements for long booms, shielding, or other measures to mitigate the potentially detrimental effects of the spacecraft's power source and other systems on its payload.

In summary, space physics observations are typically made using small, focused payloads that require limited spacecraft resources. However, experience indicates that the science return could benefit significantly from spacecraft with more robust mass, power, volume, telemetry, and propulsion capabilities enabled by nuclear power and propulsion systems. Solar and space physics priorities will also advance through joint initiatives between solar and space physicists and astronomers, astrophysicists, and planetary scientists.

REFERENCES

1. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.
2. National Research Council, *Exploration of the Outer Heliosphere and the Local Interstellar Medium*, The National Academies Press, Washington, D.C., 2004.

3. National Aeronautics and Space Administration, *The Vision for Space Exploration: February 2004*, National Aeronautics and Space Administration, Washington, D.C., 2004.

4. President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, U.S. Government Printing Office, Washington, D.C., 2004.

5. See, for example, National Research Council, *Scientific Prerequisites for the Human Exploration of Space*, National Academy Press, Washington, D.C., 1993, pp. 3 and 17–24.

6. See, for example, National Research Council, *Solar and Space Physics and Its Role in Space Exploration*, The National Academies Press, Washington, D.C., 2004.

7. See, for example, "Subsatellite Missions," section 2.5 of *Enabling Exploration with Small Radioisotope Power Systems*, R.D. Ableson, ed., JPL Publication 04-10, Jet Propulsion Laboratory, Pasadena, Calif., 2004.

4

Applications of Nuclear Power and Propulsion in Solar and Space Physics: Missions

MISSIONS ENABLED OR ENHANCED BY NUCLEAR POWER AND PROPULSION

Solar and space physics missions that can be enabled or enhanced by nuclear power and propulsion can be organized under four headings as follows:

- Existing missions endorsed by the solar and space physics (SSP) decadal survey[1] that are enhanced or enabled by nuclear-electric propulsion (NEP) technology;
- Existing missions endorsed by the SSP decadal survey that are enhanced or enabled by radioisotope power system (RPS) technology;
- Preliminary concepts for missions enhanced or enabled by NEP and RPS technologies; and
- Cross-disciplinary opportunities that are compatible with missions of primary interest to the solar system exploration community.

Decadal Survey Missions Enhanced or Enabled by NEP

Because most of flight missions discussed in the SSP decadal survey are designed to operate in near-Earth space, nuclear technologies would not be particularly enhancing or enabling. Two of the missions are, however, worth considering for implementation using NEP technologies. They are as follows:

- *Interstellar Probe*, a mission that would traverse the outer solar system and travel on into the vast expanse of gas, charged particles, dust, and magnetic fields that fills the volume of our galaxy. An enhanced version of this concept requiring NEP technologies is discussed below (see Interstellar Observatory).
- *Jupiter Polar Mission*, a high-priority, medium-class mission that could be implemented using NEP but whose scope would have to be significantly enhanced beyond what was considered in the SSP decadal survey, a possibility discussed below (see Jupiter Magnetospheric Multiprobe).

Interstellar Probe/Interstellar Observatory

Interstellar Probe. A mission to explore the distant outer solar system and the interstellar medium has been studied by the science community (Table 4.1) and discussed in National Research Council (NRC) reports for more than 25 years.[2-5] The scientific objectives of such a mission have been articulated by a variety of panels and studies, most recently by NASA's Interstellar Probe Science and Technology Definition Team (IPSTDT).[6]

The principal scientific goals of an interstellar probe are as follows:[7]

- Explore the outer heliosphere and the nature of its boundaries;
- Explore the outer solar system in search of clues to its origin;
- Explore the interaction of the solar system with the interstellar medium; and
- Explore the nature of the nearby interstellar medium.

Although an interstellar probe was rated as a high scientific priority by the SSP decadal survey, it was deferred

TABLE 4.1 Selected Studies of a Mission to the Interstellar Medium

Mission	Propulsion System	Reference
Interstellar Precursor	Nuclear-electric system to 400+ AU	a
Thousand Astronomical Units	Nuclear-electric system to 1,000 AU	b
Interstellar Probe (NASA's 1990 Space Physics Roadmap)	Chemical system sending a 1,000-kg spacecraft to 200 AU using powered solar flyby	c
Interstellar Probe (NASA's 1994 Space Physics Roadmap)	Chemical system sending a small spacecraft to 200 AU	d
Interstellar Probe (NASA's 1999 Space Physics Roadmap)	Solar-sail system to 200 AU	e, f
Realistic Interstellar Explorer	Jupiter flyby and use of a solar-thermal propulsion system at 4 solar radii to send a small payload to 1,000 AU in <50 years	g
Innovative Interstellar Explorer	Ion propulsion powered by radioisotope power systems used to send a small payload to 200 AU in 30 years	h

a. L.D. Jaffe, C. Ivie, J.C. Lewis, R. Lipes, H.N. Norton, J.W. Stearns, L.D. Stimpson, and P. Weissman, *An Interstellar Precursor Mission*, Jet Propulsion Laboratory, Pasadena, Calif., 1977.

b. M.I. Etchegaray, *Preliminary Scientific Rationale for a Voyage to a Thousand Astronomical Units*, JPL 87-17, Jet Propulsion Laboratory, Pasadena, Calif., 1987.

c. T.E. Holzer, R.A. Mewaldt, and M. Neugebauer, "The Interstellar Probe: A Frontier Mission to the Heliospheric Boundary and Interstellar Space," *Proceedings of the 22nd International Cosmic Ray Conference* (Dublin, Ireland) 2, 535, 1991.

d. R.A. Mewaldt, J. Kangas, S.J. Kerridge, and M. Neugebauer, "A Small Interstellar Probe to the Heliospheric Boundary and Interstellar Space," *Acta Astronautica Supplement* 35: 267–276, 1995.

e. P.C. Liewer, R.A. Mewaldt, J.A. Ayon, and R.A. Wallace, "NASA's Interstellar Probe Mission," p. 911 in *Space Technology and Applications International Forum-2000*, AIP CP504, M.S. El-Genk, ed., American Institute of Physics, Melville, N.Y., 2000.

f. R.A. Mewaldt and P.C. Liewer, "Scientific Payload for an Interstellar Probe mission," p. 451 in *The Outer Heliosphere: The Next Frontiers*, K. Scherer, H. Fichtner, H.J. Fahr, and E. Marsch, eds., COSPAR Colloquia Series 11, Pergamon Press, Amsterdam, 2001.

g. R.L. McNutt, Jr., G.B. Andrews, J. McAdams, R.E. Gold, A. Santo, D. Oursler, K. Heeres, M. Fraeman, and B. Williams, "A Realistic Interstellar Probe," pp. 431–434 in *The Outer Heliosphere: The Next Frontiers*, K. Scherer, H. Fichtner, H.J. Fahr, and E. Marsch, eds., COSPAR Colloquia Series 11, Pergamon Press, Amsterdam, 2001.

h. R.L. McNutt, Jr., J. Leary, M. Gruntman, P. Koehn, S. Oleson, D. Fiehler, R. Gold, S. Krimigis, E. Roelof, G. Gloeckler, and W. Kurth, "Innovative Interstellar Explorer: Radioisotope Electric Propulsion to the Interstellar Medium," *41st Joint Propulsion Conference*, AIAA-2005-4272, Tucson, Arizona, 2005.

from the final list of high-priority missions because its propulsion technology—a solar sail in the IPSTDT concept—was deemed not likely to become available in the coming decade.[8] Of all the missions studied in the SSP decadal survey, an interstellar probe has the highest priority for implementation via the use of a nuclear-electric propulsion system. This mission embodies exploration and is designed to redefine the frontier of modern space science by conducting a comprehensive set of in situ and remote-sensing observations as it travels from near-Earth space to the heliosphere and beyond into the local interstellar medium (see Figure 4.1).

Interstellar Observatory. A nuclear-electric mission concept, the Interstellar Observatory is a significant enhancement of the interstellar probe in two major aspects:

- The >100-kg instrument suite is substantially larger than the 25-kg payload defined in IPSTDT's implementation of an interstellar probe. Individual instruments will be much more capable because of the larger mass, power, and data transmission rates available with an NEP mission. As a result, the wide range of plasma parameters (e.g., density, temperature, and magnetic fields) the spacecraft is expected to encounter as it traverses the boundaries of the heliosphere can, for example, be addressed by in situ instruments with a wide dynamic range or by multiple instruments as required. Also, because of the greater data rate, the NEP mission will be able to return three-dimensional distribution functions for the plasma ions and electrons, whereas only reduced datasets could be

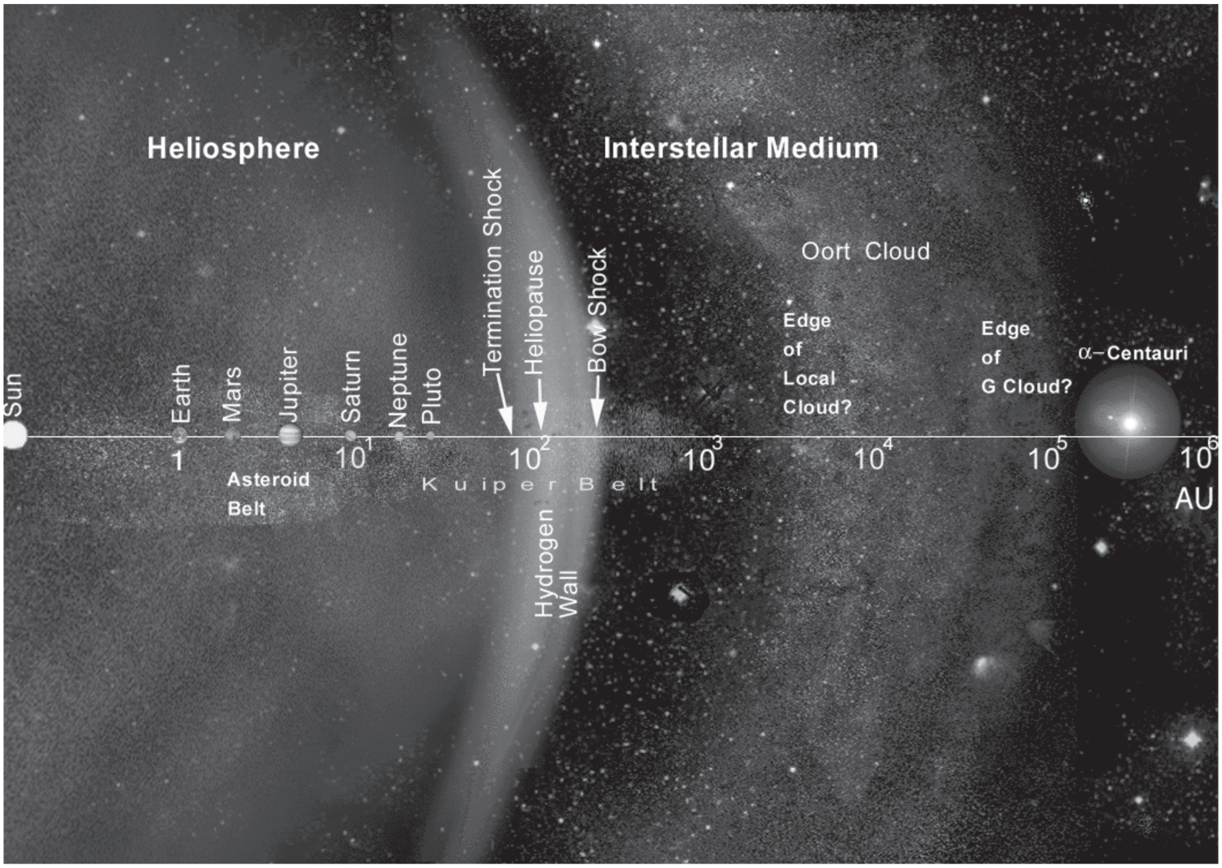

FIGURE 4.1 The scale of the local galactic neighborhood.

returned from a solar-sail mission. Similarly, spectrometers for ions, neutrals, and dust will have enhanced mass resolution.

- The Interstellar Observatory utilizes multiple subsatellites, released sequentially deep in the outer heliosphere—possibly between 50 and 80 AU—to provide redundancy, the ability to observe spatial structures of the heliosphere, and mitigation of radiation and contamination issues associated with the nuclear reactor.

For additional information about the Interstellar Observatory concept and a detailed discussion of its scientific goals, see Box 4.1 and Appendix B.

The Interstellar Observatory would also have practical benefits. Galactic cosmic radiation is a ubiquitous hazard for all voyagers beyond near-Earth space. Outside the protective shield of Earth's magnetic field and atmosphere, astronauts are fully exposed to galactic cosmic rays and, more insidiously, to secondary-radiation products whose effects can be amplified by the inappropriate choice of spacecraft shielding materials. Crew members can expect to accumulate more than half of their lifetime maximum allowable dose of radiation on a multiyear round-trip mission to Mars. It is well known that the flux of galactic cosmic rays waxes and wanes as the heliosphere responds to the Sun's magnetic cycle. But researchers currently have no detailed understanding of how the conditions in the local interstellar medium control the structure and dynamics of the heliosphere or of how this structure, in turn, regulates the radiation environment of the inner solar system. Enhanced understanding gained from data obtained with the Interstellar Observatory will be important for developing appropriate strategies for mitigating galactic cosmic radiation hazards.

Galactic cosmic radiation also has implications for global sustainability. Substantial changes in conditions in the local interstellar medium might significantly affect Earth's climate and the amount of radiation to which humans are exposed.[9] Five or six known episodes of large increases in cosmic ray intensity over the last 1,000 years appear to be associated with changes in the level of solar activity (e.g., the Maunder minimum) and with changes in terrestrial climate.[10,11] What is not known is whether these variations in cosmic radiation were caused by changes in the local interstellar medium.[12] Knowledge gained from use of the Interstellar Observatory will enhance understanding of the effects of the local interstellar medium on heliospheric structure and its shielding of galactic cosmic rays. By extrapolating physical knowledge of the interstellar interaction into the distant past and future, it may be possible to address issues concerning global sustainability.

Comparison of the Two Concepts. The interstellar probe appears, at first sight, to have two advantages over the NEP mission:

1. With the interstellar probe as conceptualized by the 1999 IPSTDT, the trip time is likely to be shorter. Preliminary, low-fidelity, parametric studies undertaken by Project Prometheus indicate that an Interstellar Precursor mission equipped with a propulsion system derived from the Jupiter Icy Moons Orbiter (JIMO) (i.e., not the Interstellar Observatory described above) would take some 20 to 30 years to reach a point 200 AU from the Sun. The IPSTDT solar-sail-powered interstellar probe mission was designed to travel the same distance in about 15 years. It must be emphasized, however, that the flight time of the Interstellar Observatory NEP system is heavily dependent on the assumptions made about the propulsion system and, in particular, the mass-to-power ratio of the nuclear reactor and its associated power-conversion system. NASA's parametric studies appear to have been based on conservative estimates of this key parameter. Similarly, techniques for reducing the flight time—e.g., Jupiter flybys—do not appear to have been considered.
2. The cost of the IPSTDT concept is likely to be much lower, although no reliable current cost information is available for the solar-sail mission, the JIMO-derived Interstellar Precursor mission, or the Interstellar Observatory. On the basis of an earlier Jet Propulsion Laboratory (JPL) study,[13] the SSP decadal survey estimated the cost of the solar-sail interstellar probe at ~$500 million.[14] Although NASA has released no cost estimates for JIMO, its cost has been crudely estimated at ~$10 billion.[15] It is unlikely that either the cost of the Interstellar Precursor mission studied by Project Prometheus or the Interstellar Observatory discussed here will differ significantly from the cost of JIMO itself. It must be emphasized, however, that a simple cost comparison between the nuclear and non-nuclear options is complicated by the very different instrument complements and scientific capabilities of the

BOX 4.1
Interstellar Observatory

Mission Type: NEP-class

Objectives:

- Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our galaxy and universe;
- Explore the outer solar system in search of clues to its origin and to the nature of other planetary systems;
- Explore the influence of the interstellar medium on the solar system, including its dynamics and evolution; and
- Explore the interaction between the interstellar medium and the solar system as an example of how a star interacts with its local galactic environment.

Implementation:

- Two RPS-powered subsatellites carrying identical payloads are released from an NEP-class ferry. Each has a science payload of 100 kg, a power requirement of 100 W, and a bit rate (direct to Earth) of 1,000 bps.
- The ferry may carry instruments that are insensitive to the reactor's radiation and particulate contamination and that can make use of a much higher data rate using the power from the reactor.
- Travel time to 150 AU (toward the nose of the heliosphere and into interstellar flow) is 15 years.
- The first subsatellite is released when the ferry has reached between 80 and 90 percent of its terminal velocity. The ferry then performs a small trajectory-deflection maneuver, continues to accelerate until its propellant is depleted, and then releases the second subsatellite. The diverging trajectories of the two subsatellites allow them to sample separate regions of the boundaries of the heliosphere and interstellar medium.

various options. The preliminary nature of the cost estimates for an interstellar probe, the ill-defined nature and capabilities of the different nuclear and non-nuclear implementations of this mission, and the fact that both nuclear-electric propulsion and solar sails have yet to be demonstrated in space strongly suggest that nuclear as well as non-nuclear mission concepts should be held as options in detailed trade-off studies.

Decadal Survey Missions Enhanced or Enabled by RPS

The missions selected in the SSP decadal survey that might be enhanced or enabled by RPS technologies are as follows:

- *Solar Probe.* A Science and Technology Definition Team established in 2003 is working to finalize the scientific objectives, spacecraft design, payload complement, and mission profile for the Solar Probe. The baseline launch date is October 2014.[16] An assumption of the ongoing studies is that the Solar Probe will make use of three of the multi-mission radioisotope thermoelectric generators (MMRTGs) that are being designed for use on the

Payload:

1. In situ package
   - Magnetometer;
   - Plasma and radio wave detectors;
   - Solar-wind plasma ion and electron detectors;
   - Pickup and interstellar ion mass spectrometer;
   - Interstellar neutral atom mass spectrometer;
   - Suprathermal ion mass spectrometer;
   - Anomalous and galactic cosmic ray element/isotope spectrometer;
   - Cosmic-ray electron and positron detectors;
   - Gamma-ray-burst detectors;
   - Dust composition detectors; and
   - Other possibilities, including instruments for studying suprathermal ion charge states, molecular analyzers for organic material, and detectors for cosmic-ray antiprotons.
2. Imaging package
   - Infrared spectrometer (3 to 100 μm) cooled to <100 K;
   - Energetic neutral atom imager;
   - Ultraviolet spectrometer; and
   - Other possibilities, including an imaging system to search for Kuiper Belt objects.

Some Issues for Study:

- Is the requirement for a transit time of 15 years consistent with the expected mass to power ratios of technically plausible NEP systems?
- What is the optimum strategy for deploying the subsatellites?
- Is it possible to use the ferry as a communications relay for the subsatellites?
- What are the impacts of using a planetary gravity-assist maneuver? A Jupiter flyby can add 10 to 12 km/s to the ferry's velocity relatively early in the mission and thus shorten the flight time, but timing this maneuver places constraints on when the spacecraft can be launched.
- Is the cosmic infrared background measurement feasible given the spacecraft's radiation background?
- Is it possible to use tracking data from such a mission to search for unknown matter concentrations in the heliosphere as well as dynamical manifestations of new gravitational or other physics?

Mars Science Laboratory in 2009. The Solar Coronal Cluster, a possible follow-on to the Solar Probe, is discussed in the next section.

- *Io Electrodynamics.* This is one of the missions deferred in the SSP decadal survey's list of priority missions for the coming decade, because it is a logical follow-on to the Jupiter Polar Mission.
- *Mars Aeronomy Probe.* Designed to determine how Mars's upper atmosphere is influenced by the solar wind, this high-priority mission was deferred by the SSP decadal survey for implementation in the coming decade. A solar-powered version has been thoroughly studied and can be readied for flight without much further development. The exact enhancing or enabling role of RPS technologies for this mission requires much more study and is not discussed further here.
- *Venus Aeronomy Probe.* Designed to determine how Venus's upper atmosphere is influenced by the solar wind, this high-priority mission was also deferred by the SSP decadal survey for implementation in the coming decade. The exact enhancing or enabling role of RPS technologies for this mission requires much more study and is not discussed further here.

Preliminary Concepts for Missions Enabled by NEP and RPS Technologies

What missions besides the Interstellar Probe/Interstellar Observatory might be uniquely enabled or greatly enhanced by nuclear power and propulsion technologies? The limited scope of this study precludes a definitive answer. Distinguishing whether or not a concept is uniquely enabled, enabled, significantly enhanced, or enhanced by nuclear systems will require extensive additional study. Rather, the committee has attempted to identify some preliminary concepts for missions that it believes are plausibly enhanced or enabled by the use of nuclear technologies.

To stimulate discussion in the solar and space physics community and, in particular, to further identify the technological challenges inherent in developing nuclear power and propulsion capabilities, the committee outlines three preliminary mission concepts in some detail. The scientific objectives of these concepts and the means by which they might be addressed in the context of missions utilizing nuclear power and propulsion systems are described in Boxes 4.2 through 4.4. The committee emphasizes that it does not give these missions any priority above any other missions considered here or elsewhere.

- *Solar Coronal Cluster.* The Sun's complex magnetic fields are highly dynamic. Large amounts of energy are stored in the strong magnetic fields, which periodically undergo massive reorganization, eject matter from the Sun, and create shock waves that propagate through the interplanetary medium. As these waves and their associated energetic-particle squalls sweep through the solar system, they cause large transient changes in the radiation environments of Earth, the Moon, Mars, and the other planets. These space weather events can expose astronauts and their robotic surrogates to radiation at doses that can prove fatal in a day or less.

The space weather for the entire solar system originates in the inner heliosphere—the completely unexplored region <0.3 AU from the Sun. The proposed Solar Probe, which the Solar Coronal Cluster is to follow, will penetrate this region. It is, however, limited to one or two fast flybys, spending only 10 days or so within 0.3 AU and less than 2 days within 0.1 AU (20 R_{Sun}).[17]

The Solar Coronal Cluster consists of a large, observatory-class spacecraft in a circular heliosynchronous orbit (~35 R_{Sun}), supported by three smaller spacecraft in elliptical orbits, that would provide comprehensive imaging and spectroscopy of an active region over a sufficiently long period to follow the region's evolution over its entire life cycle. In situ instruments would be able to characterize and follow the evolution of the solar wind that originated from that region, including transients such as coronal mass ejections, since the interplanetary field would still be almost radial at 35 R_{Sun}. X-ray, gamma-ray, and neutron observations, both imaging and spectroscopy, would characterize the energetic electron and ion populations near the Sun, while other instruments would determine the characteristics of the energetic particles escaping from the region. See Box 4.2 for more details.

- *Solar System Disk Explorer.* Recent observations of the radial distribution of Kuiper Belt objects (KBOs) imply an apparent "edge" of the solar system at 50 AU.[18] The amount of material beyond 50 AU, as extrapolated from that contained within the planets, is well below the level that can be observed from Earth. This has raised many questions about the collisional evolution of the solar system. Because the present dust in the Kuiper Belt is thought to be the result of the collisions between KBOs, a study of the dust would complement the study of KBOs. More details about this mission are given in Box 4.3.
- *Jupiter Magnetosphere Multiprobe Mission.* The relative importance of internal and external forcing—e.g., forcing driven by planetary rotation and by the solar wind, respectively—on astrophysical plasma and nebular systems is an important issue in space physics. In addition to its relevance to the three-dimensional structure and dynamics of planetary magnetospheres and the generation of auroras, the balance between external and internal forcings has practical significance. The dynamic radiation environment at other planets poses significant risks for future exploration and habitation. The Jupiter Magnetosphere Multiprobe Mission (see Box 4.4 for details) is designed to provide the most complete study of the largest and most complex radiation environment of any planet in the solar system. Similar missions can be envisioned for other planets with magnetospheres.

BOX 4.2
Solar Coronal Cluster

Mission Type: NEP-class

Objective: Understand the connections between the Sun and the heliosphere and the origins of space weather by addressing the following issues:

- The source and evolution of solar flares;
- The initiation, propagation, and evolution of coronal mass ejections;
- The acceleration of solar energetic particles and, in particular, the roles played by inductive acceleration at the flare site and by shock waves driven by fast coronal mass ejections in the region ~2–40 R_{Sun};
- The origin and evolution of the low-heliolatitude solar wind and of solar-wind transients; and
- The heating of the corona.

Implementation:

- Four spacecraft in near-Sun orbits are released from an NEP-class ferry.
- One of four (possibly the ferry itself) is in a co-rotating (~35 R_{Sun}) circular orbit, with mass ~1,000 kg, power ~2,000 W, and data rate 20,000 bps.
- The other three spacecraft are in elliptical orbits (~4–30 R_{Sun}, and with a range of inclinations desired, but no higher than ±30º) with mass ~500 kg/each, power ~1,000 W, and data rate 10,000 bps.

Payload:

1. In situ measurements:
    - Energetic particles and plasma; and
    - Magnetic fields and plasma waves/radio waves.
2. Remote sensing/imaging:
    - Hard x-ray;
    - Gamma ray;
    - Neutron;
    - Extreme ultraviolet/soft x-ray; and
    - Coronagraph.

Some Issues for Study:

- Does the design of the spacecraft's radiator system place any fundamental limits on the operation of an NEP system inside the orbit of Mercury?
- What are the relative advantages and disadvantages of using NEP as opposed to solar-electric propulsion?

Cross-Disciplinary Missions Enabled by NEP Technologies

NEP-class missions to the magnetospheres of Saturn, Uranus, and Neptune would allow system-wide studies of these complex environments to a degree not possible with conventional power and propulsion. This enhanced capability is due, in large part, to the greater power, data volume, and payload mass afforded by nuclear-electric propulsion.

BOX 4.3
Solar System Disk Explorer

Mission Type: NEP-class

Objectives: Study the collisional evolution of the solar system by conducting complementary observations of dust and Kuiper Belt objects in order to address the following issues:

- The state and evolution of the Kuiper Belt and outer solar disk;
- The composition of outer heliospheric and interstellar grains and the implications for the current state of the local interstellar medium and origin of the solar system;
- The properties of the outer heliosphere; the interactions between the solar wind, KBOs, and outer heliospheric grains and implications for the formation and evolution of solar and stellar disks;
- The nature of the organic material in the outer heliosphere; and
- The global distribution of mass in the Kuiper Belt as probed through precision tracking.

Implementation:

- An NEP-class ferry deploys four spacecraft, two targeted to undertake flybys of KBOs and two to probe different parts of the solar disk beyond 50 AU.
- Each spacecraft targeting KBOs has a science payload of 200 kg, a power requirement of 200 W, and a bit rate of 2,000 bps (a Ka-band system with 20 W (radio frequency) through a 2-m high-gain antenna, transmitting to a 34-m ground station, can easily meet the data rate requirement). The pointing requirement will be rather tight, less than 0.1 degrees, and Deep Space Network (DSN) upgrades, such as the Next Generation DSN antenna arrays, would ease the requirements on the spacecraft.
- Each spacecraft going beyond 50 AU each has a science payload of 100 kg, a power requirement of 100 W, and a bit rate of 1,000 bps. Telecommunications is not a problem; a system like that for the KBO spacecraft will suffice.
- Travel time to 75 AU is 10 years.
- The KBO spacecraft, deployed at about 40 to 50 AU, will be targeted for high-speed flybys only, so that neither they nor the ferry will need to decelerate.

Scale is an additional argument for including studies of planetary magnetospheres on NEP-class missions. While the exact cost of JIMO and possible follow-on missions is not clear at this time, most observers expect them to be much more expensive than flagship-class spacecraft such as Galileo and Cassini. To justify such investments in missions to the far-flung regions of the solar system, the science return from these efforts must be commensurate with their cost.

NEP-class missions break the mold of traditional missions to the outer planets. The additional payload resources allow for studies of fundamental physical processes usually restricted to near-Earth missions. There has been great progress made in the study of the magnetospheres of the outer planets by using more limited measurements and then drawing analogies with fully instrumented measurements at Earth. However, with exotic sources of plasma and different sources of energy in outer-planet magnetospheres, these terrestrial analogies might break down, and it is likely that there are processes with no known terrestrial counterpart.

Some solar system exploration missions involve the delivery of satellites or entry probes to bodies in the outer solar system including planets, their moons, and KBOs. A reactor-powered bus used for delivering such spacecraft

- The outer heliosphere spacecraft will be deployed sequentially as in the Interstellar Observatory (see Box 4.1) to place them on diverging trajectories.

Payload:

1. In situ package
    - Magnetometer;
    - Plasma and radio wave detectors;
    - Solar-wind plasma ion and electron detectors;
    - Pickup and interstellar ion mass spectrometer;
    - Interstellar neutral atom mass spectrometer;
    - Suprathermal ion mass spectrometer;
    - Anomalous and galactic cosmic-ray element/isotope spectrometer;
    - Cosmic-ray electron and positron detectors;
    - Gamma-ray-burst detectors;
    - Dust composition detectors; and
    - Other possibilities, including instruments for studying suprathermal ion charge states, molecular analyzers for organic material, and detectors for cosmic-ray antiprotons (on the outer heliosphere spacecraft only).
2. Imaging package
    - Infrared spectrometer (on the outer heliosphere spacecraft only);
    - Energetic neutral atom imager (on outer heliosphere spacecraft only);
    - Ultraviolet spectrometer; and
    - Kuiper Belt object cameras (on the KBO spacecraft only).

Issues for Additional Study:

- Is the required transit time consistent with the expected mass to power ratios of technically plausible NEP systems?
- Can the KBO spacecraft be targeted so that each can study multiple targets?

could, in such cases, also carry a package of particles and fields instrumentation designed for space physics studies in the outer heliosphere (see Box 6.4 for an example of such a mission). Upon completion of the initial delivery phase of the mission, the bus could be re-aimed toward a selected direction in the heliosphere, possibly using a gravity assist from a planetary flyby.

TECHNOLOGY ENHANCEMENTS AND ISSUES

Nuclear power and propulsion systems offer benefits but also raise new technological issues. Although nuclear systems potentially offer expanded capabilities in a variety of areas (see the section “Implementation and Techniques” in Chapter 3), their background radiation highlights the need for technology development in such areas as high-bandwidth communications, radiation-hardened components, and radiation-tolerant detectors. The technology enhancements and issues associated with the use of nuclear power and propulsion systems in solar and space physics missions can be summarized under the following headings (in no particular order):

BOX 4.4
Jupiter Magnetosphere Multiprobe Mission

Mission Type: NEP-class

Objectives: Understand the dynamics of the jovian magnetosphere by addressing the following issues:[1]

- The relative importance of internal and external forcing on astrophysical plasma and nebular systems by comparing the magnetospheric response of Jupiter to solar-wind dynamics;
- How internal and external forcing establishes the three-dimensional structure of the jovian magnetosphere and its dynamics;
- The connection between Jupiter's aurora and distant regions of the magnetosphere; and
- The flow of mass and energy throughout the jovian magnetosphere, particularly the fate of iogenic plasma and gas at Jupiter.

Implementation:

- An NEP-class ferry carries multiple (three or more) independent, spin-stabilized spacecraft each with RPS power. Each has a scientific payload of ~50 kg.
- One subsatellite is dropped into a low-inclination, low-eccentricity orbit with a semi-major axis of about 15 R_J to monitor the middle magnetosphere and the outer edge of the Io torus.
- A second subsatellite is dropped into a low-inclination, high-eccentricity orbit with a semi-major axis of >80 R_J to monitor the outer magnetosphere and magnetotail.
- A third subsatellite is dropped into a high-inclination, high-eccentricity orbit to study the auroral regions.
- The fourth subsatellite, which could be the ferry itself, will monitor the solar wind at either the Sun-Jupiter L1 point or from a transfer orbit upstream of Jupiter.

Payload:

1. In situ package
   - Magnetometer;
   - Radio and plasma wave detectors (3-E components 1 Hz to 40 MHz, 3-B components 1 Hz to 20 kHz);
   - Instruments to characterize the three-dimensional properties of the ambient plasma (electrons, ions, with composition and charge state);
   - Instruments to characterize the three-dimensional properties of energetic particles, including composition and charge state; and
   - Dust-composition analyzer.
2. Imaging package
   - Auroral imagers (ultraviolet and infrared);
   - Io torus imager (ultraviolet); and
   - Energetic neutral atom imager.

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[1] Similar missions could be envisioned for the solar system's other gas planets.

- High-bandwidth communications;
- Multiple-spacecraft systems;
- Radiation-hardened components and radiation-tolerant detectors;
- New classes of instrumentation;
- Studies of trade-offs to assess alternative power and propulsion technologies; and
- Radioisotope power systems and nuclear-propulsion technologies.

High-Bandwidth Communications

Limited telemetry resources have traditionally restricted the volume of data reported from space physics measurements, resulting in the loss of high-resolution spectral, temporal, and spatial information. Many future studies (e.g., rapid solar imaging and studies of the microphysics of plasma structures) will drive the need for data with higher temporal and spectral resolution than has typically been required in the past. The high-bandwidth communications capacity needed to transmit such large data streams to Earth might be achieved by increasing a spacecraft's transmitting power via the use of nuclear systems. The demand for telemetry systems that can handle large data streams also drives expansion of the Deep Space Network.

Multiple-Spacecraft Systems

Nuclear power and propulsion technologies provide some interesting new options for implementing multiple-spacecraft missions. Important technological aspects of multiple-spacecraft scenarios include the following:

- The control of formation flying;
- The deployment of multiple subsatellites from a mother ship; and
- The creation of distributed networks linking identical spacecraft so that the loss of any one satellite does not interrupt the flow of information among the remaining satellites or to ground stations.

The concept of a mother-craft carrying multiple smaller spacecraft may be particularly well suited to nuclear power and propulsion systems. The Interstellar Observatory (Box 4.1), the Solar Coronal Cluster (Box 4.2), the Solar System Disk Explorer (Box 4.3), and the Jupiter Magnetosphere Multiprobe Mission (Box 4.4) are good examples of missions utilizing multiple-spacecraft systems.

Technology issues associated with multiple-spacecraft systems include power distribution, communications, optimization of spacecraft trajectories, tracking, propulsion, and coordination of high-time-resolution observations. Development of technologies and the systems analysis framework associated with multiple-spacecraft scenarios would substantially enhance more routine implementation of multipoint measurements.

Radiation-Hardened Components and Radiation-Tolerant Detectors

A general concern for both near-Earth and deep-space missions is that spacecraft subsystems, especially radiation-hardened electronics, are becoming more expensive to acquire and qualify for flight. This concern is heightened for missions utilizing nuclear systems, because radiation backgrounds may be elevated. The impact on a mission of the unavailability of radiation-hardened components, particularly spacecraft processors, includes increased cost and risk, change of scope, and schedule delays.

For processors in particular, a promising emerging technology is field programmable gate arrays (FPGAs). These devices are inherently faster and more flexible, and can be configured to be more radiation hard, than traditional computer chips. The development of flight-qualified electronic components and, in particular, more capable and radiation-hardened FPGAs would enhance measurement capabilities and alleviate the issues associated with the paucity of flight processors.

Use of advanced nuclear power and propulsion systems on both long-duration missions and missions to planets with harsh radiation environments requires radiation-tolerant detectors that can maintain sensitivity and spectral response without substantial increases in noise over the lifetime of a mission. Issues associated with these detectors include detector annealing, permanent detector damage, and activation of detector material or nearby components. Developing new detector materials and detection concepts, and understanding detectors' responses to and damage by radiation from advanced nuclear power and propulsion technologies, would enhance, and in some cases enable, the scientific return from missions in these radiation environments.

New Classes of Instrumentation

Exploitation of the emerging capabilities enabled by advanced nuclear power and propulsion systems for high-mass, high-power, and high-data-rate instrumentation suggests the need for a program equivalent to the High Capability Instruments for Planetary Exploration (HCIPE) program. Such a program could support the development of spacecraft-based instrument technologies with capabilities well beyond those of existing flight instruments. The primary goal of this program would be to develop a new generation of scientific instruments for solar and space physics exploration that could take advantage of the capabilities enabled by nuclear-electric power and propulsion. For example, an interstellar probe mission could benefit substantially from energetic neutral atom imagers with significantly higher sensitivity, angular resolution, and energy resolution than are currently available for flight. Other examples of instruments that could have increased capabilities with more resources than previously available include mass spectrometers, solar imagers, and active magnetospheric experiments. One such experiment, designed to study the motion of electrons trapped in a planetary magnetosphere, would be uniquely enabled by positron production, which is a unique property of operational nuclear reactors in a magnetospheric environment.[19] The Jupiter Magnetosphere Multiprobe Mission (Box 4.4) and the Neptune-Triton System Explorer (Box 6.5) are both examples of concepts that could benefit from the inclusion of new types of active magnetospheric experiments.

Studies of Trade-offs to Assess Alternative Power and Propulsion Technologies

Although enhanced propulsion capabilities are necessary to send more massive payloads to their destinations more quickly, the most appropriate means to achieve that end for individual missions remains unclear. At this time, for example, it is not possible to say definitively whether NEP-enabled missions such as the elaborate Interstellar Observatory (Box 4.1) or the less-elaborate Titan Express/Interstellar Pioneer (Box 6.4) are more appropriate means of addressing the science goals for the study of the outer heliosphere than are the non-NEP interstellar probes discussed in the SSP decadal survey. Therefore, the development of alternative power and propulsion technologies should continue in parallel with the development of nuclear technologies until such time as even-handed studies of trade-offs are able to draw clear distinctions between missions that embody different power and propulsion approaches to meeting the same science goals. Breakthroughs in the development of, for example, solar-sail technology may enhance or enable several of the missions identified in the SSP decadal survey.

Radioisotope Power Systems and Nuclear Propulsion Technologies

The solar and space physics community would greatly value development of a wide range of RPS technologies, including lighter and more efficient devices that could enhance a diverse set of missions, including the subsatellites deployed by the NEP missions described in this chapter (see Boxes 4.1 through 4.4). Advanced nuclear propulsion technologies would be most beneficial if they greatly reduced transit times to mission targets and significantly increased science payload capacities and capability. For these reasons, Project Prometheus is encouraged by the committee to expand the scope of power and propulsion technologies it is studying.

CONCLUSIONS

The new paradigm in space exploration enabled by nuclear power and propulsion should be highlighted by missions that engage broad, high-impact, and programmatically cross-cutting scientific themes. The exploration of the outer solar system and the local interstellar medium appears to present a particular opportunity to use nuclear technologies. Granted the limited scope of this present study, nevertheless it appears that the Interstellar Observatory concept is extremely compelling in that it would redefine the modern frontier of space science and address important issues in planetary science, solar and space physics, and, potentially, astronomy and astrophysics.

Important scientific objectives are enabled by advanced nuclear power and propulsion technologies, but the concepts addressing these objectives need to be studied in much more detail before the priority of these missions can be adjudicated. Ancillary developments in areas such as communications and spacecraft subsystems will be needed to allow full use of these technologies.

Although the solar and space physics community has made use of RPS in the past and will certainly utilize emerging RPS technologies, nuclear-electric propulsion enables a much different and larger class of missions. An appropriate strategy is to pursue nuclear propulsion technologies as long as they do not interfere with the current diversity of solar and space physics missions. Such diversity gives scientific breadth and depth to these pursuits and is essential for the long-term health and vitality of solar and space physics as a discipline.

REFERENCES

1. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.
2. Assembly of Mathematical and Physical Sciences, National Research Council, *Astronomy and Astrophysics for the 1980's*, National Academy Press, Washington, D.C., 1982.
3. National Research Council, *Space Science in the Twenty-First Century: Imperatives for the Decades 1995 to 2015—Solar and Space Physics*, National Academy Press, Washington, D.C., 1988, pp. 41–43.
4. National Research Council, *A Science Strategy for Space Physics*, National Academy Press, Washington, D.C., 1995, pp. 3, 37, 66, and 74.
5. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.
6. Interstellar Probe Science and Technology Definition Team, NASA, *Interstellar Probe: Exploring the Interstellar Medium and the Boundaries of the Heliosphere*, Jet Propulsion Laboratory, Pasadena, Calif.,1999, available only online at <http://interstellar.jpl.nasa.gov/> last accessed February 2, 2006.
7. National Research Council, *The Sun to the Earth—and Beyond: Panel Reports*, The National Academies Press, Washington, D.C., 2003, pp. 36–38.
8. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003, p. 78.
9. N.J. Shaviv, "The Spiral Structure of the Milky Way, Cosmic Rays, and Ice Age Epochs on Earth," *New Astronomy* 8: 39–77, 2003.
10. G.M. Raisaisbeck, F. Yiou, M. Fruneau, J.M. Loiseaux, M. Lieuvin, J.C. Ravel, and C. Lorius, "Cosmogenic ^{10}Be concentrations in Antarctic ice during the past 30,000 years," *Nature* 292: 825–826, 1981.
11. J. Beer, U. Siegenthaler, and A. Blinov, "Temporal ^{10}Be Variations in Ice; Information on Solar Activity and Geomagnetic Field Intensity," pp. 297–313 in *Secular Solar and Geomagnetic Variations in the Last 10,000 Years*, F.R. Stephenson and A.W. Wolfendale, eds., Kluwer Academic Publishers, Dordrecht, the Netherlands, 1988.
12. National Research Council, *The Astrophysical Context of Life*, The National Academies Press, Washington, D.C., 2005, pp. 20–21.
13. S.A. Gavit, "Interstellar Probe Mission Architecture and Technology Report," Internal document JPL-D-18410, Jet Propulsion Laboratory, Pasadena, Calif., 1999.
14. National Research Council, *The Sun to the Earth—and Beyond: Panel Reports*, The National Academies Press, Washington, D.C., 2003, p. 38.
15. Congressional Budget Office, *A Budgetary Analysis of NASA's New Vision for Space Exploration*, Congress of the United States, Washington, D.C., 2004, p. 22.
16. For more details about Solar Probe see, for example <sec.gsfc.nasa.gov/solarprobe/solarprobe.htm>.
17. For more details on Solar Probe see, for example, Applied Physics Laboratory and Jet Propulsion Laboratory, *Solar Probe: An Engineering Study*, NASA-Goddard Spaceflight Center, Greenbelt, Md., 2002. Available at <http://solarprobe.gsfc.nasa.gov/solarprobe_apl_study.pdf> last accessed February 2, 2006.
18. See, for example, J.X. Luu and D.C. Jewitt, "Kuiper Belt Objects: Relics from the Accretion Disk of the Sun," *Annual Reviews of Astronomy and Astrophysics* 40: 63–101, 2002.
19. See, for example, E.W. Hones, Jr., "On the Use of Positrons as Tracers to Study the Motions of Electrons Trapped in the Earth's Magnetosphere," *Journal of Geophysical Research* 69: 182–185, 1964.

5

Applications of Nuclear Power and Propulsion in Solar System Exploration: Background

SCIENTIFIC AND PROGRAMMATIC CONTEXT

The Goals of Solar System Exploration

How did the Sun's retinue of planets originate and evolve? How did life develop in the solar system? How do basic physical and chemical processes determine the main characteristics of the planets? These are some of the fundamental questions of solar system exploration that motivate planetary science, a discipline that encompasses the study of objects in our solar neighborhood, including planets similar to Earth and Jupiter; smaller bodies like asteroids, comets, and Kuiper Belt objects; and larger features such as planetary magnetic fields and magnetospheres. Increasingly, the field also includes the characterization of extrasolar planets. Planetary science tries to understand not only the basic physical properties of planetary bodies, but also the processes responsible for the formation and evolution of planets.

Solar system exploration pushes the frontiers of human knowledge to worlds beyond our planet, revealing a diversity of nature and processes that challenge current comprehension. The excitement of discovery and the challenge of exploration fuel the human spirit and inspire our imagination. We are born to be explorers. Our successful exploration answers old questions and raises new ones, challenging us to probe farther and deeper.

In 2001, the U.S. planetary science community initiated a major study to outline pressing scientific questions and prioritize future solar system exploration missions and programs. The results of their efforts are embodied in two volumes, *New Frontiers in the Solar System: An Integrated Exploration Strategy* (hereafter, the solar system exploration [SSE] decadal survey)[1] and a compilation of contributed papers published under the title *The Future of Solar System Exploration*.[2] As explained in the SSE decadal survey, the key scientific questions to be addressed in the coming decade are as follows:

- What processes marked the initial stages of planet formation?
- Over what period did the gas giants form, and how did the birth of the ice giants (Uranus, Neptune) differ from that of Jupiter and its gas-giant sibling, Saturn?
- How did the flux of objects impacting planetary bodies decay during the solar system's youth, and in what ways(s) did this decline influence the timing of life's emergence on Earth?
- What is the history of volatile compounds, especially water, across our solar system?

- What is the nature of organic material in our solar system, and how has this matter evolved?
- What global mechanisms affect the evolution of volatiles on planetary bodies?
- What planetary processes are responsible for generating and sustaining habitable worlds, and where are the habitable zones in the solar system?
- Does (or did) life exist in the solar system, beyond Earth?
- Why have the terrestrial planets differed so dramatically in their evolutions?
- What hazards do solar system objects present to Earth's biosphere?
- How do the processes that shape the contemporary character of planetary bodies operate and interact?
- What does our solar system tell us about the development and evolution of extrasolar planetary systems, and vice versa?

High-Priority Missions in the SSE Decadal Survey

Addressing these key questions will, as discussed in the SSE decadal survey, require a combination of large, medium, and small space- and ground-based projects backed up by theoretical and laboratory studies, and related research and data-analysis programs.

In response to ground rules set by NASA,[a] the SSE decadal survey prioritized spacecraft missions in large (>$650 million), medium (between $325 million and $650 million), and small (<$325 million) cost categories[b] and ranked non-Mars and Mars missions separately. Thus, the highest-priority large, non-Mars and Mars missions were, respectively:

- *Europa Geophysical Explorer.* An orbiter of Jupiter's ice-encrusted satellite to assess the nature and depth of its putative ocean; and
- *Mars Sample Return.* A program to return several samples of the Red Planet to Earth for studies to search for life, develop chronology, and define ground truth.

Priorities in the SSE decadal survey for medium-cost missions to destinations other than Mars were, in priority order, as follows:

1. *Kuiper Belt-Pluto Explorer.* A flyby mission of several Kuiper Belt objects, including Pluto/Charon, to discover their physical nature and understand their endowment of volatiles;[c]
2. *South Pole-Aitken Basin Sample Return.* A mission to collect and return to Earth samples from the solar system's largest and deepest impact basin, which pierces the Moon's crust and may expose the lunar mantle;[d]
3. *Jupiter Polar Orbiter with Probes.* A mission consisting of a close-orbiting polar spacecraft equipped with various instruments that also acts as a relay for three probes to make in situ measurements of the jovian atmosphere below the 100+ bar level;[e]
4. *Venus In Situ Explorer.* A mission to acquire and lift a core sample of Venus into the atmosphere for compositional analysis and to make simultaneous atmospheric measurements; and
5. *Comet Surface Sample Return.* A mission to return several pieces of a comet's surface to Earth for organic analysis.

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[a] These included the following: The Mars program was to be considered independently from the rest of the solar system; there would be no more than one large- and two medium-class missions per decade; only available technology could be considered; and the availability of new radioisotope power systems could not be assured within the decade 2003–2013.

[b] Missions were assigned to the various cost categories according to the best estimates available at the time the SSE decadal survey was drafted. Note that the cost categories used in the SSE decadal survey are not the same as those used in the solar and space physics decadal survey.

[c] Currently being implemented as New Horizons, the first mission in NASA's New Frontiers program.

[d] A version of this mission known as Moonrise was the runner-up in the competition NASA organized for the second New Frontiers launch opportunity.

[e] A version of this mission known as Juno was the winner of the competition NASA organized for the second New Frontiers launch opportunity.

Priorities for medium-cost missions to Mars in the SSE decadal survey were, in priority order, as follows:

1. *Mars Science Laboratory.* A lander to carry out sophisticated surface observations and to validate sample-return technologies;[f] and
2. *Mars Long-Lived Lander Network.* A globally distributed suite of landers equipped to make comprehensive measurements of the planet's interior, surface, and atmosphere.

Priorities in the SSE decadal survey for low-cost missions to destinations other than Mars were, in priority order, as follows:

1. *Discovery.* A continuing line of innovative, principal-investigator-led exploration missions, to be launched every 18 months; and
2. *Cassini Extended.* An extension of the planned operational life of the comprehensive, multidisciplinary Cassini orbiter mission at Saturn.

Priorities for low-cost missions to Mars were, in priority order, as follows:

1. *Mars Scout.* A continuing line of missions similar in concept to Discovery, to be launched at a rate of one for every other Mars-launch opportunity; and
2. *Mars Upper Atmosphere Orbiter.* A spacecraft dedicated to studies of Mars's upper atmosphere and plasma environment.

Recent Scientific Developments

In the short time since the completion of the SSE decadal survey, ongoing discoveries have not resulted in major changes in the recommended priorities. Several areas of current research do, however, have the potential for generating priority-altering major discoveries. Indeed, results from Cassini in the Saturn system (including Titan), as well as ongoing results from the Spirit and Opportunity rovers on Mars, present particular opportunities for major discoveries that could shift priorities and drive programmatic decisions. These possibilities and a few other promising research directions are examined in subsequent sections.

Exploration of Mars

The resilience of the rovers Spirit and Opportunity, and the wealth of data they have gathered on Mars, are opening a new chapter in scientists' understanding of the Red Planet's early history. Discoveries of stratigraphic layers, evaporite deposits, and mineral forms show clearly that Mars experienced a somewhat Earth-like warmer and wetter era.[3,4] Questions remain as to how this era came to be and how Mars changed to its current cold and dry climate.

Another significant set of results from Mars concerns the spectroscopic detection of methane in the planet's atmosphere by ground-based telescopes[5,6] and the Mars Express spacecraft.[7] Although the result obtained from Mars Express is still somewhat controversial, all three sets of observations indicate methane at concentrations of about 10 parts per billion (ppb). This is significant in that methane is unstable in the martian atmosphere and would disappear in ~300 years if not continuously replenished. Although the origin of the methane has not yet been determined, possible sources include volcanic activity, chemical reactions between water and iron-bearing minerals in a hydrothermal system, and biological activity.[8]

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[f] Currently being implemented as an advanced rover mission scheduled for launch in 2009.

Exploration of Titan

Cassini's exploration of Saturn and its moons and rings has only just begun. Nevertheless, the successful descent of the Huygens probe through Titan's atmosphere and the bonus of an unexpectedly long period of surface observations have confirmed some longstanding expectations and revealed some intriguing new characteristics of Saturn's largest satellite.[9] Images from the Huygens descent imager, for example, showed features highly reminiscent of drainage channels and shorelines. Similarly, images obtained on Titan's surface appear to show icy pebbles rounded, perhaps, as a result of fluvial activity; standing bodies of liquid hydrocarbons, however, were not seen.

Data from the Huygens probe on the variations of temperature and pressure as a function of altitude were virtually indistinguishable from the values that were expected on the basis of models derived from observations made during Voyager 2's flyby in 1981. However, the atmosphere appears to lack the expected argon (in the form of ^{36}Ar and ^{38}Ar), krypton, and xenon—a possible sign that Titan accreted at a somewhat higher temperature than previously expected. Huygens' instruments did, though, detect ^{40}Ar, a daughter product of ^{40}K released from Titan's interior, perhaps as a result of cryovolcanic activity. Chemical analyses performed by Huygens' gas chromatograph/mass spectrometer revealed that methane became more abundant relative to nitrogen as the proximity to Titan's surface increased. Huygens also registered a sharp increase in methane abundance soon after landing, possibly indicating the presence of liquid methane just below Titan's surface.

The instruments on Cassini itself are also returning important data, whose significance is still not entirely clear. Images of Titan's surface show few craters, indicating a geologically active world. The surface does not, however, appear to exhibit any significant compositional variations. Data from initial radar investigations of Titan's surface—covering just a few percent of the globe—are intriguing, and continued radar mapping, in conjunction with the ground truth provided by the Huygens landing, will improve researchers' understanding of Titan as an active world.

Another highly unexpected finding was the detection of significant amounts of benzene in Titan's upper atmosphere, as determined by in situ analysis performed during one of Cassini's first close flybys. With so many tantalizing initial findings and with Cassini scheduled to make many dozens of additional Titan flybys during the next 3 years, it is clear that Titan will be a prime objective for additional studies long after Cassini itself has ceased operation.

The Solar System's Giant Planets and the Search for Extrasolar Planets

The search for Earth-like planets and habitable environments around other stars is a key goal for planetary scientists as well as an important programmatic goal for NASA. The search for extrasolar planets is best addressed by a combination of ground- and space-based surveys and a better theoretical understanding of the processes leading to the formation of planetary systems. New observational results highlight the need for a systematic approach to better understanding the outer solar system, including in situ sampling of the giant planets. For example, a striking correlation has been discovered between the metallicity of a host star and the probability of its harboring one or more giant planets.[10] One interpretation of these results is that the metallicity of a protostellar gas-dust disk is related to the mass and number of solid cores that can grow in the nebula to trigger the collapse of hydrogen-rich planets.[11]

Studies of this type are emblematic of the natural synergy between astrophysics and planetary science. Indeed, extrasolar planetary research forms a continuum ranging from astrophysical studies relating to the search for, and astronomical characterization of, planets orbiting other stars to planetary studies concerning physical characteristics of extrasolar planets—e.g., their structure, atmospheric chemistry, and biological potential. Researchers need to understand the solar system's giant planets more fully to place the new discoveries concerning extrasolar planets into context.

These new astrophysical results demonstrate the importance of carrying out in situ measurements of the metallicity of the solar system's giant planets. Recent downward revisions of the estimates of carbon and oxygen abundances in the Sun indicate the importance of in situ measurements of these elements in the atmospheres of the solar system's four giant planets.[12] In the cases of Saturn, Uranus, and Neptune, in situ measurements of helium may yield results of great astrophysical significance.

Programmatic Context

In the last decade, NASA has dispatched robotic missions to Mars, the jovian and saturnian systems, asteroids, and comets. To the public, these have been successes and have both spurred increases in the breadth of the discipline (e.g., the development of astrobiology as a distinct, but related, scientific endeavor) and sustained a healthy planetary science community. Much of this program has been driven by science and discovery. NASA's new exploration initiative,[13,14] initiated following President Bush's January 14, 2004, policy speech on space, is built on these successes.

The new exploration initiative has already had an impact on the field of planetary science, and although it is too early to fully appreciate all of the ramifications, some general points are clear. Planetary science, as a field, is strongly supported in the new initiative. An increased emphasis on robotic missions to the Moon and Mars is, to the planetary science community, the most strongly supported component of the initiative articulated to date. For example, immediate responses to the President's speech have been the initiation of the Lunar Reconnaissance Orbiter, scheduled for launch in 2008; the inclusion of a Mars Scout mission in 2011; and planning for the launch of additional missions to Mars starting in 2013. Top SSE decadal survey science priorities that are consistent with the new exploration initiative include the exploration of the Moon and Mars within the context of a program of comparative terrestrial planetology.

The boundaries are not yet clear regarding what science objectives for the Moon and Mars should be addressed by remote sensing and robotic exploration, and what should be addressed by human exploration. The most sensible strategy is to push remote sensing and robotic exploration to its limits, leaving human explorers to address those objectives that most strongly require a human presence.

Concerns remain, though. A balanced program of planetary exploration, whether science- or mission-driven, should include a portfolio of diverse exploration activities directed toward diverse planetary bodies. A major concern is that the rest of the solar system, exclusive of the Moon and Mars, may be inadequately represented in the current program sequence. To understand the differences among Earth, the Moon, and Mars, for example, will require additional exploration of Venus (Earth's twin in size), and care will be needed early to identify and plan for key outer solar system missions. Some might argue that outer solar system science is robust because of Cassini's ongoing exploration of the saturnian system, the recent launch of the New Horizons mission to Pluto, and the selection of the Juno mission to Jupiter. However, Cassini's scope is finite, New Horizons will not reach Pluto until 2015, and Juno will not launch until 2010 at the earliest.

An especially troubling issue for the planetary science community is the relative scarcity of missions to the outer solar system. If launches occur only once every 10 to 15 years, then interest in this area will fade because of the absence of continuing activities and new results that attract established researchers and new students alike to the field. Even with the advanced propulsion systems that are currently in development, missions to the outer solar system will require flight times of a decade or more. If the interval between launches is factored in as well, then the time for such a mission from conception to data return rapidly approaches, and may exceed, the professional lifespan of the average researcher.

For the planetary science community, a particularly positive aspect of the new exploration initiative is the recognition that nuclear power sources—both fission reactors and radioisotope systems—are important enablers for future human and robotic voyages beyond low Earth orbit. Reaching distant destinations and exploring in new ways both depend on having adequate power for long-term operation and survival. However, when the SSE decadal survey was drafted, only one fully fueled RPS—a Cassini spare—remained in the inventory available for NASA's use. Indeed, it was far from clear to the survey's authors whether additional RPSs, let alone more exotic nuclear technologies, would be available for future high-priority missions. For this reason, the SSE decadal survey placed a very high priority on the development of advanced RPSs and nuclear-electric propulsion systems.[15] With adequate power, once-future visions of exploration can become reality: whether roving along the winter ice cap of

Mars, exploring Titan's methane playas, surviving in the long term on the surface of Venus, or sending long-lived probes into the atmospheres of the outer planets, just to name a few.

IMPLEMENTATION AND TECHNIQUES

To address their scientific priorities planetary scientists use a combination of in situ, remote-sensing, laboratory, and theoretical studies. Of these approaches, the in situ and remote-sensing studies conducted by landers, orbiters, rovers, and other types of robotic spacecraft dispatched to diverse planetary bodies are the most apparent and are the focus of this chapter, which, together with Chapter 6, discusses how the capabilities of nuclear power and/or propulsion can significantly enhance or enable a broad range of solar system exploration missions.

A typical robotic planetary mission is likely to require many, if not all, of the following characteristics:

- *Propulsion to get the spacecraft to its destination.* All robotic spacecraft require propulsion systems to get them to their destinations. Current chemical systems are adequate to provide access to the Moon, Mars, and Venus, but missions to Jupiter and beyond are much more challenging in the demands they place on propulsion systems. Chemically propelled spacecraft, enhanced with gravity assists, can travel to the outer solar system. Once there, their instruments and communications systems can be powered by an RPS. However, the mass and power limits of such spacecraft in the outer solar system constrain the choice of the types of instruments that can be used, as well as their sequencing and data-transfer rates. In addition, it is challenging for these craft to make a detailed study of more than one body, even in the same planetary system. For example, while orbiting Jupiter, Galileo was only able to make fast flybys of the Galilean satellites. To travel expeditiously to the outer solar system and then investigate individual bodies for extended periods requires large propulsive capabilities, which may be provided by nuclear-electric or bimodal systems. The Titan Express/Interstellar Pioneer concept (see Box 6.4) is an example of such a propulsion-enabled mission.
- *Access to multiple observing locations.* The scientific return from robotic spacecraft is greatly enhanced if, for example, a static lander can be replaced with a rover, or if an orbiter can change its orbit, or if a rendezvous mission can visit multiple objects. Conventional chemical propulsion, coupled with gravity assists, has been the mainstay of the solar system exploration program for decades. However, such propulsion systems allow for observation of more than one object only if a spacecraft's trajectory happens to allow it to pass by additional objects, and even then the spacecraft can go into orbit only around one body, owing to limited fuel. As the era of simple flybys comes to an end and knowledge improves, the desire grows for increasingly sophisticated observations, requiring longer durations in orbit around target bodies. In addition, it is cost-effective and beneficial for comparative science to utilize a single spacecraft to rendezvous with more than one target. An example of such a mission is Dawn, which will use a solar-electric propulsion system to visit the two large, main-belt asteroids Vesta and Ceres. Multiobject rendezvous for many more than two objects or for destinations beyond the asteroid belt is likely to be practical only if nuclear propulsion systems are available. The Neptune-Triton System Explorer concept (see Box 6.5) is an example of a mission with enhanced capability to maneuver.
- *Survival in hostile environments.* The surfaces and atmospheres of many planets are far from benign, subjecting spacecraft to environmental extremes that challenge spacecraft designers. Spacecraft on the surface of Venus, for example, are subject to very high temperatures and pressures and to corrosive atmospheric constituents; it is not surprising, therefore, that the record for spacecraft operations on the surface of Venus is only about 2 hours. Most science investigations cannot be performed in such a short period. Additionally, sunlight cannot power surface or atmospheric probe experiments if the atmosphere is substantially opaque. An RPS may, however, be used to enable the operation of a refrigerated Venus lander capable of functioning for a month or more. With refrigeration, it is possible to envision a network of long-lived Venus landers equipped to measure seismic and geochemical activity, to study any volcanic emissions, and to quantify the interaction of the surface and the atmosphere. The Long-Lived Venus Lander concept (see Box 6.1) discussed in Chapter 6 is an example of a mission with enhanced capabilities for survival in a hostile environment.
- *Power to ensure reliable operation of instruments.* Whether a spacecraft is on a simple flyby mission or is a complex rover, it needs a reliable power system to ensure the long-term operation of its subsystems. Although

solar cells coupled with batteries yield enough power for many types of orbital and surface exploration missions, there are other experiments that require sustained power for months to years. When the solar flux is too low (e.g., beyond the asteroid belt), the Sun is not visible for long periods (e.g., during the lunar night), or solar cells are likely to deteriorate over time (e.g., from dust on Mars or radiation damage incurred close to the Sun), then experiments powered by solar power sources have limited utility. However, some experiments, such as monitoring the seismic properties of a planetary body or atmosphere/surface seasonal interactions, require the availability of power over a span of months to years. Such experiments often do not need large quantities of power, but rather need power that can be available continuously for long periods or periodically over long timescales. Advanced RPSs are a solution for such needs, providing moderate power outputs for extended periods. The Long-Lived Mars Network concept (see Box 6.2) is an example of such a power-enabled mission.

- *Communications to return data to Earth.* High-priority investigations discussed in the SSE decadal survey will generate very large datasets that must be transmitted to Earth. The data rates required for timely transfer of these datasets can outstrip the current capabilities of the Deep Space Network (DSN) as well as of spacecraft telecommunications and power systems. All other parameters such as communication distance and receiver performance being equal, telecommunication systems' signal strengths (and thus data rates) for two-station systems (i.e., no intervening "repeater" stations) are proportional to three parameters: the transmitted power, the area of the transmitting antenna, and the area of the receiving antenna. Practical approaches to significantly increasing data rates from a given location in the solar system must involve increases in at least one of those three parameters. In the past, spacecraft power and launch constraints limited transmitted power and transmitting antenna size, which tied the limits of data-transmission rates to fixed DSN assets. Nuclear power sources, in particular fission, promise to greatly enhance data-transmission rates via large increases in transmitted power. Some increase in the transmitting aperture might also be possible. Another possibility being explored by NASA is to migrate from radio-frequency to optical communications systems. And a fourth option should be considered: a large increase in ground-based receiving apertures, possibly involving arrays of many antennas that would offer flexibility and simultaneous servicing of multiple missions and would obviate the requirement for high power on all serviced missions.
- *Transfer to Earth of samples collected for study.* The collection of samples from the surfaces of planetary bodies for return to Earth is an important goal of solar system exploration. The capabilities of analytic instruments available in terrestrial laboratories far exceed what can conceivably be packaged to fit on a planetary spacecraft in the foreseeable future. Ices abound in the solar system. Many of these ices are highly evolved, but some are primitive, enabling studies of material left from the early solar nebula. Although in situ laboratories are useful for the initial studies of these ices, more can be learned by analyzing them in the superior laboratories on Earth. Careful collection and preservation of samples, then, would allow for more in-depth study of the structure of the ices, which would yield information about their deposition and evolution. Holding a sample of ice at low temperatures in space is within the bounds of current technology and can be accomplished with low-power refrigeration or radiators. However, returning these samples to Earth in their ice phase is a very difficult process that will require excellent refrigeration and protection, something that may be advantageously accomplished using RPSs. Cryogenic sample return is a technology that will have to be developed for future cometary and Mars polar-sample missions. The Cryogenic Comet Sample Return mission concept (see Box 6.3) discussed in Chapter 6 is an example of a sample-return-enabled mission.

REFERENCES

1. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.
2. Mark Sykes, ed., *The Future of Solar System Exploration 2003–2013—Community Contributions to the NRC Solar System Exploration Decadal Survey*, ASP Conference Proceedings 272, Astronomical Society of the Pacific, San Francisco, Calif., 2002.
3. S.W. Squyres et al., "The Spirit Rover's Athena Science Investigation at Gusev Crater Planum, Mars," *Science* 305: 794–799, 2004. Also see subsequent papers (pp. 800–845) in this issue of *Science*.
4. S.W. Squyres et al., "The Opportunity Rover's Athena Science Investigation at Meridiani Planum, Mars," *Science* 306: 1698–1703, 2004. Also see subsequent papers (pp. 1703–1756) in this issue of *Science*.

5. M.J. Mumma, R.E. Novak, M.A. DiSanti, and B.P. Bonev, “A Sensitive Search for Methane on Mars,” AAS/DPS 35th Meeting, September 1–6, 2003.

6. V.A. Krasnopolsky, J.P. Maillard, and T.C. Owen, “Detection of Methane in the Martian Atmosphere: Evidence for Life,” European Geophysical Union Meeting, Nice, May 2004.

7. V. Formisano, S. Atreya, T. Encrenaz, N. Ignatiev, and M. Giuranna, “Detection of Methane in the Atmosphere of Mars,” *Science* 306: 1758–1761, 2004.

8. J.S. Kargel, “Proof for Water, Hints of Life?” *Science* 306: 1689–1691, 2004.

9. See, for example, T. Owen, “Huygens Rediscovers Titan” and references therein, *Nature* 438: 756–757, 2005.

10. D.A. Fischer and J.A. Valenti, “Metallicities of Stars with Extrasolar Planets,” *Scientific Frontiers in Research on Extrasolar Planets*, D. Deming and S. Seager, eds., ASP Conference Series 294, pp. 117–128, 2003; available online at <http://exoplanets.org/iau_ proc.pdf>.

11. S. Ida and D.N.C. Lin, “Toward a Deterministic Model of Planet Formation II: The Formation and Retention of Gas Giant Planets Around Stars with a Range of Metallicities,” *Astrophysical Journal* 616: 567–572, 2004.

12. The solar oxygen and carbon abundances were revised downward by a factor of 1.38 and 1.35, respectively, in: C.A. Prieto, D.L. Lambert, and M. Asplund, *Astrophysical Journal Letters* 556: 63–66, 2001; and C.A. Prieto and D.L. Lambert, *Astrophysical Journal Letters* 573: 137–140, 2002. For more details, see for example, W.B. Hubbard, “The Core Problem,” *Nature* 431: 32, 2004.

13. National Aeronautics and Space Administration, *The Vision for Space Exploration: February 2004*, National Aeronautics and Space Administration, Washington, D.C., 2004.

14. President’s Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, U.S. Government Printing Office, Washington, D.C., 2004.

15. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 203 and 205.

6

Applications of Nuclear Power and Propulsion in Solar System Exploration: Missions

PRIORITIES ENHANCED OR ENABLED BY NUCLEAR POWER AND PROPULSION

What high-priority solar system exploration objectives could be uniquely enabled or greatly enhanced over the next 25 years by the development of advanced spacecraft nuclear power and propulsion systems? The answer depends on the assumptions. Given the technical uncertainties surrounding space applications of nuclear power—e.g., the United States has flown only one space-reactor experiment, and that was 40 years ago—budgetary vagaries, and the distant time horizon of this study, very broad assumptions are necessary if any progress is to be made in answering this question. The basic assumptions used are as follows:

- The science priorities as laid out in the solar system exploration (SSE) decadal survey[1] have been unchanged by recent discoveries;
- NASA continues to follow a reasonable, steady, and well-justified course based on sound science strategic planning exercises, e.g., the priorities and recommendations of the SSE decadal survey;
- The current administration's new exploration initiative does not have a negative impact on the long-term stability of NASA and its budget lines; and
- A heavy-lift launch vehicle and/or on-orbit assembly is developed to accommodate intrinsically massive nuclear-electric propulsion (NEP) systems.

Project Prometheus and the capabilities it may enable were not public knowledge at the time the SSE decadal survey was undertaken. Thus, in light of this new potential, the committee identifies here opportunities that merit new studies of feasibility and science return. The committee has neither the expertise nor the resources to undertake trade-off studies of alternative ways of doing these missions; that is, it has not performed a detailed quantitative analysis of the relative merits of alternative power and propulsion technologies, nor has it made a comparison of alternate means of achieving the same scientific goals. The goal has been to indicate where studies are needed, not what the mission priorities should be.

SSE Decadal Survey Missions That Do Not Need Radioisotope Power Systems or Nuclear-Electric Propulsion Technologies

A variety of the missions given high priority in the SSE decadal survey do not have any need for the various nuclear power and propulsion systems being developed under the aegis of Project Prometheus. These missions include the following:

- *Cassini Extended.* The logical extension to the observations of the saturnian system following the end of Cassini's 4-year prime mission. By definition, an operating spacecraft does not require new power and propulsion technologies.
- *Mars Upper Atmosphere Orbiter.* Missions of this type do not, in general, require nuclear power or propulsion for their operation because solar power is adequate and cost-effective inside 2 AU.
- *Kuiper Belt-Pluto Explorer.* Currently being implemented as New Horizons, this is the first of the New Frontiers line of medium-class, principal-investigator (PI)-led missions. It is making use of the last remaining radioisotope thermoelectric generator (RTG) available from the Department of Energy (DOE) and therefore cannot directly benefit from Project Prometheus and related technological developments.

NASA's current ground rules for several continuing lines of small, PI-led missions specifically exclude the use of radioisotope power systems (RPSs). These lines, given high priority in the SSE decadal survey, include the following:

- *Mars Scout.* These missions are designed to address priorities outside the principal objectives of the Mars Exploration Program and, as such, provide the planetary science community with a means to respond to discoveries and technological advancement. Because these missions are selected via an open competition, the exact scope of each such mission is unknown at this time. If RPSs were allowed, the availability of a range of small to medium-size power sources (i.e., ones providing an electrical output in the range from ~10 mW to ~10 W) would likely enhance capabilities.[2]
- *Discovery.* Missions in this line are suitable for exploration of Mercury, Venus, near-Earth and main-belt asteroids, comets, and the Moon. Some future missions could potentially benefit from use of RPSs if they were permitted.

SSE Decadal Survey Missions Enhanced by RPS Technologies

Currently viable missions described in the SSE decadal survey that might be significantly enhanced by RPS technologies include the following:

- *Venus In Situ Explorer.* This mission is designed to make compositional and isotopic measurements of the atmosphere (especially the lower atmosphere) and the surface of Venus to characterize the geochemistry, mineralogy, and past tectonic history of Earth's sister planet. The battery-powered concept in the SSE decadal survey takes samples from the lower atmosphere and surface of Venus and lofts them to a higher and cooler altitude for further analysis. However, the high-temperature and high-pressure environment near the surface of Venus makes such a mission extremely challenging. Refrigeration using an RPS and pressure equalization of the Explorer while keeping it cool would greatly simplify the tasks of both obtaining the samples and analyzing them in situ. A concept for a refrigerated, long-lived Venus lander is described in a subsequent section.
- *South Pole-Aitken Basin Sample Return.* This mission is intended to collect rock and soil samples from one or more locations in the largest and deepest impact basin in the solar system. The capability of this cost-capped, New Frontiers mission to select optimal samples will be limited by its reconnaissance capabilities and by the design of the landers.[a] If this mission is less rigorously cost capped, one or more rovers with drilling capability could be added to carry out long-term exploration of this very large region. For elaboration of such a mission concept see the discussion of the Lunar Polar Rover/Driller in Appendix C.

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[a] Moonrise, an implementation of this mission concept, was the runner-up in NASA's Phase-A competition for the second New Frontiers launch opportunity.

- *Mars Long-Lived Lander Network.* This network will monitor ground seismic activity and ground-level atmospheric chemistry and dynamics for at least 1 martian year in multiple locations. Although solar power is adequate for missions lasting weeks or months near the equatorial regions, solar-powered network stations at higher latitudes are not viable because of inadequate solar flux. Martian dust and ultraviolet irradiation will also reduce the efficiency of solar cells over time. The multiple stations would benefit immensely from the availability of continuous power from RPSs. The Long-Lived Mars Network, a possible RPS implementation of this mission concept, is described in a subsequent section.
- *Mars Science Laboratory.* This mission is currently scheduled for launch in 2009. It is designed to perform in situ studies of a water-modified site to provide ground truth for orbital data and to test hypotheses for the formation and composition of water-modified environments. It may also test and validate sample-handling and other technologies required for a sample-return mission. Long-term operation and long-range roving are clearly enhanced by the availability of RPSs. For information on a more advanced mission of this type, see the discussion of the Mars Advanced Science Laboratory in Appendix C.
- *Mars Sample Return.* Collection of samples from Mars's surface and crust requires significant roving and drilling capabilities, which are enhanced by the use of RPSs. A more advanced concept, the Mars Cryogenic Sample Return mission, is outlined in Appendix C.
- *Jupiter Polar Orbiter with Probes.* This New Frontiers concept is representative of a class of mission that will study the inner magnetic field, determine the size of the cores, and provide in situ measurements of water and other volatiles in the deep atmospheres (at depths exceeding 100 bars) of the giant planets.[b] The use of RPS potentially enables a more capable mission.
- *Comet Surface Sample Return.* This mission is designed to collect material from one or more sites from the surface of a comet and transport those samples back to Earth for detailed analysis. Both ices and organic materials are of great interest in order to understand the initial processes that led to the formation of the solar system. An attempt to land on the surface of a comet is best undertaken while the comet is still in the outer solar system and is not outgassing violently. The mission outlined in the SSE decadal survey is enhanced by RPS technologies, but more advanced RPS- and NEP-enabled concepts are possible. For an example of the former, see the description of the Cryogenic Comet Sample Return mission in a subsequent section.

SSE Decadal Survey Missions That Require Prometheus RPS Technologies

Europa Geophysical Explorer

Only one of the priority missions for the period up to 2013 described in the SSE decadal survey absolutely requires the RPS technologies that are being developed as part of Project Prometheus. This mission, the Europa Geophysical Explorer, is the SSE decadal survey's highest-priority large endeavor. It is designed to confirm the presence of Europa's interior ocean, characterize the satellite's ice shell, and understand its geological history. The intensity of the jovian radiation belts precludes the use of photovoltaic arrays and limits the operational lifetime of a spacecraft in orbit about Europa to about 1 month only.

The potential availability of Prometheus-derived RPS and NEP technologies was not known at the time the SSE decadal survey was drafted. Because there were only limited nuclear options available at the time (i.e., the spare Cassini RTGs), the survey's authors focused on keeping the spacecraft's payload small, and therefore selected only relatively simple sets of science objectives. However, the availability of nuclear power and propulsion technologies enables a mission with a much more comprehensive payload and expanded exploration goals encompassing both Europa and the other icy satellites of Jupiter. For a description of an NEP implementation of a Europa mission, see the details on the Jupiter Icy Moons Orbiter in a subsequent section.

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[b] Juno, a probe-less implementation of this mission concept, was the winner of NASA's Phase-A competition for the second New Frontiers launch opportunity.

New Mission Concepts Enhanced or Enabled by RPS and NEP Technologies

What missions, besides those mentioned in one form or another in the SSE decadal survey, might be uniquely enabled or greatly enhanced by nuclear power and propulsion technologies? Providing a definitive answer is not possible given the limited scope of this study. Determining whether or not a particular concept is uniquely enabled or just somewhat enabled, as opposed to significantly enhanced or just somewhat enhanced, will require extensive additional study. Rather, the committee has attempted to identify missions that, in its collective experience, can be plausibly enhanced or enabled by the use of nuclear technologies.

To promote a broad range of science objectives, to stimulate discussion in the planetary science community, and in particular to further identify the technological challenges in bringing forward nuclear power and propulsion capabilities, the committee has developed more detailed descriptions of a subset of five missions. Boxes 6.1 through 6.5 describe the scientific objectives of these concepts and the means by which they might be addressed in the context of missions utilizing nuclear power and propulsion systems. The committee strongly emphasizes that it does not prioritize these missions above any other missions considered here or elsewhere.

The missions selected as examples are organized into three broad categories, based on the principal power and propulsion technologies they will employ and a rough assessment of the scientific or technical issues that might determine if they are ready for initiation in the period 2015 to 2020 or after 2020. These categories are as follows:

1. Missions envisioned as possible in the period 2015 to 2020 that would be enhanced or enabled by RPSs, but would be unlikely to require NEP or other fission-reactor-based propulsion systems.
2. Missions envisioned as possible in the period 2015 to 2020 that would be enhanced or enabled by NEP and/or the substantial power provided by a fission reactor. These missions might also require an auxiliary RPS to accomplish their objectives.
3. Missions envisioned as possible in the period 2015 to 2020 that would use reactor-based power and/or propulsion systems for which there are scientific or technical considerations suggesting deferral of flight until after 2020.

RPS-Enhanced or RPS-Enabled Missions Envisioned by 2020

The development of a new RPS capability is extremely important for enabling solar system exploration. With the era of quick reconnaissance over, more detailed examination requires additional power, whether for heaters, refrigeration, or longer life. A variety of mission types are enabled by the RPS technologies being developed by Project Prometheus. Individual missions are listed in each category to illustrate the richness of the science questions that can be addressed. The order listed here does not imply priority.

Long-Lived Landers. Solar cells and batteries enable many types of surface-based science operations. However, they are not the solution for experiments that require sustained power for lengthy periods of time ranging from months to years. When the solar flux is too low, the Sun is not visible for long periods of time, or photovoltaic cells deteriorate, experiment life is limited with solar power sources. The monitoring of seismic or atmospheric properties of a planet benefits from the extended availability of power. Although these experiments often do not need large amounts of power, they require that power be available continuously. The advanced RPSs being developed as part of the Prometheus project are a likely solution for such needs.

Possible missions include the following:

- *Venus Long-Lived Lander.* Researchers are ignorant of the dynamics of Venus's atmosphere and of the composition, structure, and activity of its surface and interior. The planet's 740 K surface temperature and 90-bar pressure are significant challenges to surface exploration. Liquid-cooled pressure vessels, such as those used by the former Soviet Union's Venera probes, can support only several hours of operation. The high power provided by an RPS can, potentially, provide long-term (months) refrigeration for Venus surface craft. More details of such a mission are described in Box 6.1.

BOX 6.1
Long-Lived Venus Lander

Mission Type: RPS-class

Objectives:

- Pioneer new technologies to enable long-lived surface operations on Venus;
- Provide new insights into why the terrestrial planets have evolved so differently;
- Conduct seismic observations on the surface of Venus;
- Retrieve and analyze surface samples at high-priority locations, to address questions about the diversity of crustal geochemistry and mineralogy, and also surface/atmosphere interactions and processes;
- Analyze the atmosphere during descent (particularly the lower-most 20 km) and on the surface; and
- Determine the structure of the outer 10 to 20 cm of surface material.

Implementation:

- Lander utilizing an active cooling system capable of surviving on the surface of Venus for a minimum of 1 month;
- Total landed mass of ~200 kg;
- Cooled volume of <1 cubic meter; and
- Power for instruments of between 20 and 60 W.

Payload:

- Seismometer;
- Multispectral imaging system (0.3–2.5 μm) down to centimeter resolution;
- Surface chemistry package including x-ray fluorescence and subsurface sampling mechanism;
- Atmospheric chemistry package capable of determining abundances of the principal oxygen isotopes to 0.1‰); and
- Meteorology package.

Other:

- Multiple lander packages enabling compositional measurements of several diverse terrains; and
- Three or more landers operating simultaneously as a seismic lander network to detect seismic activity and assess crustal thickness and internal structure (currently unknown).

Some Questions for Additional Study:

- What is an appropriate data rate for the seismometer and how does the inclusion of this instrument drive other aspects of the mission?

- *Additional long-lived lander concepts.* Examples of such missions, described in Appendix C, include the following, in heliocentric order:

—Mercury Polar In Situ Explorer,
—Mars Deep Driller,
—Mars Polar Profiler,
—Io In Situ Explorer,
—Europa Astrobiology Lander,
—Icy Satellite Deep Driller, and
—Comet Nucleus and KBO Surface laboratories.

Rovers. Robotic laboratories mounted on rovers powered by RPSs can, in principle, explore large areas and operate in severe conditions. Equipped for in situ analysis and aggressive sampling techniques, they can characterize the geochemical and geophysical properties of a variety of solar system bodies. Use of RPSs allows for operation when there is no sunlight and temperatures are cold. Examples of possible missions of this type, described in Appendix C, include the following, in order of heliocentric distance:

- Venus Mobile Laboratory,
- Lunar Polar Rover/Driller,
- Mars Advanced Science Laboratory, and
- Titan Surface Laboratory.

Global Networks. Networks of scientific stations that make coordinated, global measurements are of great interest for addressing a variety of scientific issues. Global networks can detect seismic activity and measure heat flow, providing constraints on internal structure, and, in the case of bodies with atmospheres, can make extensive synoptic measurements of the atmosphere and weather. These measurements by definition require multiyear observations. RPSs enable the longevity and continuous operation of these stations. Examples include the following:

- *Long-Lived Mars and Venus networks.* The highest-priority goals are seismological determination of internal structure, including the core, global sampling of a range of surface chemical and material properties, and extensive synoptic measurements of the atmosphere and weather. For Venus, the emphasis should be on understanding the nature of any tectonic activity and the planet's lack of magnetic field as well as the processes relating to the interaction between the surface and the atmosphere. More details of a Mars network mission are contained in Box 6.2.
- *Additional network concepts.* Examples of other possible network missions are described in Appendix C, and include the following, in no particular order:

  —Mercury and Lunar Long-Lived Networks, and
  —Icy Satellite Long-Lived Networks.

Sample-Return Missions. Ultimately, rovers are limited by their small size and low power. Bringing samples back to Earth-based laboratories allows for more sophisticated analysis, which can be done only with large, complicated equipment. In addition, curation allows for samples to be analyzed as techniques improve. Returned samples can take the form of rock, dust, gas, and even ices, with the last being the most difficult to return because of the need to keep the samples frozen during transport and reentry.

Missions of this type include the following:

- *Cryogenic Comet Sample Return.* This mission would collect samples of a well-characterized comet nucleus from two or more selected sites, both from the surface and at a depth of about 1 m. To preserve the full suite of volatile materials, the samples would be actively maintained at a temperature below 150 K during the return to Earth for subsequent analysis. A mission of this complexity requires further technological developments, particularly for drilling and sample collection and for cryogenic preservation and return to Earth. Similarly, consideration will have to be paid to techniques for accomplishing this without bringing an RPS or similar device back into Earth's atmosphere. See Box 6.3 for a more complete description of this concept.
- *Additional sample-return concepts.* Examples of possible missions, described in Appendix C, include the following, in no particular order:

  —Mercury Sample Return,
  —Venus Selected Sample Return, and
  —Mars Cryogenic Sample Return.

BOX 6.2
Long-Lived Mars Network

Mission Type: RPS-class

Objectives:

- Advance understanding of the formation and evolution of planets in general and of Mars in particular;
- Resolve questions concerning the size and other physical characteristics of the martian core;
- Determine the seismic properties of the martian mantle;
- Characterize the crustal structure and thickness;
- Conduct extensive synoptic measurements of the martian atmosphere and weather at ground level to address issues relating to atmospheric dynamics;
- Contribute to an understanding of the history and nature of the volatile inventory and distribution on Mars by studying surface/atmosphere interactions;
- Address issues pertaining to climate history (external forcing) as well as volcanic history and its interaction with climate; and
- Monitor the abundance and distribution of molecules of possible biological importance, including water and methane.

Implementation:

- Deployment of a global network of small, identical sensor packages on Mars to monitor seismic activity and ground-level atmospheric dynamics and chemistry over a period of at least 1 martian year—the natural period for the atmosphere and also an appropriate time period for characterizing seismic activity;
- Operation of network stations at night and at some high-latitude and high-altitude sites;
- Separation of any two stations that should, ideally, not exceed the planetary radius (this implies more than 14 sites); and
- Individual instrument packages with the following characteristics: mass ~2 kg (total landed mass depends on delivery system); power ~80 mW; data rate ~10–100 kbit/day as a compressed dataset.

Payload:

- Seismometer with large dynamic range and broadband frequency response, which can be coupled effectively to the martain surface;
- Temperature, pressure, humidity, atmospheric opacity, and ultraviolet sensors;
- Entry accelerometers;
- Wind velocity meter;
- Computer and software to manage these data (this is very important for the seismometer so that the data rate is manageable); and
- Other possibilities, including monitors of water vapor and methane partial pressures.

Some Questions for Additional Study:

- What are the trade-offs between the number and capabilities of the stations?
- Are there any conflicting requirements between the meteorological/climatic and seismic experiments?
- What impact would a methane sensor have on a station's mass, power, and data transmission rate requirements?

Aerobots. Global surveys of a planet or satellite can be undertaken by orbiters. However, more detailed, regional surveys and, potentially, in situ studies of multiple dispersed sites are better suited to the capabilities of various types of aerial robots (aerobots), whether they are aircraft, balloons, blimps, or something else.[3] Possible aerobot missions, described in Appendix C, include the following, in order of distance from the Sun:

- Venus Aviator, and
- Titan Aerobot Explorer.

Deep Atmospheric Probes. The giant planets are the best local analog to currently known extrasolar planets. The highest-priority science questions address the internal structure and elemental composition of the gas giants (Jupiter and Saturn) and the denser, more remote ice giants (Uranus and Neptune).[4] For all the giant planets, knowing the volatile abundances has high priority, both individually and comparatively (among the giant planets and as compared with the Sun).

Experience with Galileo suggests that short-lived, single-probe experiments are not well suited for atmospheres with significant latitudinal and longitudinal diversity. Far more is learned scientifically from comparing three or more dispersed sites. Furthermore, determination of the more cosmogonically interesting atmospheric constituents requires penetration below the weather-driven upper layers and down to the well-mixed region. Cloud bases may be deep within the planet, and so the abundance of the upper atmosphere might reflect the saturation vapor pressure rather than the bulk abundance of H_2O and other volatiles such as CH_4, NH_3, and H_2S. Deep probes, combined with microwave remote-sensing observations, are needed to sample the well-mixed deep atmosphere for these compounds.

These probes are envisioned to be long lived—possibly probe-aerobot hybrids that can actively control their descent and, if feasible, ascent—both to give more complete vertical profiling and to be able to transmit deep-atmosphere information from a less-challenging depth. Power requirements for shallow probes can likely be met with advanced batteries; however, communication with deep probes (at depths of ~100 bars) will probably require more power. RPS technologies are critical both to communications and to refrigeration for thermal protection. An example of a possible mission is as follows:

- *Neptune Orbiter/Deep Multiprobes.* This concept is designed to study the gravitational and magnetic fields of an ice giant planet. In addition, entry probes will obtain in situ measurements of chemical composition to constrain theories of solar system formation. Multiple flybys of Triton and other icy satellites will yield information on the interaction of the satellites with Neptune and its magnetosphere. Although this mission is envisaged as being accomplished by gravity assists and an RPS-powered spacecraft, a more comprehensive, NEP version of this mission is possible; see the description of the Neptune-Triton System Explorer in a subsequent section.

NEP-Enhanced or Enabled Missions Envisioned by 2020

Missions requiring the use of NEP systems that may be ready for flight by 2020 include the following:

- *Jupiter Icy Moons Orbiter.* This concept combines the mission-enabling characteristics of NEP with the SSE decadal survey recommendation for a Europa Geophysical Explorer[5] to create an exciting opportunity to study in unprecedented detail the jovian system and, in particular, the icy moons, Callisto, Ganymede, and Europa. Much more information about this mission is given in Chapter 1.
- *Titan Express/Interstellar Pioneer.* This mission is specifically intended to push the envelope of what is and is not possible with NEP. It attempts to marry Titan-exploration goals with space physics priorities for the exploration of the distant outer solar system. The latter goals are addressed by the inclusion of a secondary payload that responds to some but not all of the goals of the much more elaborate Interstellar Observatory mission (see Box 4.1 and Appendix B). The basic concept involves an NEP-powered bus accelerating through the saturnian system and releasing, without first decelerating, a high-priority payload directly into Titan's atmosphere. The bus then continues on toward interstellar space while conducting space physics observations with a small instrument

BOX 6.3
Cryogenic Comet Sample Return

Mission Type: RPS-class

Objectives:

- Study the molecular, volatile, and refractory composition of cometary nuclei, including the structure of the ices;
- Compare the composition and structure of the material from the surface and from depth (1 m);
- Determine the global surface properties of the nucleus of the target comet by remote-sensing techniques, supplemented by in situ studies of one or more selected sites; and
- Determine the rotation state and heat transfer properties of the nucleus.

Implementation:

- Rendezvous with a comet when it is at least 5 AU from the Sun.
- Perform an initial reconnaissance of the comet's nucleus to pick the sample site or sites, with a full trade-off study of site safety versus site interest (for instance, vents might be dangerous to the spacecraft but landing at such a site would provide fresher material).
- The requisite remote-sensing instrument package (mass of ~200 kg and power of ~100–150 W) would need to return an initial dataset of ~100 Gbits (including full visible imaging coverage at a resolution of 1 m per pixel in 7 channels [≈13 Gbits]; full spectrometric imaging coverage in the infrared at a resolution of 5 m per pixel and 512 channels [≈39 Gbits] and in the ultraviolet at 5 m per pixel in 256 channels [≈19 Gbits], before compression and before error correction and packetization overhead—assuming a 5-km-diameter nucleus) to science team within a period of <30 days to enable the selection of potential landing sites (a Ka-band system with a radio-frequency power of 20 W through a 1.5-m high-gain antenna to the 34-m stations of the Deep Space Network [DSN] could send down about 100 Gbits in about 2 weeks of full-time coverage, or about 40 days of one DSN pass per day, at a distance of 5 AU. This is probably faster than is truly necessary, but it fits comfortably in the RPS-mission envelope).

package that takes advantage of the abundant electrical power provided by the spacecraft's reactor. More details about this mission can be found in Box 6.4.

- *Neptune-Triton System Explorer.* It will be challenging, even with the availability of NEP, to mount a comprehensive investigation of the Neptune system, including its complex magnetosphere; its dusty rings; its array of small, icy moons; and, not least, Triton, its large, geologically active moon. The feasibility of this mission hinges on providing an adequate science payload, an acceptable transit time from Earth to Neptune, the desired degree of orbital mobility, and a robust communication capability.

A candidate payload and observing scheme for the Neptune-Triton System Explorer could be expanded from that flown on Cassini. Given Neptune's distance from Earth, data transmission rates will be a significant issue and trade-off studies are needed on the balance between spacecraft transmitter power and Earth-based receiver aperture. Although it may be possible to use aerocapture to place a spacecraft into orbit about Neptune, orbiting Triton requires nuclear propulsion. Flexibility in orbit control would also be provided by NEP. Trade-off studies should involve efforts to reduce transit time and consideration of multiple craft. More details about this concept can be found in Box 6.5.

- *Additional missions.* The capabilities of NEP systems suggest several other types of mission. These possibilities are described in Appendix C and include the following:

—Saturn System Multiple Rendezvous; and
—Main-Belt, Trojan Asteroid, and Centaur Multiple Rendezvous.

- Touch down at a selected site on the surface and obtain two samples: one from the surface and one at a depth of at least 1 m. Repeat sampling at a second selected site, if feasible.
- Transfer the samples to containers that can be maintained at no warmer than 150 K for transfer back to Earth.
- Acquire the samples and return them to Earth in such a manner that the ices are not compacted.
- Fly with the comet and monitor the surface of the nucleus, especially the sampling site or sites.
- Follow the comet through the onset of activity and back to 1 AU.
- Return the sample back to Earth for analysis in the laboratory.
- Ensure that samples contain at least 1,000 cm^3 of material each.

Payload:

1. Remote-sensing package:
    - Optical camera with resolution of at least 1 m/pixel pair;
    - Near-infrared spectrometer;
    - Ultraviolet spectrometer; and
    - Other possibilities, including neutral and ion gas mass spectrometer and dust impact analyzer, and a near-infrared mapping spectrometer.
2. In situ package:
    - Surface sample collection tool;
    - Depth sample collector (which must not compact sample);
    - Materials strength tester; and
    - Other possibilities including thermal inertia detector (via microwave radiometry or an in situ instrument).

Some Questions for Additional Study:

- What are the realistic mass and power estimates for the in situ instrument package?
- What are the power requirements of the refrigeration system?
- How do the mass and power requirements of the refrigeration system scale with the total sample mass and volume?
- Are the power requirements of the refrigeration system consistent with the use of an RPS?

NEP-Enhanced or NEP-Enabled Missions Envisioned After 2020

Missions Deferred for Scientific Reasons Until After 2020. Although certain missions are plausibly enabled by nuclear power and/or propulsion systems, scientific arguments can be made for delaying their launch until after 2020. Examples of such missions, described in Appendix C, include the following:

- Titan Surface Sample Return,
- Uranus System Explorer, and
- Multiple Kuiper Belt Object Rendezvous.

Missions Deferred for Technical Reasons Until After 2020. Although many missions are plausibly enabled by nuclear power and/or propulsion systems, the necessary technologies may not be available until after 2020. Examples of such missions, described in Appendix C, include the following:

- Icy Moons Subsurface Sample Return; and
- Main-Belt, Trojan Asteroid, and Centaur Multi-Sample Return.

BOX 6.4
Titan Express/Interstellar Pioneer

Mission Type: NEP-class

Objectives:

- Conduct an extended close study of Titan's surface, subsurface, and lower atmosphere: its geomorphology and meteorology, as well as the identification of sites of astrobiological interest;
- Study the composition and distribution of organic compounds and the processes and energy sources resulting in the creation, modification, and destruction of organic compounds;
- Conduct in situ chemical analysis of selected surface sites;
- Explore the interstellar medium and its implications for the origin and evolution of matter in our galaxy and universe;
- Explore the outer solar system for clues to its origin and to the nature of other planetary systems;
- Explore the influence of the interstellar medium on the solar system and its dynamics and evolution; and
- Explore the interaction between the interstellar medium and the solar system as an example of how a star interacts with its local galactic environment.

Implementation:

- An NEP-class spacecraft travels to Saturn under continuous acceleration to minimize delivery time, and releases an aerobot (inside an entry shield) directly into Titan's atmosphere as the spacecraft flies by.
- The aerobot is an RPS-powered airship that inflates during the parachute descent after entry. The aerobot would conduct a 6- to 12-month mission, using an RPS of ~100 watts of electrical power (We). It would communicate directly to Earth at ~1 kbps. The total mass of the aerobot system M_{aero} (floating mass plus deployment/inflation) is nominally 400 kg, but if the system design is not sensitive to delivered mass, consider also M_{aero} = 1,000 kg to 2,000 kg. The entry shield is assumed to have a mass that depends on entry speed, as follows

$$M_{shield} = 0.5 \bullet M_{aero} \bullet (V_{entry}/\, 6)^{1.5}$$

(where V_{entry} is in km/s and M_{shield} is in kg).

- After the delivery of the aerobot to Titan, the trajectory of the carrier spacecraft is directed as close as is feasible toward the nose of the heliosphere and into interstellar flow. The Interstellar Pioneer's payload mass is <100 kg, its power requirement is >100 W, and it has a bit rate of >1,000 bps. The desired flight time to a distance of 200 AU is more than 15 years but less than 30 years.

Payload:

1. Titan Aerobot:
    - Side- and down-looking imagers, with some spectral and/or fluorescence capability for identifying organic deposits;

- Small subsurface radar sounder;
- In situ surface chemistry package; and
- Environment sensors (meteorological and also radiation detectors for radiocarbon).

2a. Interstellar Pioneer (in situ):

- Magnetometer;
- Plasma and radio wave detectors;
- Instruments for studying solar-wind plasma and electrons;
- Pickup and interstellar ion mass spectrometer;
- Interstellar neutral atom mass spectrometer;
- Suprathermal ion mass spectrometer;
- Anomalous and galactic cosmic-ray element/isotope spectrometer;
- Cosmic-ray electron and positron detectors;
- Gamma-ray-burst detector;
- Dust composition analyzer; and
- Other possibilities, including an instrument for studying the charge states of suprathermal ions, molecular analyzer for organic material, and cosmic-ray antiproton detector.

2b. Interstellar Pioneer (remote sensing):

- Infrared spectrometer;
- Energetic neutral atom imager;
- Ultraviolet spectrometer; and
- Other possibilities, including a small Kuiper Belt object detector and an infrared background/zodiacal light mapper.

Additional Questions for Study:

1. How sensitive is the system to Titan delivery time?
    - Is the mass of the aerobot plus its entry system so small compared with the mass of the delivery spacecraft that additional entry mass is not a significant factor and there can be therefore a large M_{aero}?
    - How does the delivery system change if the mass delivered to Titan is 1,500 kg, 2,000 kg, or 2,500 kg?
    - Is there anything to be gained in M_{entry} by having a coast or retropropulsion phase prior to Titan delivery, or should the propulsion be continuous to simply get there as fast as possible, given propulsion capabilities?
2. What are the direction and trip-time capabilities for the interstellar portion of the mission, given the Titan delivery requirement?
    - Does a gravity assist from Saturn contribute significantly to modifying direction, or would this be a complication better avoided?
    - How do direction and time to heliopause vary with launch date?
    - Is continued propulsion (after Saturn encounter) worthwhile?

BOX 6.5
Neptune-Triton System Explorer

Mission Type: NEP-class

Objectives:

- Explore differences between the ice giants and the gas giants. Measure the elemental atmospheric composition; determine the constraint on the planet's interior structure; and investigate the processes that control the distribution of gases, clouds, temperatures, and winds.
- Investigate Triton, a large captured object (perhaps a KBO). Measure the composition of Triton and the global distribution of volatiles; investigate processes that control Triton's orbital history, surface morphology, and internal structure; determine if a subsurface water layer exists; characterize the diverse cryovolcanic features on Triton's surface, including its geyser-like features; and study the diffuse atmospheric haze (possibly condensed hydrocarbons) and the discrete polar clouds (likely N_2).
- Study Neptune's small satellites and the vertical and radial structure of its rings. Measure the composition, size, and dynamical properties of ring particles; explore how Neptune's satellite-ring interactions control ring structure and evolution.
- Probe Neptune's magnetosphere. Measure structure, composition, density, and dynamics; sample the magnetosphere in latitude, longitude, altitude, and local time; and determine how the magnetosphere interacts with other Neptune-system elements and the solar wind.
- Pioneer new technologies to explore the outer solar system within a decade.

Implementation:

- Desired flight time of 10 years or less from Earth to the Neptune system;
- Orbital insertion at Neptune;
- Delivery, deployment, and support of Neptune miniprobes with a mass of 100 kg (excluding propulsion system, if needed); power of 100–150 W (may be higher for depths below 200-bar level); data rates of ~200 bps (above 10-bar level) down to ~10 bps (very deep); and delta-V (probes released after orbit insertion might need delta-V capability).

Science Categorization of New Mission Concepts

The SSE decadal survey defined a set of 12 fundamental science questions to be addressed by solar system exploration missions.[6] Table 6.1 presents a cross-matrix of the new mission concepts discussed in this report relative to these 12 questions. Further prioritization of these concepts will require further understanding and study of the ability and applicability of nuclear power and/or propulsion to achieve the respective science objectives.

TECHNOLOGY ENHANCEMENTS AND ISSUES

Of the 17 important technologies identified by the Aldridge Commission as enabling the new exploration initiative,[7] eight technology areas are particularly relevant to solar system exploration missions:

- Advanced power and propulsion;
- Cyogenic fluid management;
- High-bandwidth communications;

- Delivery, deployment, and support of a Triton lander with a mass of $\gtrsim$500 kg; power of 200–300 W; data rate of ~100–300 bps; and delta-V (needs to be determined).
- Multiyear tour of Neptune system supported by in situ and remote-sensing instruments on the carrier spacecraft (instrument mass of ~300 kg assuming post-Cassini instrument development; power of ~500 W and more if radar is carried; and data rates of >30 kbps).

Payload:

1. Carrier instruments:
    - Multispectral imaging system (0.3 to 2.5 μm) down to 100-m resolution;
    - Microwave radiometer;
    - Telecommunications system incorporating a two-frequency coherent transponder for radio science/celestial mechanics (gravitational field measurement);
    - Ultrastable oscillator for radio science occultations;
    - Subsurface radar profiler (for Triton, possibly other satellites as well); and
    - Space physics package (e.g., magnetometer, ion and neutral mass spectrometer, plasma wave spectrometer, charged-particle spectrometer).
2. Atmospheric Miniprobe:
    - Gas chromatograph/mass spectrometer;
    - Temperature, pressure, and acceleration sensors;
    - Ultrastable oscillator for Doppler-wind experiments; and
    - Nephelometer.
3. Triton lander:
    - Multispectral imaging system (0.3 to 2.5 μm) down to centimeter-level resolution;
    - Surface chemistry package including x-ray fluorescence and subsurface sampling mechanisms; and
    - Meteorology package.

Issues for Additional Study:

- Does the requirement for a transit time of 10 years translate into a technically feasible value for the specific mass parameter α?

- Autonomous systems and robotics;
- Scientific data collection/analysis;
- Entry, descent, and landing;
- Affordable heavy-lift capability; and
- Automated rendezvous and docking techniques.

Detailed discussions of the other nine technologies (i.e., advanced structures; high-acceleration, high-life-cycle, reusable in-space main engine; large-aperture systems; formation flying; closed-loop life support and habitability; extravehicular activity systems; biomedical risk mitigation; transformational spaceport and range technologies; and planetary in situ resource utilization) are beyond the scope of this chapter. However, some of these additional technologies are highly relevant to astronomy and astrophysics (e.g., large-aperture systems) and solar and space physics (e.g., formation flying).

Table 6.2 provides a summary description of Prometheus-driven technologies whose development is needed to significantly enhance or enable future missions discussed above.

TABLE 6.1 Science Questions Addressed by New Mission Concepts

	SSE Decadal Survey Science Questions[a]											
Missions	1	2	3	4	5	6	7	8	9	10	11	12
RPS Missions												
Envisioned by 2020												
Venus Long-Lived Network				X		X	X		X		X	
Lunar Polar Rover/Driller				X	X	X					X	
Mars Advanced Science Laboratory				X	X	X	X	X	X		X	
Titan Aerobot Explorer				X	X	X	X				X	
Neptune Deep Multiprobes	X	X		X	X	X	X				X	X
Comet Nucleus Surface Laboratory	X			X	X					X	X	X
Science Suggests >2020												
Mercury Polar In Situ Explorer	X			X		X			X		X	
Venus Long-Lived Network	X			X		X			X		X	
Venus Aviator				X	X	X			X		X	
Lunar Long-Lived Network	X								X	X	X	
Mars Long-Lived Network	X			X		X	X		X	X	X	
Europa Astrobiology Lander				X	X	X	X	X			X	
Io Observer				X		X					X	
Titan Surface Laboratory				X	X	X	X				X	
Technology Suggests >2020												
Mercury Long-Lived Network	X					X			X		X	
Venus Mobile Laboratory				X		X	X		X		X	
Venus Selected Sample Return	X			X		X	X		X		X	
Mars Polar Profiler[b]				X	X	X	X	X	X		X	
Mars Deep Driller[b]			X	X	X	X	X	X	X		X	
Mars Cryogenic Sample Return				X	X	X	X	X	X		X	
Icy Satellite Long-Lived Network	X			X	X	X	X				X	
Icy Satellite Deep Driller[b]	X			X	X	X	X	X			X	
Io In Situ Explorer	X			X		X			X		X	
Cryogenic Comet Sample Return	X			X	X					X	X	X
KBO Surface Laboratory	X			X	X					X	X	X
Prometheus Propulsion Missions												
Envisioned by 2020												
Jupiter Icy Moons Orbiter	X		X	X	X	X	X	X			X	X
Saturn System Multiple Rendezvous	X	X	X	X	X	X	X				X	X
Titan Express/Interstellar Pioneer				X	X	X	X				X	
Main-Belt/Trojan/Centaur Multiple Rendezvous	X			X	X					X	X	
Neptune-Triton System Explorer	X	X	X	X	X	X					X	X
Science Suggests >2020												
Titan Surface Sample Return	X			X	X	X	X	X			X	
Uranus System Explorer	X	X	X	X	X	X					X	X
Multiple KBO Rendezvous	X			X	X					X	X	X
Technology Suggests >2020												
Icy Moons Subsurface Sample Return	X		X	X	X	X	X	X			X	
Main-Belt/Trojan/Centaur Multi-Sample Return	X			X	X					X	X	

[a] SSE Decadal Survey Science Questions:

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?
4. What is the history of volatile compounds, especially water, across the solar system?
5. What are the nature and the history of organic material in the solar system?

TABLE 6.1 Continued

6. What global mechanisms affect the evolution of volatiles on planetary bodies?
7. Where are the habitable zones for life in the solar system, and what are the planetary processes responsible for producing and sustaining habitable worlds?
8. Does (or did) life exist beyond Earth?
9. Why did the terrestrial planets differ so dramatically in their evolution?
10. What hazards do solar system objects present to Earth's biosphere?
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?

For more details, see National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 177–188.

[b] May require a surface reactor, depending on the speed and depth of drilling.

CONCLUSIONS

The availability of nuclear power and propulsion technologies has the potential to enable a rich variety of solar system exploration missions. A particularly exciting prospect for the planetary science community is the likely availability of a new generation of RPSs that will enable missions ranging from long-lived surface landers to deep-atmospheric probes.

If nuclear propulsion is developed and demonstrated, then it will enable radically new mission concepts capable of conducting activities of a scope never before contemplated by planetary scientists. This prospect has both positive and negative aspects. NEP missions, such as the Jupiter Icy Moons Orbiter (JIMO), will be able to reach previously inaccessible objects and conduct comprehensive studies with a degree of flexibility unprecedented in the history of solar system exploration. The potential scientific return from a single such mission is difficult to appreciate. But spacecraft nuclear propulsion is in its infancy and will require a great deal of technological development. By today's standards, the spacecraft using these technologies will be very large, very heavy, very complex, and, almost certainly, very expensive. The question, then, is to what extent the development and deployment of such technologies will interfere with the diversity of solar system exploration missions. Mission diversity in solar system exploration gives scientific breadth and depth to these pursuits and is essential for the long-term health and vitality of the solar system exploration activities.

It is difficult to imagine that the planetary-science goals of one, two, or three decades hence will still be addressed with the power and propulsion technologies of the Mariners, Pioneers, and Voyagers. It is equally difficult to imagine, however, how to transition smoothly from an era of Cassini, Mars Exploration Rovers, New Frontiers, and Discovery to one whose mix of activities will be as diverse but will now also include JIMO-class missions.

With the launch of JIMO now delayed to beyond 2017, or later, there is a lack of flight opportunities to the outer solar system. Exploration of the outer solar system is the area where nuclear power systems have their greatest potential but, ironically, the lack of maturity of NEP or hybrid systems, combined with the current emphasis on lunar and martian exploration, may cause such long delays that an effective program cannot be sustained.

The travel times, costs, and complexities, which are increasing the time to flight of the currently studied NEP system envisaged for JIMO, are making it unattractive to the science community. Further studies of nuclear thermal propulsion or bimodal systems may at least alleviate the concerns with trip times, but the concerns with cost and complexity will remain.

Given the limited scope of this study, the various RPS and NEP mission concepts developed in this chapter appear to be capable of addressing expanded exploration of the inner solar system and providing limited support to robotic and human missions to the Moon and Mars, as well as increasing the flexibility for exploring the outer solar system. Nevertheless, the capabilities of competing technologies need to be studied in much more detail

TABLE 6.2 Technologies Enabling the New Mission Concepts

Category (Heliocentric Order)	Space Reactors	Planetary Environment Reactors[a]	Radioisotope Power (vacuum)	Radioisotope Power[a] (atmosphere)	Radioisotope Heater Units	Active Cooling	Low-Power Electronics	Radiation-Hard Electronics	High-Thrust and I_{sp} Nuclear Propulsion
A: Enhanced/Enabled by Prometheus Power Sources (Envisioned by 2020)									
Mercury Polar In Situ Explorer			X		X		X		
Mercury Long-Lived Network			X[b]		X		X		
Venus Long-Lived Lander				X		X[c]	X		
Venus Long-Lived Network				X		X[c]	X		
Venus Aviator				X		X[c]	X		
Venus Mobile Laboratory				X		X[c]	X		
Venus Selected Sample Return				X		X[c]	X		
Lunar Polar Rover/ Driller		X[d]	X[d]		X		X[d]		
Lunar Long-Lived Network			X[e]		X		X		
Mars Advanced Science Laboratory				X	X		X		
Mars Long-Lived Network				X[e]	X		X		
Mars Polar Profiler		X[d]		X[d]	X[d]		X[d]	X[d,e]	
Mars Deep Driller		X[d]		X[d]	X[d]		X[d]		
Mars Cryogenic Sample Return		X[d]		X[d]	X	X[f]	X[d]		
Neptune Deep Multiprobes				X		X[c]	X		
Io Observer			X		X		X	X	
Io In-Situ Explorer			X		X		X	X	
Europa Astrobiology Lander			X		X		X	X	
Titan Aerobot Explorer				X	X		X		
Titan Surface Laboratory				X	X		X		
Icy Satellite Long-Lived Network			X		X		X	X[e]	
Icy Satellite Deep Driller			X[d]		X[d]		X[d]	X[d,e]	
KBO Flyby with Giant Planet Gravity Assist			X		X		X		
Comet Nucleus Surface Laboratory			X		X		X		
Cryogenic Comet Sample Return			X[g]		X[f]		X		
KBO Surface Laboratory			X		X		X		
B: Enabled by Prometheus Propulsion (Envisioned by 2020)									
Jupiter Icy Moons Orbiter	X		X[h]		X[h]		X[h]	X	
Saturn System Multiple Rendezvous	X		X[h]		X[h]		X[h]	X	X[i]
Titan Express/Interstellar Pioneer	X			X	X		X		

Main-Belt/Trojan/Centaur Multiple Rendezvous	X				X	X	X		X
Neptune-Triton System Explorer	X		X[h]		X[h]		X[h]	X	
C: Enabled by Prometheus Propulsion and/or Power (Scientific Rationale Beyond 2020)									
Titan Surface Sample Return	X	X[g]		X[g]	X[g]	X[f]	X[g]	X	X[g]
Uranus System Explorer	X				X[h]		X[h]	X	
Multiple KBO Rendezvous	X				X		X	X	
D: Enabled by Prometheus Propulsion and/or Power (Capability Beyond 2020)									
Icy Moons Subsurface Sample Return	X				X[g]	X[f]	X[g]	X	X
Main-Belt/Trojan/Centaur Multi-Sample Return	X		X[h]		X[h]		X[h]	X	X[g]

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[a] Design factors include atmosphere compatibility (temperature, corrosion), gravitational effects on structure, coolant transport, planetary protection.

[b] Part of network may be viable with solar power, but full coverage needs RPS.

[c] Refrigeration power required to maintain vehicle systems cool in a hot environment.

[d] Reactor may be required for rapid, deep drilling. Lower-capability (slower/shallower) mission may be possible with RPS/RHUs and low-power electronics.

[e] All missions require some radiation tolerance. Severe radiation issues exist for missions to Europa and Io, or if a close Jupiter flyby is needed en route to another destination.

[f] Refrigeration power required to maintain sample in pristine cryogenic conditions during return.

[g] Depends on mission architecture: land entire vehicle or have small subvehicle to retrieve sample.

[h] RPS required if mission includes surface element (e.g., Triton lander, Enceladus, Europa, Oberon, etc.).

[i] Higher thrust than JIMO ion propulsion needed for full ring access or larger small body landing.

NOTE: Definitions of column heads.

***Space reactors*—**In-space power generation by fission systems. Previously flown systems, the configuration envisaged for the Jupiter Icy Moons Orbiter (JIMO), NTP, and bimodal systems are examples.

***Planetary environment reactors*—**Space reactors as defined above may be unworkable in a number of environments on, near, or in planetary bodies. Particular complications may include gravity that imposes structural requirements on the radiators and the heat transfer implications of an atmosphere or surface. The challenges and requirements vary from body to body; an asteroid surface is little different from deep space, while the venusian surface would be particularly difficult.

Radioisotope power (vacuum) refers to radioisotope (nonfission) power systems, including existing and planned RPSs and Stirling converters. Heat rejection is via radiators.

Radioisotope power (atmosphere) refers to RPSs designed to operate within a planetary atmosphere. Efficiency of heat rejection and corrosion resistance are particular issues.

Radioisotope heater units are heat sources without energy converters. Although little or no technology development appears required, they are listed here because the demand for them has implications for the radioisotope inventory.

Active cooling refers to power-consuming heat management techniques such as Stirling coolers or other refrigeration, either for maintaining systems under operating conditions in Venus's near-surface environment, or for maintaining a sample under refrigerated or even more stringent cryogenic conditions for return to Earth.

***Low-power electronics*—**Specific components may be required to permit systems to operate at milliwatt power levels for decades from miniature RPSs. This may also include the ability to operate in harsh environments without active thermal control.

***Radiation-hard electronics*—**Electronic systems suffer prompt ("bit-flip" and latchup) and cumulative (total dose) damage from radiation, both natural and from any nearby nuclear power sources. Specific fabrication materials and architectures for components are required to survive high-radiation environments.

***High-thrust and I_{sp} nuclear propulsion*—**The JIMO mission assumes fission-powered ion propulsion, which has high specific impulse (I_{sp}) but very low thrust. Some missions require higher thrust levels (e.g., asteroid landing, hovering above Saturn's ring plane etc.) that would ideally also have high I_{sp}—an example of such a system is the magnetoplasmadynamic arcjet.

before the priority of specific approaches for implementing these missions can be adjudicated. There is a particularly strong need for trade-off studies of large NEP-powered craft versus other modes for implementing the same science goals.

The development of nuclear technologies must go hand in hand with ancillary developments in such areas as communications, data entrapment, and spacecraft subsystems. Planetary exploration is a rich field that allows public involvement and generates student interest in engineering and science. A mix of exploration capabilities should be developed that will allow diverse pursuits that will enhance this capability and ensure the long-term health and vitality of the planetary exploration enterprise.

REFERENCES

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

2. R.B. Abelson, ed., *Enabling Exploration with Small Radioisotope Power Systems*, JPL 04-10, Jet Propulsion Laboratory, Pasadena, Calif., 2004.

3. Space Studies Board, National Research Council, *A Scientific Rational for Mobility in Planetary Environments*, National Academy Press, Washington, D.C., 1999, pp. 42–43.

4. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 96.

5. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 196.

6. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 177–188.

7. President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, U.S. Government Printing Office, Washington, D.C., 2004, p. 28.

7

Applications of Nuclear Power and Propulsion in Astronomy and Astrophysics: Background

SCIENTIFIC AND PROGRAMMATIC CONTEXT

The Goals of Astronomy and Astrophysics

How did the universe begin and evolve? How did we get here? Where are we going? Are we alone? The big questions of astronomy and the majesty of the universe capture the imagination of the public and excite young people's interest in science and technology. The public's enthusiasm for the images returned by the Hubble Space Telescope and people's perennial interest in black holes and cosmology are just two examples.

The fundamental goal of astronomy and astrophysics is to understand how the universe and all its constituents formed, how they evolved, and what their destiny will be. To determine the optimum strategy for addressing these big questions, the astronomy and astrophysics community initiated the fifth of its so-called decadal surveys in 1999.[1] The results of the survey committee's deliberations, published in 2001 as *Astronomy and Astrophysics in the New Millennium* (hereafter the AAp decadal survey), advised that astronomers do the following:[2]

- Map the galaxies, gas, and dark matter and dark energy in the universe as these evolve through cosmic time, and survey the gas, stars, and planets in the galaxy;
- Use the universe as a unique laboratory for probing the laws of physics in regimes not accessible on Earth, such as the very early universe or near the event horizon of a black hole;
- Search for life beyond Earth, and if it is found, determine its nature and distribution in the Milky Way galaxy; and
- Develop a conceptual framework that accounts for all that astronomers have observed.

The AAp decadal survey concluded that the key problems for astronomers and astrophysicists to address in the coming decade were the following:

- Determine the large-scale properties of the universe—the amount, distribution, and nature of its matter and energy; its age; and the history of its expansion;
- Study the dawn of the modern universe when the first stars and galaxies formed;
- Understand the formation and evolution of black holes of all sizes;

- Study the formation of stars and their planetary systems, and the birth and evolution of giant and terrestrial planets; and
- Understand how the astronomical environment affects Earth.

As discussed below, new discoveries since the publication of the AAp decadal survey motivated the development of a subsequent report on the interface between physics and astrophysics, *Connecting Quarks with the Cosmos*.[3]

High-Priority Missions in the AAp Decadal Survey

To achieve the priority goals listed above, the AAp decadal survey selected as its highest priorities a number of ground- and space-based initiatives, grouped according to cost as major, moderate, and small.[a]

The major space-based initiatives recommended are, in priority order, as follows:

1. *Next Generation Space Telescope.* A large telescope optimized for near-mid-infrared imaging and spectroscopy;[b]
2. *Constellation-X.* A suite of four x-ray telescopes optimized for high-throughput spectroscopic observations;
3. *Terrestrial Planet Finder (TPF).* A telescope system intended to image faint planets orbiting nearby Sun-like stars;[c] and
4. *Single Aperture Far Infrared Observatory.* A large telescope designed to study the important but relatively unexplored spectral region between 30 and 300 microns (μm).

The moderate space-based initiatives include, in priority order, the following:

1. *Gamma-ray Large Area Space Telescope.* A joint NASA-Department of Energy mission to study gamma rays with energies from 10 MeV to 300 GeV;
2. *Laser Interferometer Space Antenna.* A gravitational wave detector sensitive to radiation in the 0.1- to 100-mHz band likely to be emitted by merging supermassive black holes and close binary stars;
3. *Solar Dynamics Observatory.* A telescope to study the Sun's outer convection zone and the structure of the solar corona;
4. *Energetic X-ray Imaging Survey Telescope.* An instrument designed to map the highly variable, hard x-ray sky; and
5. *Advanced Radio Interferometry between Space and Earth.* An orbiting radio antenna designed to work in conjunction with ground-based radio arrays to provide high-resolution observations of active galactic nuclei.

In addition, the AAp decadal survey strongly encouraged the continued development of small space missions (e.g., sounding rockets, Explorer-class and Discovery-class principal investigator (PI)-led missions). These provide low-cost opportunities to test new ideas or to use groundbreaking new technologies, and also serve to give personnel experience in mission development and implementation.

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[a] Note that unlike the SSP and SSE surveys, the AAp decadal survey did not define strict cost limits for these categories.

[b] Now being implemented as the James Webb Space Telescope.

[c] Now being implemented as two different spacecraft: TPF-I, an interferometric array working at infrared wavelengths, and TPF-C, a coronagraph working at visible wavelengths.

Recent Scientific Developments

The two most startling observational discoveries of recent years in astronomy and astrophysics are as follows:

- Super-massive black holes are present at the center of virtually all galaxies; and
- The familiar forms of matter (e.g., gas, stars, and planets) represent only about 4 percent of the mass-energy in the local universe, and most of the content of the universe is dark energy and dark matter.

Recent theoretical predictions have also motivated new experimental work. The two most notable predictions are the following:

- Gravitational waves created during inflation when the universe was some 10^{-37} s old can make a detectable signature in the polarization of the cosmic microwave background and may also be detectable directly; and
- "Cosmic censorship" can be violated, and black holes can have "quantum hair." Cosmic censorship is the widely held speculation, originally espoused by Roger Penrose, that a gravitational singularity is always shrouded by an event horizon so that it can never be seen by a distant observer. "Quantum hair" refers to possible deviations from the conventional view developed by Stephen Hawking and Roger Penrose that the only external clues to the nature of material swallowed up by a black hole are manifested in terms of changes to the hole's mass, angular momentum, and electric charge.

Some 26 percent of the mass-energy in the universe is in a mysterious "dark" form of matter, which might be exotic fundamental particles as yet not known from accelerator experiments, or might be black holes or some as-yet-undreamed-of objects. In addition, some 70 percent of the mass-energy is in an even more mysterious constituent, the so-called dark energy, which has exotic properties such as a sound speed of nearly the speed of light and exerts a negative pressure that is pulling the universe apart.

The fact that 96 percent of the universe is in the form of matter of an unknown nature has convinced most astronomers that a new fundamental physics is needed to understand the universe. But these frontiers of physics—grand unified theories of particles and their interactions, string theory, quantum gravity—have proved to be difficult to test in the conditions accessible to ground-based experiments. Much greater extremes of energy and gravity are reached in astronomical objects such as supernovas and black holes, as well as in the early universe. Many physicists have thus become convinced that astronomical studies hold keys to the future development of fundamental physics.

The Interface Between Fundamental Physics and Astrophysics

Recognition of the increasing importance of the close interplay among astronomy, astrophysics, and fundamental physics led to the publication in 2003 of *Connecting Quarks with the Cosmos*,[4] a report that made recommendations and defined priorities for the field, informed by the developments since the release of the AAp decadal survey. The principal questions of interest identified were as follows:

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

Connecting Quarks with the Cosmos reaffirmed, with increased importance, two space missions—the Laser Interferometer Space Antenna (LISA) and Constellation-X—already listed as priorities of the AAp decadal survey. The report also recommended two new space-based missions that were not listed as priorities in the 2001 astronomy decadal survey:

- A mission to measure the polarization of the cosmic microwave background radiation; and
- A wide-field optical imaging telescope in space to investigate the properties of the dark energy.

NASA's response to *Connecting Quarks with the Cosmos* was the 2003 *Beyond Einstein* roadmap.[5] The latter document, which remains of vital interest and importance to the astronomical and physics communities,[6] sought funding for LISA and Constellation-X (as facility-class missions) and for a line of moderate-cost Einstein Probes. The first three recommended Einstein Probes are as follows:

- *Dark Energy Probe.* A wide-field optical imaging telescope in space;
- *Inflation Probe.* A mission to measure the polarization of the cosmic microwave background radiation; and
- *Black Hole Probe.* A mission to survey the universe for hidden black holes.

Programmatic Context

Access to space uniquely enables astronomers and astrophysicists to achieve many of the goals of the AAp decadal survey and *Connecting Quarks with the Cosmos*. There is a great diversity of objects in the universe. Many of the important objects reveal themselves only through particular types of radiation. To discover the interactions between these diverse objects, and to thus gain an understanding of the workings of the universe, requires the study of both bright and faint objects at many different wavebands. Using a wide range of different detectors of electromagnetic and gravitational radiation, astronomers seek the diverse objects hiding in the universe.

Astronomy is inextricably tied to observations made from space because most of this radiation is absorbed and blurred by Earth's atmosphere. X-rays, gamma rays, ultraviolet light, and most infrared radiation cannot penetrate Earth's atmosphere: space-based instruments are the only way to discover what constituents of the universe emit this radiation. The changing gravitational fields from moving bodies on Earth's surface make it impossible, on Earth, to discriminate gravitational waves with frequencies below 1 Hz. Thus, astronomers go to space to escape the atmosphere and the thermal, radiation, and seismic environment of Earth. With a very few exceptions discussed below, any space observatory close to but well separated from Earth (e.g., at the Sun-Earth L2 point, such as the Wilkinson Microwave Anisotropy Probe [WMAP], or in an Earth-trailing, 1-AU orbit, such as the Spitzer Space Telescope) can perform as well as one located anywhere else in the solar system or beyond.

The Exploration Initiative

The implementation of NASA's new exploration initiative should, at first glance, have a positive impact on astronomy and astrophysics. The report of the Aldridge Commission,[7] charged to define a plan for implementing the initiative, proposes a notional science agenda that is consistent with the science goals outlined in NASA's *Beyond Einstein* roadmap.[8] Nevertheless, members of the astronomy and astrophysics community are concerned that current and future budgetary pressures will impact the implementation of the science priorities in the AAp decadal survey and in *Connecting Quarks with the Cosmos*.[9]

Why a Diversity of Missions Is Needed

As indicated above, the diverse contents of the universe span a vast range of brightness and distance and emit an enormous diversity of radiation, only narrow bands of which can penetrate Earth's atmosphere. Other objects of interest may not be visible at all and can be studied only through detection of their gravitational radiation or their influence on the surrounding medium.

Many of the important scientific priorities in astronomy and astrophysics can be addressed most easily through small, low-cost, focused space missions. An excellent example is the tremendous success of WMAP in revolutionizing understanding of the early evolution of our universe. Other investigations require medium-sized, space-based facilities. Only the most wide-reaching scientific problems should require development of large observatory-class spacecraft such as the James Webb Space Telescope (JWST), LISA, or Constellation-X. Telescope and detector technologies evolve and improve rapidly, making small-scale testing of new paradigm-breaking instruments and techniques vital. The AAp decadal survey recognized that regular access to a variety of mission opportunities in many wavebands is essential to the health of astrophysical science, stating that "NASA should continue to encourage the development of a diverse range of mission sizes, including small, moderate, and major, to ensure the most effective returns from the U.S. space program."[10]

IMPLEMENTATION AND TECHNIQUES

Unlike explorers of Earth and the solar system, astronomers cannot get better views of the distant reaches of the universe by moving their space-based telescopes closer to the object under study. Nor can they determine the characteristics of extrasolar planets, for example, by actively probing them with high-powered instruments. Astronomical discoveries are made simply by pointing telescopes in the appropriate directions and then looking farther, longer, or with a better resolution than ever before. Astronomers using space-based instruments accomplish this by doing one or more of the following:

- *Building bigger and/or more telescopes.* Space-based telescopes are limited by the size and mass that can be launched from Earth to Earth-escape, and also by the high cost of launch. The past few decades have not seen significant improvements in launch size, mass, or cost. If this trend continues, bigger telescopes will instead be enabled by technological advances in such areas as large lightweight mirrors and support structures, precision metrology and formation-flying capabilities, long-lifetime lasers, and in-space deployment and assembly.
- *Pushing the limits of detector technology until the laws of physics prevent further improvements.* New, more sensitive detectors with more pixels and better time or spectral resolution, and improved cryogenic techniques to reduce local backgrounds, are often low-cost substitutes for bigger telescopes.
- *Designing detectors with wider fields of view to study more objects at once.*

Astronomical observations typically involve passive, low-noise activities, which thrive with the least possible disturbance from local effects. For example, observatories seek to minimize the diffuse background of photons and cosmic rays, the thermal loading on the telescope from the Sun or Earth, and contamination of mirror surfaces. Similarly, most of the fundamental physics missions carried out so far have been either passive ranging experiments in near-Earth space (e.g., Lunar Laser Ranging and LAGEOS) or experiments on Earth-orbiting platforms (e.g., the Lambda Point and Confined Helium experiments, and Gravity Probe B).

These shared characteristics imply that the potential benefits of large nuclear power sources and propulsion systems are less apparent for astrophysics and fundamental physics missions than for planetary exploration. The following sections explore some relevant considerations and discuss some potential niche applications of nuclear systems.

Propulsion

Astrophysics and fundamental physics missions make very light demands on propulsion systems once the missions reach their observing orbits. It is possible, however, to conceive of a few very specific applications in which nuclear propulsion systems might allow researchers access to favorable observing locations that would otherwise be unattainable:

- *Generating long baselines between two or more telescopes.* Among the various possibilities are the following:

—*Geometrical parallax.* Telescopes separated by many tens to hundreds of AU can potentially improve the astronomical distance scale. (See "Geometrical Parallax Mapper" in the section "Generating Very Long Baselines" in Chapter 8.)

—*Localizing gamma-ray bursts (GRBs).* A very small and low-power GRB detector on an interstellar-probe type mission (see Chapter 4) would provide GRB positions with arc-second accuracy even if there were no afterglow. Although these detectors cannot operate near a fission reactor, they have operated successfully on spacecraft powered by radioisotope power systems (RPSs). (See "Gamma-Ray Burst Locator" in the section "Generating Very Long Baselines" in Chapter 8.)

—*Radio interferometry.* Interferometers operating at long radio wavelengths require baselines of more than 1 AU to provide very high resolution observations. (See "Long-Baseline Radio Interferometer" in the section "Generating Very Long Baselines" in Chapter 8.)

—*Microlensing parallax.* Telescopes separated by distances of up to a few AU can be used to disentangle the effects of the tranverse-velocity and the mass of the lensing object. (See "Microlensing Parallax Mapper" in the section "Permitting More Favorable Observing Locations: Accessing Special Alignments" in Chapter 8.)

- *Permitting observations from a more favorable location.* To date, astronomers have made use of spacecraft in low and geosynchronous orbits about Earth (e.g., the Hubble Space Telescope and the International Ultraviolet Explorer, respectively), at the Sun-Earth L2 point (e.g., the Wilkinson Microwave Anisotropy Probe), and in 1-AU heliocentric orbits that gradually drift away from Earth (e.g., the Spitzer Space Telescope). But other locations can be more favorable in various ways, including the following:

—*Other locations can provide a lower diffuse background, rendering background-limited observations more sensitive, and can vastly reduce the level of uncertainty in cosmic background observations.* Moving a telescope from 1 AU to between 3 and 5 AU from the Sun can reduce the background by a factor of up to 100. This improvement occurs only for optical through far-infrared wavelengths. For ultraviolet and shorter wavelengths, and for wavelengths of 100 μm and longer, the foreground from interplanetary matter is less prominent. At these greater distances from the Sun, RPSs are certainly competitive in cost and weight with solar panels as a way to provide power. (See "5-AU Optical/Near-Infrared Observatory" in the section "Permitting More Favorable Observing Locations: Beyond 3 AU" in Chapter 8.)

—*They can enable the use of a cooler telescope.* Cooler telescopes make infrared observations much more sensitive, extend the lifetime of cryostats, and make the job of cryocoolers much easier. Since the outer skin of the Spitzer Space Telescope is passively cooled to 35 K at 1 AU from the Sun, it is clear that careful attention to using sunshades may be a more economical approach to creating a cooler telescope. (See "5-AU Far-Infrared Observatory" in the section "Permitting More Favorable Observing Locations: Beyond 3 AU" in Chapter 8.)

—*They can provide an environment free of manmade radio-frequency interference.* This is extremely important for low-frequency radio astronomy. A radio observatory on the farside of the Moon could well be an application for an RPS, since operation through a lunar night relying on solar cells and batteries will be quite difficult. (See "Farside Radio Observatory" in the section "Permitting More Favorable Observing Locations: The Moon and Moons of Mars" in Chapter 8.)

- *Accessing special alignments.* By placing a telescope at carefully selected places in the solar system, it may be possible to make use of gravitational lensing to obtain ultrahigh-resolution images of extragalactic objects. Possibilities include the following:

—Some of the lines connecting known active galactic nuclei (AGN) and known binary stars pass within tens of AU of the Sun. A telescope located on such a line could use the caustics from the binary star to undertake extremely high resolution observations of the AGN. (See "Binary-Star Gravitational Telescope" in the section "Permitting More Favorable Observing Locations: Accessing Special Alignments" in Chapter 8.)

—The Sun itself can be used as a gravitational lens. The telescope would have to be located at least 550 AU from the Sun. Indeed, effective shielding against the light from the Sun would require placement at distances greater than 800 AU and very large occulting disks. (See "Solar Gravitational Telescope" in the section "Permitting More Favorable Observing Locations: Accessing Special Alignments" in Chapter 8.)

Power

Current and planned astrophysics missions are in general not constrained by the currently available power. Operating even the biggest telescopes and detectors does not require large amounts of electrical power. Although the capabilities of onboard computers have increased exponentially, electrical power requirements have remained nearly constant. Major missions have electrical power requirements in the range of 1 to 10 kWe (see Table 7.1), requirements that solar power meets with only a minor impact on the cost, weight, and risk of missions. Indeed, the current cost for solar-electric power on spacecraft is low enough that it is only a minor component of mission cost at 1 AU, whereas the cost estimated for nuclear-electric power is substantially higher (Figure 1.1). There may conceivably be electrical power needs in the range of 10 kilowatts or greater in the foreseeable future for massive onboard computation or for lasers on gravitational-wave detectors.

Although access to sources of electric power over a wide power range is important, it is likely that except for a few niche applications (see, e.g., “Lunar Astronomical Observatory” in the section “Permitting More Favorable Observing Locations: The Moon and Moons of Mars” in Chapter 8), solar power will remain more cost- and weight-effective than nuclear power for applications near 1 AU. If in fact the currently estimated kg/kWe for nuclear fission reactors, multiplied by the cost of launch (in $/kg) to an escape trajectory, is much higher than the cost of solar power, even a reactor supplied at zero cost to the mission would not be cost-effective.

Communications

Transmitting the increasing volumes of data from, for example, wide-field detectors back to Earth could consume large amounts of radio power, but Shannon’s theorem suggests that it is generally far more cost-effective to increase the bandwidth and collecting area of the ground-based receivers than to provide each mission with more powerful transmitters. As indicated in Table 7.1, the expected data-transmission rates of future major astronomy and astrophysics missions are, with a few notable exceptions, expected to be relatively modest.

TABLE 7.1 Important NASA Astronomy and Astrophysics Missions

Mission	Orbit	Power (kWe)	Data Rate (Mbps)	NRC Recommendation[a]
Launch Before 2015				
GLAST	LEO	1	2	1
SIM	1 AU	6	6.4	2
JWST	L2	3	3	1
LISA	1 AU	0.2	0.001	1, 3
Launch After 2015				
TPF-C	L2	1.8	64	1
TPF-I[b]	L2	2, 0.8	1, 0.02	1
Constellation-X	L2	1	2	1, 3
SAFIR	L2 or 3 AU	4	1	1
Black Hole Probe	LEO or HEO	1	1	1, 3
Dark Energy Probe (JDEM)	HEO	1.5	55	3
Inflation Probe	L2	?	?	3
Black Hole Imager (ARISE)	HEO	?	4000	1
Black Hole Imager (MAXIM)	1 AU	1	0.05	—
Big Bang Observer	1 AU	9	0.1	—
Life Finder	?	?	?	—

[a] Source of NRC recommendation: 1—AAp decadal survey 2001; 2—AAp decadal survey 1991; and 3—*Connecting Quarks with the Cosmos*.

[b] Power and data rates are quoted for the combiner and collector spacecraft, respectively.

Radiation and Environmental Factors

Onboard detectors in nearly all experiments reach quantum-limited levels of sensitivity and hence tend to be quite sensitive to disturbance by local high-energy particles and photons. The effects of other environmental factors such as vibrations, stray magnetic fields, and outgassing of spacecraft components are also of concern. The radiation emanating from nuclear power systems, particularly fission reactors, is especially worrisome because it can significantly degrade the sensitivity of astrophysical observations. This issue is most acute for x-ray and gamma-ray observatories, which are by design exquisitely sensitive to exactly the types of radiation produced by fission reactors. Shielding of nuclear power systems is therefore a leading issue in their application to astrophysical missions.

REFERENCES

1. The four previous decadal surveys are as follows: Committee on Science and Public Policy, National Academy of Sciences, *Ground-Based Astronomy: A Ten-Year Program*, National Academy of Sciences, Washington, D.C., 1964; Committee on Science and Public Policy, National Academy of Sciences, *Astronomy and Astrophysics for the 1970's*, National Academy of Sciences, Washington, D.C., 1973; Assembly of Mathematical and Physical Sciences, National Research Council, *Astronomy and Astrophysics for the 1980's*, National Academy Press, Washington, D.C., 1982; and Board on Physics and Astronomy, National Research Council, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991.
2. National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.
3. National Research Council, *Connecting Quarks with the Cosmos—Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., 2003.
4. National Research Council, *Connecting Quarks with the Cosmos—Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C., 2003.
5. The Structure and Evolution of the Universe Roadmap Team, *Beyond Einstein: From the Big Bang to Black Holes*, NP-2002-10-510-GSFC, National Aeronautics and Space Administration, Washington, D.C., 2003.
6. The February 11, 2005, letter report of the NRC's Committee to Review Progress in Astronomy and Astrophysics Toward the Decadal Vision (The National Academies Press, Washington, D.C., 2005) commented that the *Beyond Einstein* roadmap "is an excellent implementation and synthesis of the [AAp decadal survey] and *Connecting Quarks with the Cosmos*."
7. President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, U.S. Government Printing Office, Washington, D.C., 2004.
8. National Research Council, "Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision: Letter Report," The National Academies Press, Washington, D.C., 2005, p. 11.
9. National Research Council, "Review of Progress in Astronomy and Astrophysics Toward the Decadal Vision: Letter Report," The National Academies Press, Washington, D.C., 2005, p. 10.
10. National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001, p. 28.

8

Applications of Nuclear Power and Propulsion in Astronomy and Astrophysics: Missions

NUCLEAR POWER AND PROPULSION FOR SPECIFIC ASTROPHYSICAL APPLICATIONS

To gauge the possibility that radioisotope power systems (RPSs) and/or fission reactors might enhance or enable the achievement of important astrophysical goals, this chapter examines several types of astrophysical missions for which nuclear systems might potentially be considered. The discussion focuses on several of the important categories of applications outlined in the section "Implementation and Techniques" in Chapter 7. As the discussion below makes clear, nuclear power and propulsion technologies are not enabling nor enhancing for any of the current high-priority scientific goals of astronomy and astrophysics.

Generating Very Long Baselines

Nuclear power systems would be truly enabling for astronomical observations that require multiple telescopes separated by distances of >5 AU and involve operation of (at least) one observatory far enough from the Sun that solar power would be more expensive than nuclear power. One such new opportunity is created by the ability to conduct radio interferometry using baselines extending over many AU. Figure 8.1 shows the angular resolution obtained from interferometry as a function of observing wavelength (λ) and baseline. It is notable that an interferometer with 1-AU baseline—for which nuclear power systems offer no advantage—is capable of achieving an angular resolution of a nanosecond of arc at all wavelengths less than 1 mm. Such a resolution is sufficient to resolve neutron stars or active galactic nuclei (AGN) black holes, or to measure parallaxes at 100 megaparsecs. There is limited return from obtaining yet finer angular resolution, and in any case a telescope much larger than any currently imagined as remotely feasible would be required to obtain observations with a sufficient signal-to-noise ratio for such small features.

Three other possibilities for the use of nuclear systems include the following:

- *Geometrical Parallax Mapper.* A 1980s study of the so-called Thousand Astronomical Units (TAU) mission emphasized the possibility of microarcsecond parallax measurement, which would enable determination of geometric distances to Local Group galaxies and hence a more accurate extragalactic distance scale.[1] It is now believed to be far more feasible to obtain these measurements using interferometry with baselines well below 1 AU.

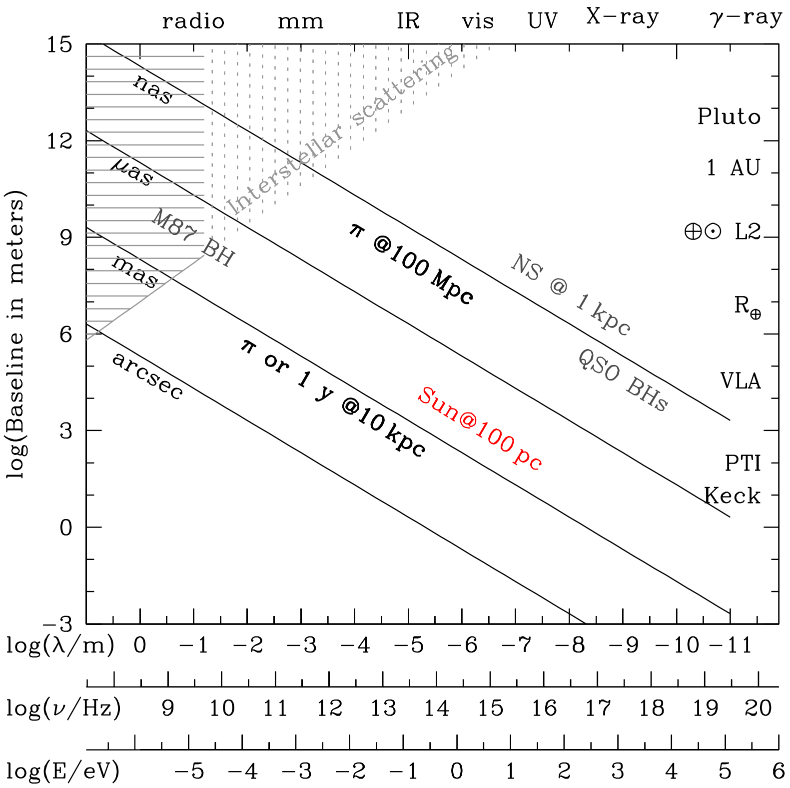

FIGURE 8.1 Diagram illustrating that there is little justification for astronomical interferometry on baselines longer than the Earth-Sun distance (1 AU). Sloping black lines: angular resolution as a function of baseline (ordinate) and photon wavelength λ, frequency ν, or energy E (abscissas). One arcsecond is 1/3600 degree. Right ordinate: bottom to top, baselines of the Keck Telescope, Palomar Testbed Interferometer (PTI), Very Large Array (VLA), Earth's radius ($R_\oplus$), the distance to the Earth-Sun L2 point ($\odot\oplus$ L2), the Earth-Sun separation (1 AU), and the semi-major axis of Pluto's orbit. Lightface labels—angular diameters of a Sun-like star at 100 pc, of the horizon of the 3 billion solar-mass black hole in the nearby galaxy M87 (the black hole in the center of the Milky Way appears 3 times larger), of the 100 million solar-mass black holes in typical quasars at redshift of 2, and of a nearby neutron star at 1-kpc distance. Boldface labels: resolution needed to obtain a 1 percent parallax (π) or resolve a 1-year period solar-mass binary at 10 kpc and to measure a 1 percent parallax at a distance of 100 Mpc. Scattering in the interstellar medium causes the images formed by combinations of wavelength and baseline falling in the hatched region (upper left) to be blurred to the size of the region's lower boundary line. Thin horizontal lines: strong multipath scattering. Dotted vertical lines: weak scattering, with images appearing as scattered speckles; some information about source size may remain.

- *Gamma-Ray Burst Locator.* Time-of-arrival triangulation on ≈50-AU baselines can localize the sources of gamma-ray bursts (GRBs) down to the arcsecond scales required for unambiguous identification of the host galaxy. The Swift mission may demonstrate that all GRBs have afterglow emissions that can be used to locate the host galaxy. But if there are classes of GRBs with no localizable afterglow, a long-baseline GRB network would be scientifically compelling. GRB detector sensitivities would be enormously degraded by the gamma-ray background from a nearby fission reactor, but GRB detectors have successfully coexisted with the radioisotope thermoelectric generator (RTG) on the Ulysses spacecraft. For a small payload like a GRB detector, solar sails may offer a faster transit to 50 AU than would nuclear-electric propulsion (NEP). Even if a solar sail is used, an RPS would still be required to supply the spacecraft's electrical-power requirements.

- *Long-Baseline Radio Interferometer.* Radio (λ >1 mm) interferometry on interplanetary baselines appears, at first glance, to be an ideal application for the use of nuclear power, given that it is only at that wavelength that an attempt has been made, successfully, to correlate wavefronts using a space-based antenna. However, the scattering of radio waves by the interstellar medium blurs radio images to angular sizes much greater than can be resolved by a radio interferometer with >1-AU baselines (see Appendix D for additional details). Some AGN are relatively bright sources at high radio frequencies where scattering is minimized. Nevertheless, sources with the brightness temperatures required to produce correlated signals on such large baselines may not exist. Moreover, without an armada of observatories, the time to fill in the so-called UV plane would likely exceed the time over which source structures on the smallest observable scales could vary. The only sources with sufficiently high intrinsic brightness temperature and stable morphologies are radio pulsars, but these are intrinsically low-frequency objects that thus suffer too much scattering. There thus appears to be no compelling justification for radio interferometry on baselines greatly exceeding the radius of Earth's orbit.

Permitting More Favorable Observing Locations: The Moon and Moons of Mars

The question of observatories on the Moon and elsewhere in the solar system has received new attention within the context of NASA's new exploration initiative. Four possibilities are considered below:

- *Lunar Astronomical Observatory.* The use of the Moon as a site for an observatory was carefully considered by the astronomical community 20 years ago and found to offer science potential at that time.[2,3] The Moon offers a solid surface on which to anchor telescopes, no absorbing atmosphere, and, in lunar polar craters that are permanently shadowed, a thermally convenient place to locate sensitive infrared telescopes. In these respects, the surface of the Moon is vastly better for astronomy than the surface of Earth. These facilities would need power for operations and communication, and in some cases would need heat sources for survival. Providing such power through the lunar night would likely require nuclear systems.[a]

Within the astronomical community, however, enthusiasm for lunar surface observatories has waned considerably over the last two decades.[4] During this time, enormous progress has been made in free-space telescope operations—e.g., guiding, tracking, and stabilization—and there is no longer the need for a solid surface to anchor telescopes. Furthermore, the lunar surface has distinct disadvantages over free-space sites, including the presence of gravity—which imposes serious structural requirements on precision optical systems that are pointed around the sky—and dust. Free space offers the same vacuum as does the lunar surface, and although the lunar polar craters are naturally very cold, similarly low temperatures have been achieved in free space with deployable sun shields. Although human-aided deployment and maintenance of astronomical instruments on the Moon could be advantageous, it is by no means clear that, in the context of the new exploration agenda, free-space sites will be less accessible than lunar surface sites to human service crews. Thus, for achieving most astronomical goals (see the discussion below for two possible exceptions), the use of the lunar surface as an observatory site does not appear to offer any enabling advantages over the use of free space.

- *Farside Radio Observatory.* The Moon's farside is a generally radio-quiet location, because it is effectively shielded from both natural and human-caused electromagnetic emissions from Earth. The effect of terrestrial radio noise on passive scientific research such as radio astronomy is enormous. A variety of astronomical objects are expected to emit in the spectral regions affected by terrestrial interference, and study of these objects is likely to be scientifically interesting (see Appendix D for details).

Is a lunar-based radio telescope essential to the continued existence of radio astronomy as a science? The answer to this question is not yet clear. Some locations on Earth are still relatively radio quiet, although whether

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[a] Although by careful selection of the observing site, operations in permanently shadowed craters on the Moon's polar regions could be enabled by power transmitted from sites, such as crater rims, located in permanent sunlight.

they will remain so is a primary issue. However, quantifying the deleterious effects of interference, and projecting them into the future, is extremely difficult. Techniques for mitigating radio-frequency interference are currently under very active development in preparation for the next generation of Earth-based radio telescopes. Certainly more will be known regarding the growth in the sources of interference, as well as the ability to mitigate it, once these telescopes are operating, over the next two decades.

The use of a free-flying fleet of dipole receivers reliant on solar power could reduce the terrestrial radio-frequency interference by r^{-2} and might possibly suffice to achieve high-priority science goals, obviating the need to leverage the shielding effect of the Moon and the concomitant need to use nuclear power systems. A farside dipole array could possibly be operated with an RPS rather than a reactor, with telecommunications and/or computing requiring most of the power. These alternatives suggest that a nuclear reactor-powered farside observatory is not a uniquely enabling solution to the problem of radio interference.

- *Lunar Gravitational Wave Array.* The Moon could be instrumented as a sensitive gravitational-wave detector. By combining signals from several superconducting (2 K) displacement sensors distributed over the surface of the Moon, a sensitive detector ($h_{min} \leq 10^{-22}$ $Hz^{-1/2}$) with full-sky coverage could be constructed. Such displacement sensors could be tuned to the lowest quadrupole mode of the Moon (1 mHz) or operated as a wideband detector below the fundamental frequency (<1 mHz).
- *Phobos/Deimos Gravitational Wave Array.* Another interesting possibility is instrumenting the martian moons, Phobos or Deimos, as gravitational-wave detectors. With a radius of only several kilometers, one of the moons of Mars will cover a medium frequency band (0.1 to 1 Hz), which will be missed by both the ground detectors and the Laser Interferometer Space Antenna (LISA). RPSs would be needed to cool and operate these displacement sensors continuously. The cryocooler is expected to dominate the power budget (requiring ~100 to 200 watts of electrical power per site). However, the sensitivity of such gravitational-wave detectors would be substantially less than that of currently envisioned free-flying (solar-powered) laser interferometer gravitational wave detectors in the same 0.1- to 1-Hz band, such as the proposed Big Bang Observer. Detailed studies of cost trade-offs would be necessary to determine if there is a niche for such detectors.

Permitting More Favorable Observing Locations: Beyond 3 AU

Both the zodiacal-light background (Figure 8.2) and the solar thermal load on a telescope decrease with increasing distance from the Sun. Beyond ~2 to 3 AU from the Sun, nuclear power might become more cost-effective than solar power for propelling or powering an observatory.

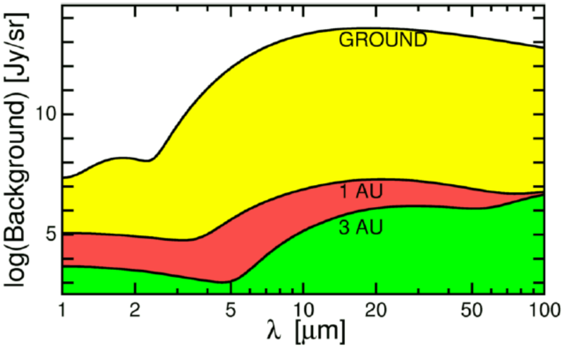

FIGURE 8.2 Brightness of the infrared background as a function of wavelength at high ecliptic latitudes from the ground, in Earth-trailing solar orbit (1 AU), and at 3 AU.

The maximization of scientific benefit per dollar invested involves a complex trade-off between the advantages offered by the superior ~3- to 5-AU environment versus the larger mass/aperture and earlier operations obtainable for the same cost with a telescope located at the Sun-Earth L2 or the Spitzer-like drift-away orbits. Two major possibilities and one mission of opportunity are considered below. Note that there is no incentive for placing radio or high-energy observatories at 5 AU.

- *5-AU Optical/Near-Infrared Observatory.* For observations at $\lambda \approx 0.2$ to 3 μm, sunlight scattered by zodiacal dust grains is the dominant source of diffuse background emissions and can, thus, be the dominant source of noise for observations of faint sources. An observatory at 5 AU could have ≈ 50× lower zodiacal background than current or planned ultraviolet/optical/infrared observatories in Earth-trailing or L2 orbits. For nuclear power and propulsion systems to be enabling for a 5-AU observatory mission, placing and operating a 2-meter telescope at 5 AU from the Sun would have to cost much less than placing and operating a 15-meter telescope (or 50 2-meter telescopes) at the Sun-Earth L2 point. Otherwise, the clear choice would be the L2 option, which would offer a superior signal-to-noise ratio (see Appendix D for details) for other observations, as well as better resolution. Certainly, the priorities of the ultraviolet/optical/infrared community will emphasize first building a larger collecting area near 1 AU.
- *5-AU Far-Infrared Observatory.* At thermal infrared wavelengths ($\lambda > 1$ μm), space observatories with ambient temperature at 1 AU (300 K) are strongly background limited by emissions from the telescope itself. Therefore, cooling the observatory's optical system greatly increases observing sensitivity. For smaller telescopes, such as the 0.8-m Spitzer Space Telescope, onboard expendable cryogens can be used for this purpose, resulting in telescope temperatures on the order of between 4 and 8 K. Such a cooling strategy is more difficult for larger astronomical telescopes. Active cooling with onboard refrigerators is probably the best way to ensure a long observatory lifetime (see Appendix D for details). These systems do, however, have substantial power requirements, which can be met by solar arrays at 1 AU. Telescopes at larger heliocentric distances, however, may be enabled by RPSs. Of some interest is the possibility that an infrared observatory at a large heliocentric distance could be powered by a separate spacecraft, with reactor power beamed across a distance that would obviate problems associated with waste heat and radiation.[5,6] With enormous generation capability, the power-plant spacecraft could be outfitted for propulsion as well, and could serve as a tug to bring the observatory to the science venue before standing off Sun-ward of the observatory. Such a tug could be outfitted for a powerful communication link back to Earth and could act as a relay station for observatory communications. In this case, the communication power budget for the observatory itself could be quite modest, because it would only need to link to the relay station.
- *Infrared Background/Zodiacal Light Mapper.* It could be argued that missions such as the Interstellar Observatory (see Box 4.1 and Appendix B) or, possibly, the Titan Express/Interstellar Pioneer (see Box 6.4) present opportunities for the conduct of astronomical observations. These missions are designed to travel out to 200 AU, where zodiacal light is no longer a concern. A small (~10-cm-aperture) mid/far-infrared telescope on such a mission could measure the cosmic background at wavelengths from 3 to 100 μm, believed to be a result of the superposition of emissions from dusty galaxies at high redshifts. Knowledge gained from such measurements would help identify how much had been "missed" at low surface brightness or low flux in imaging missions such as the Spitzer Space Telescope and the James Webb Space Telescope. This is an interesting, but not a high-priority opportunity, because the relevant observations can be made at distances of between 3 and 5 AU from the Sun and do not require travel to 200 AU. And similar measurements could also be performed by a large infrared telescope at 5 AU that would have much wider applicability, such as described above.

Permitting More Favorable Observing Locations: Accessing Special Alignments

In gravitational lensing events, the alignment between the photon source, the lensing mass, and the observer can grossly affect the received image. Adjustment of the observer's position can therefore be exploited, opening a window for nuclear propulsion systems to enable new scientific opportunities. Three types of missions have been proposed:

- *Microlensing Parallax Mapper.* The amplification of background stars in the Local Group galaxies through gravitational lensing by foreground stars or dark masses is now routinely detected. The proper motions of the source and lens cause the amplification pattern to sweep across Earth. The time-series information gives the characteristic Einstein-ring size divided by the (projected) transverse velocity of the source/lens.[7] With additional telescope(s) separated by ~1 AU, the characteristic size can be determined independent of the velocity. When applied to Local Group microlensing events, this approach results in improved knowledge of the masses and dynamics of the lensing and source populations. Because the sizes of the projected Einstein rings are typically a few AU, there is no gain from baselines of 5 AU or greater. Similarly, distant AGN can be microlensed by the individual stars in intervening galaxies, and observations from a network of three telescopes on ~10-AU baselines can provide sufficient information to disentangle the effects of transverse velocity and size imprinted on the lensing caustic sweeping across the solar system. In this way, improved constraints on the sizes of AGN can be determined.
- *Binary-Star Gravitational Telescope.* Gould and Gaudi propose placing a telescope in a location where the gravitational lensing caustic of a nearby binary star aligns with a distant AGN.[8] Under these circumstances, it may be possible to map the AGN with AU-scale resolution, relying on the extreme (one-dimensional) magnification that the lensing caustic provides. To find the nearest point that lies along the line connecting an AGN with a known binary star would require traveling tens of AU and having substantial maneuverability once there. It is likely, however, that equivalent resolution in the mapping of AGN could be obtained using interferometers with baselines much smaller than 1 AU.
- *Solar Gravitational Telescope.* Several studies have investigated the possibility of placing an observatory 550 AU or more beyond the Sun, where the gravitationally lensed rays near the Sun's limb come to a focus.[9,10] Proper placement of the observatory would use the Sun as a gravitational telescope to provide enormous flux and angular magnification (in one dimension) for a chosen target. This could be an attractive method for resolving a terrestrial planet (or several) around another star. However, in addition to the great distance involved, there are severe practical difficulties in, for instance, blocking the Sun's light or observing through the surface brightness of the solar corona.

None of these applications offer a compelling, unique scientific value that would justify the development of nuclear propulsion systems. The Solar Gravitational Telescope could be interesting, but it is either completely infeasible or must be left to the consideration of astronomers later in this century.

TECHNOLOGY ENHANCEMENTS AND ISSUES

The report of the Aldridge Commission identified 17 technologies as enabling for NASA's exploration initiative.[11] One of these—advanced power and propulsion, primarily nuclear thermal and nuclear electric—is the focus of this report. As is demonstrated above, however, nuclear power and propulsion technologies are far less likely to promote progress in space astronomy and astrophysics than are several of the other 16 enabling technologies identified in the commission's report. As is discussed below, some of these other technical capabilities—e.g., affordable heavy lift, advanced structures, large-aperture systems, formation flying, cryogenic fluid management, high-bandwidth communications, and scientific data collection/analysis—are much more relevant to addressing the scientific goals of astronomy and astrophysics.

Enabling technologies for astrophysical missions over the next decades are expected to be those that make possible larger collecting areas; better high-precision optics; on-orbit assembly; precision formation flying; active cooling of telescopes and detectors; and high-communication bandwidth. These are not technologies that benefit obviously from nuclear power or propulsion.

Nuclear power and propulsion are neither uniquely enabling of nor even clearly enhancing for missions that address the high-priority science goals of astronomy and astrophysics. The missions require power in the range of 100 We to 10 kWe per spacecraft. Cost and mass per watt are important considerations, because they affect allowable science capabilities under established mission budget and launcher constraints. Only if nuclear power were to become sufficiently cheap, reliable, and low risk might it be of interest for astrophysics missions. For operations at nonshadowed 1-AU locations, solar-electric power generation is a low-risk, low-cost benchmark against which any nuclear system application must be measured.

Current Cassini-class radioisotope thermoelectric generators weigh 56 kg and provide 285 We or 190 kg/kWe, about 20 times the mass/power ratio of solar-electric power at 1 AU, and the proposed Stirling radioisotope generators have even lower mass/power ratios.[b] Thus, such power systems do not become cost-effective until well beyond 3 AU except in locations that are shadowed for long periods (e.g., the lunar surface).

Important technical challenges for space astrophysics that may prove more relevant than power and propulsion technologies include the following:

- *High-bandwidth communications.* As sensor format size becomes larger, data rate rises proportionally. Opportunities for system control and robotic assembly and servicing are also greatly enhanced by improvements in data rate. Higher power transmitter output is an option for which nuclear systems can be considered. For a fleet of co-located spacecraft in which the power budget is dominated by communications, a high-power communications relay station that is nearby could offer significant advantages. However, there are alternatives that appear to be cheaper, including:

  —Provision of high-bandwidth optical communications links; and

  —Improvement and upgrades of the bandwidth and collecting area of the Deep Space Network (DSN). Such an upgrade, whose cost can be amortized over all future missions, saves the expense of installing high-power transmitters on every subsequent spacecraft.

- *Onboard processing.* The processing power of onboard computer systems is increasingly important, and such power relates to the electric power available. Missions now being proposed must satisfy the substantial (~10 kWe) power demands (see Table 7.1) of, for example, the correlators supporting coherent detection, the processors required for efficient compression of large data sets (relating to communication bandwidth), and the hardware necessary for autonomous operations. Developing highly capable processing hardware that is radiation hardened would be of particular importance for operations near nuclear power systems and would also be of value for the harsh particle and radiation environment outside low Earth orbit.
- *Faster transit times.* Although it is anticipated that most astrophysics missions will operate near 1 AU, minimizing transit times for both deployment and servicing can maximize mission efficiency and reduce risk. With the Sun-Earth L2 point as an important destination for astrophysics missions, it is particularly important to minimize transit times between low Earth orbit and that site. Low-energy travel to L2 with lunar-gravity assist, used by the Wilkinson Microwave Anisotropy Probe and baselined for JWST, takes several months to complete. To the extent that a nuclear propulsion system, whether in the form of a ferry/tug or a spacecraft component, could reduce these transit times substantially and cost-effectively, science might benefit.
- *Multiple spacecraft systems.* There is a general trend in astrophysics toward multiple-spacecraft systems, and certain destinations such as L2 will become heavily populated with observatories. Some missions require substantially similar craft operating independently in physical proximity to each other to enhance capability and are often launched and delivered to orbit on a single craft. As the number of craft in a cluster grows, the total demand for power and communications also grows, increasing the attractiveness of a centralized source of power for operations and communications.

Although not directly relevant to power and propulsion considerations, there are technology needs for space astrophysics that could be advanced as an indirect consequence of Project Prometheus. These technologies include the following:

- *Heavy-lift launch.* Astrophysics, with its continuous need for greater sensitivity, will move inexorably toward larger, more massive instruments. Improved heavy-lift capability would enable new classes of instrumentation with greater sensitivity to be affordably built and launched.

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[b] The Stirling radioisotope generator has a nominal power of 112 We at the beginning of a mission and a mass of 34 kg.

- *Large launcher fairings.* Many missions feature large, lightweight structures that are launch-limited not by weight but by size. Larger fairing sizes are needed.
- *Contamination mitigation.* Astronomical instrumentation has always been sensitive to environmental factors, including sources of instrument contamination and background. As the instrument requirements for new, cutting-edge science grow more challenging, the environment must be better controlled. Any new support technology must meet these constraints. Specifically, sensors must be shielded, instrument radiation-hardness requirements met, and gaseous contaminants kept from sensitive areas.
- *In-space assembly.* Between the current instruments sized to fit inside a launch shroud and the large, formation-flying arrays lies a class of instruments that is better supported by large, deployable structures. Significant advances are being made in this area in the context of the development of the JWST and the Space Interferometry Mission. Nevertheless, additional attention needs to be paid to the technologies for deployment and assembly of large, precision structures in space.
- *Space interferometry.* A new generation of observatories (both optical and gravitational wave) is coming that uses the techniques of physical optics to create long-baseline interferometers for vastly improved imaging of the sky and detection of gravitational waves. These missions require long-lived, space-qualified lasers, and also formation flying, often over great distances with the associated large, tidally disruptive forces. Many will need continuous precision thrusting to hold position, precise metrology, drag-free sensors, and in some cases high-speed inter-craft communications.
- *Sensors.* Development of next-generation sensors offers enormous advantages to space astrophysics. Recent technological progress suggests order-of-magnitude improvements in sensitivity per sensor element at many wavelengths. New array technology multiplies this progress by offering large numbers of detectors at telescope focal planes, providing huge increases in the figure of merit for astronomical instruments.
- *Materials research.* High-performance Sun shields, solar sails, tethers, and low mass/area mirrors are all empowering for space astrophysics.

CONCLUSIONS

Nuclear power and propulsion are neither uniquely enabling nor unambiguously enhancing for any of the current high-priority goals of astronomy and astrophysics. Most envisaged missions (radio, infrared spectroscopy, optical, ultraviolet, x-ray, gamma ray, and gravitational radiation) work as well at 1 AU as anywhere and have power requirements of <10 kWe, and so the clearly preferred cheap and reliable choices are solar power and chemical propulsion (aided in some cases by solar-electric propulsion). Nuclear power is more costly, heavier (hence more costly to launch), and has dauntingly malign effects on most astronomical detectors. The lifetime of, and the risks posed by, nuclear systems are also significant concerns.

The one major exception is infrared imaging, for which there is a cost trade-off to consider between a larger telescope in the high-zodiacal-light background at 1 AU versus a smaller one in the lower background at $\gtrsim$3 AU. Nuclear power (e.g., RPSs or a small reactor) might be attractive for such a mission, but there are serious issues—e.g., the effect of radiation on sensitive detectors—that would have to be addressed.

Some of the more exotic missions considered in this chapter (but not previously evaluated in any recent NRC decadal survey or NASA strategic planning exercise), including lunar observatories, gravitational lensing telescopes, and the use of moons as gravitational wave detectors, might be enabled or enhanced by the use of nuclear technologies. They do not, however, uniquely address high-priority goals of the astronomy and astrophysics community.

There are interesting small instruments of opportunity that might be considered in the context of missions to the outer solar system and interstellar space (whether nuclear powered or not). These opportunities include a small telescope to measure infrared background radiation and small gamma-ray burst detectors. Although these opportunities also do not address major, high-priority questions in astronomy and astrophysics, they may be considered as cost-effective add-ons. Finally, the direct measurement of the properties of the local interstellar medium beyond the heliosphere is of astronomical interest, although again it is not a high-priority goal enunciated in either *Astronomy and Astrophysics in the New Millennium* or *Connecting Quarks with the Cosmos*.

REFERENCES

1. M.I. Etchegaray, ed., *Preliminary Scientific Rationale for a Voyage to a Thousand Astronomical Units*, JPL Publication 87-17, Jet Propulsion Laboratory, Pasadena, Calif., 1987.

2. See, for example, National Research Council, *The Decade of Discovery in Astronomy and Astrophysics*, National Academy Press, Washington, D.C., 1991, pp. 100–109.

3. See, for example, J.O. Burns and W.W. Mendell, eds., *Future Astronomical Observatories on the Moon*, NASA Conference Publication 2489, National Aeronautics and Space Administration, Washington, D.C., 1988.

4. D.F. Lester, H.W. Yorke, and J.C. Mather, "Does the Lunar Surface Still Offer Value as a Site for Astronomical Observatories?" *Space Policy* 20: 99–107, 2004.

5. M.W Henley, J.C. Fikes, J. Howell, and J.C. Mankins, "Space Solar Power Technology Demonstration for Lunar Polar Applications," 34th COSPAR Scientific Assembly, The Second World Space Congress, 2002, p. R-4-04.

6. M.W. Henley, S.D. Potter, J. Howell, and J.C. Mankins, "Wireless Power Transmission Options for Space Solar Power," 34th COSPAR Scientific Assembly, The Second World Space Congress, 2002, p. R-4-08.

7. C. Alcock, R.A. Allsman, D. Alves, T.S. Axelrod, D.P. Bennett, K.H. Cook, K.C. Freeman, K. Griest, J. Guern, M.J. Lehner, S.L. Marshall, B.A. Peterson, M.R. Pratt, P.J. Quinn, A.W. Rodgers, C.W. Stubbs, and W.C. Sutherland, "First Observation of Parallax in a Gravitational Microlensing Event," *Astrophysical Journal Letters* 454: 125, 1995.

8. A. Gould and B.S. Gaudi, "Femtolens Imaging of a Quasar Central Engine Using a Dwarf Star Telescope," *Astrophysical Journal* 486: 687, 1997.

9. C. Maccone and G.L. Matloff, "SETIsail: A Space Mission to 550 AU to Exploit the Gravitational Lens of the Sun for SETI and Astrophysics," *Journal of the British Interplanetary Society* 47: 3–4, 1994.

10. S.G. Turyshev and B.-G. Andersson, "The 550-AU Mission: A Critical Discussion," *Monthly Notice of the Royal Astronomical Society* 341: 577–582, 2003.

11. President's Commission on Implementation of United States Space Exploration Policy, *A Journey to Inspire, Innovate, and Discover*, U.S. Government Printing Office, Washington, D.C., 2004, p. 28.

9

Findings and Recommendations

This chapter presents the findings and recommendations developed by the committee in response to its two tasks—(1) identification of a series of promising mission concepts to help define space nuclear systems' potential to enable major scientific advances and (2) discussion of some of the likely technological, programmatic, societal, and budgetary consequences of the potential applications of nuclear power and propulsion systems by the space science community.

SPACE SCIENCE APPLICATIONS OF NUCLEAR POWER AND PROPULSION

The material presented in Chapters 4 and 6 clearly demonstrates that the availability of nuclear power and propulsion technologies has the potential to enable a rich variety of solar and space physics and solar system exploration missions. Of the various nuclear technologies considered, radioisotope power systems (RPSs) are directly enhancing or enabling for missions identified in the solar and space physics (SSP) and solar system exploration (SSE) survey reports as priorities for the coming decade[1,2] and also for missions mentioned there as likely candidates for consideration as priorities in subsequent decades.

None of the missions identified in the SSP and SSE survey reports as priorities for implementation in the coming decade explicitly require a nuclear propulsion system. Both survey reports did, however, call for the development of nuclear-electric propulsion (NEP) systems to enable important candidate missions in future decades. The SSE survey report was much more explicit in this regard and, in addition to recommending the development of NEP, specifically identified several candidate missions likely to benefit from this technology. The discussions in Chapters 4 and 6 identify a number of promising mission concepts that would appear to be enhanced or enabled by RPS technologies and/or NEP.

The prospective contributions of these nuclear technologies in the areas of astronomy and astrophysics are, as shown in Chapter 8, far less promising at the moment. Nuclear power and propulsion systems are not enhancing or enabling for any of the current high-priority goals of astronomy and astrophysics. Most of the astronomy and astrophysics missions envisioned work as well at 1 AU as anywhere and have power requirements that can most readily be met with photovoltaic systems. The one major exception is infrared imaging, for which a case can be made between deploying a larger telescope in the high-zodiacal-light background at 1 AU versus a smaller telescope in the lower background at $\gtrsim 3$ AU. There are some more exotic mission possibilities that might be enhanced or enabled by the use of nuclear technologies, but they do not uniquely address high-priority goals of the astronomy and astrophysics community.

Overall Finding

NASA and its partners in other federal agencies such as the Department of Energy have taken some important first steps in what will be a long-term program to harness nuclear power and propulsion technologies for the benefit of space exploration activities. Nevertheless, while these technologies hold promise, their positive and negative aspects must be clearly understood. If nuclear propulsion systems are developed and demonstrated, they will give researchers access to previously inaccessible objects and destinations, enabling them to conduct comprehensive studies of a type, and with a flexibility, not previously contemplated in the history of space exploration (see text boxes in Chapters 4 and 6). However, spacecraft nuclear propulsion is in its infancy and will require a great deal of technological development. As shown in Chapter 2, the performance figures from NASA's studies of the Jupiter Icy Moons Orbiter (JIMO) and its parametric studies of candidate post-JIMO missions reveal a significant performance gap (in terms of, for example, transit time and launch mass) between what appears to be currently feasible and what is desirable from a scientific perspective.

The material presented in Chapter 2 also suggests that NASA's current nuclear propulsion activities may be too narrowly focused on a single technology—nuclear-electric propulsion—and might benefit from a broader assessment of other technological approaches. Unfortunately, the study committee's ability to examine technical factors related to these concerns was somewhat limited because circumstances beyond its control indefinitely postponed the second phase of the study, which would have provided detailed inputs from a panel of space nuclear power experts.

By today's standards, the spacecraft using nuclear propulsion systems, regardless of the exact technologies employed, will be very large, very heavy, very complex, and, almost certainly, very expensive. To what extent will the development and deployment of such technologies interfere with the diversity of space science missions? Such diversity gives scientific breadth and depth to these pursuits and is essential for the long-term health and vitality of all space science activities.

On the other hand, it is difficult to imagine that the space science goals of the period beyond 2015 will still be addressed with the power and propulsion technologies of the Mariners, Pioneers, and Voyagers. But it is equally difficult to imagine how it will be possible to transition smoothly from an era of Cassini, Mars Exploration Rovers, New Horizons, Discovery, and Explorers to one whose mix of activities is as diverse but now also includes super-flagship-class NEP missions.

> *Finding:* **Nuclear power and propulsion technologies appear, in general, to have great promise and may in some senses be essential for addressing important space science goals in future decades. This is particularly true for the fields of solar and space physics and solar system exploration, and especially so with respect to near- to mid-term applications of radioisotope power systems. Nevertheless, the committee has significant reservations about the scientific utility of some of NASA's current nuclear research and development activities, about NASA's current technological approach to the implementation of nuclear propulsion, and about the agency's ability to integrate a new class of large and potentially very expensive nuclear missions into its diverse and healthy mix of current missions.**

The committee elaborates on this finding below and makes specific related recommendations.

Additional Major Findings

Radioisotope Power Systems

> *Finding:* **Radioisotope power system technologies will enable varied and rich space science activities.**

NASA is investing in both RPSs and fission reactors as power sources for future missions. RPSs, which have a long history of enabling science investigations, could provide power for a broad range of missions, from landers at Mars or Venus to orbiters at the planets of the outer solar system. To do so they must be able to operate in a number of modes (e.g., on orbiters, landers, and rovers) and environments (e.g., extremes of hot and cold, the vacuum of deep space, or planetary atmospheres). RPSs might also be useful for different classes of missions and should be seriously considered for small principal-investigator (PI)-led missions, such as Mars Scout and Discovery.

Of particular interest to the space science community in the near term is the ongoing development of two new types of RPSs—the multi-mission radioisotope thermoelectric generator (MMRTG) and the Stirling radioisotope generator (SRG). The committee notes that both the MMRTG and the SRG are less efficient in terms of their specific mass (i.e., kg/kWe) than the devices they are replacing. Further, the SRG has moving parts that may limit its lifetime as well as cause vibrations and electromagnetic interference.

To produce electrical power, RPSs utilize the nuclear decay of radioactive isotopes, typically ^{238}Pu. The committee is concerned that interruptions in the production, supply, or packaging of ^{238}Pu fuel could impact future missions. Currently Russia is the only source of ^{238}Pu, at a cost of between \$2.2 million and \$2.5 million per kilogram (kg).[3] This material is currently processed and packaged in the United States, principally at the Los Alamos National Laboratory.[a] A steady and reliable source of ^{238}Pu is required if the scientific potential of missions enhanced and enabled by RPS technologies is to be realized.

> ***Recommendation:*** **NASA should expand the development and application of radioisotope power system (RPS) technologies. Advances in these technologies should be pursued for such purposes as reducing specific mass, minimizing electromagnetic and other forms of contamination, and developing systems that can work in a variety of environments, from the surfaces of diverse planetary bodies to orbiters to the outer solar system. Attention should be given to the development of new types of RPSs that have smaller and, possibly, larger electrical power outputs than those currently in use or under development.**

Prometheus Propulsion Technologies

> ***Finding:*** **Nuclear propulsion technologies will likely be used initially for moving relatively large scientific payloads (~1,000s kg) to destinations in the outer solar system and beyond and extremely large payloads (~10,000s kg) in support of human exploration activities in the inner solar system. But it is necessary to investigate nuclear propulsion technologies more thoroughly to determine if they can provide fast, affordable access to the outer solar system and beyond and can move large payloads in the inner solar system cost-effectively and efficiently.**

The current focus of Project Prometheus is on development of a nuclear-electric propulsion system. NASA's parametric studies of the potential applications of this propulsion system indicate that a number of desirable missions require a transit time of more than 10 years (e.g., Neptune, 13 to 15 years; Kuiper Belt object, 17 to 19 years; interstellar probe, ~30 years). Transit times of a decade or more create problems for sustaining continuous systems operations, maintaining public support, and ensuring systems reliability and would lead to instrument obsolescence. The committee is worried that the failure to achieve transit times to priority destinations in the outer solar system of 10 years or less will render the NEP technology NASA is developing of little interest to the scientific community.

In Chapter 1, the committee expresses its concern that insufficient foundational work was undertaken by NASA to support a qualitative assessment of the opportunities enhanced or enabled by nuclear systems. This concern has been borne out. The committee did not find that adequate work had been done to demonstrate that a viable NEP system with wide scientific applicability could be developed. For example, estimates provided by NASA for an interstellar probe to reach 200 AU in ~30 years cannot be verified because specific assumptions have not been provided concerning important factors such as mass-to-thrust ratio, spacecraft mass, power-conversion efficiencies, payload mass, and planetary gravitational-assist scenarios. Alternative technologies, for example, nuclear-thermal propulsion (NTP) and bimodal systems, may provide a more cost-effective, faster means of transport to the outer solar system and beyond.

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[a] DOE has announced its intention to consolidate all RPS-related activities, including the production of ^{238}Pu, at the Idaho National Laboratory.

NASA missions that might be enabled by nuclear propulsion will require high delta-V, fast transit times, and/or high levels of electric power at the destination. To determine the benefits of nuclear propulsion for such missions will require "level-playing-field" trade-off studies that compare various propulsion options in terms of such metrics as cost, initial mass in low Earth orbit, launch-vehicle requirements, and transit time. Such studies should incorporate the impact on the systems of requiring risk mitigation through the use of redundant subsystems and extensive ground testing.

To determine suitable space reactor system designs and operational profiles, trade-off studies should also consider the impact of system reliability, especially for those systems designed to operate continuously without maintenance or repair for extended periods. For example, the current NEP concepts being considered for missions to the outer solar system require that the systems function without human intervention for durations between 10 and 20 years. However, no high-power-density reactor has ever been operated on Earth, without maintenance shutdowns, for any time period longer than one order of magnitude or more below such a duration. To operate reliably in space, nuclear systems must be tested extensively on Earth in environments and with operational sequences that approximate actual expected conditions as closely as possible. Such testing will require establishing operational margins—i.e., systems must be tested at full power for longer, if possible, than full mission duration. If NASA deems a full-duration-testing requirement to be infeasible for NEP systems, a full risk analysis of the system must be completed, including the option of providing for redundancy of the reactor on the spacecraft. Reliability requirements could also substantially increase system-mass requirements, depending on the extent to which redundant subsystems will be needed to meet reliability goals. Because of the weight of the massive heat rejection system they require, NEP systems also carry a considerable mass penalty.

Missions recommended for future study are described in Chapters 4 and 6. These, together with additional promising robotic missions (e.g., those resulting from NASA's so-called Vision Missions competition) and human missions to the Moon or Mars, should be considered. Studies of trade-offs between chemical systems, solar-electric propulsion systems, solar sails, NEP and NTP systems, and bimodal systems should be completed for missions over a wide range of delta-V. These studies of trade-offs should take into account considerations of mission complexity, reliability, and risk. Only those missions for which the nuclear power significantly enhances the science return or that are otherwise effectively impossible merit the application of NEP or NTP power and/or propulsion. The most cost-effective application relative to the science return must be the deciding factor.

> *Recommendation:* **NASA should commission detailed, comprehensive studies—supported by external independent reviews and the broad participation of the space science and space technology communities—to examine the feasibility of developing space nuclear propulsion systems with reduced transit times and costs, in order to determine which nuclear propulsion technologies should be pursued at this time, and to ensure that investments in advanced propulsion technologies yield the greatest benefit for the NASA community.**

COLLATERAL IMPACTS OF NUCLEAR POWER AND PROPULSION

Decadal Survey Science and Program Balance

> *Finding:* **Program balance is critical to the long-term health of the space science enterprise. An important aspect of a balanced program is a flight program encompassing a range of flagship missions combined with moderate and small missions.**

In Chapter 1 the committee expresses concern about two issues relating to the decadal surveys. The first issue was the potential invalidation of decadal survey science priorities that were based on technical assumptions made before the initiation of Project Prometheus. This concern has abated. Nothing that the committee heard during its study or discussed during its deliberations caused it to question the continuing validity of the science priorities articulated in the three space science decadal surveys. As partial validation of this conclusion, the committee points to the results of NASA's recent strategic roadmapping exercise. Many of the roadmapping teams were fully briefed on the technical capabilities opened up by Project Prometheus, yet their reports are virtually devoid of missions enabled by nuclear technologies.

The second issue was related to the potential impact of super-flagship NEP missions on the programmatic balance inherent in the decadal surveys, which recommend a range of mission types and classes. This concern has not abated. The most recent decadal surveys placed high importance on overall program balance. All three surveys reiterated the need for a mix of more frequent, PI-led small- and medium-class missions combined with less frequent, more costly, larger missions. This overall program balance is considered practical, given the size of NASA budgets, and is necessary for nurturing a healthy scientific and engineering community. The potentially very large cost of NEP-class missions could threaten this programmatic balance, a possibility that is of extreme concern to this committee.

The balance between small, focused missions and more challenging missions is a pillar of the space science enterprise and must be maintained. In particular, the space science community relies directly on mission lines such as Explorer, the Solar-Terrestrial Probe, Discovery, and New Frontiers. In fact, such a mix of mission costs and sizes lends itself well to making progress and discovery on a broad front. The current projections of scientific benefit versus cost for nuclear-electric propulsion indicate that its value to the scientific community would be limited. For example, although exploring Europa remains an extremely high priority, doing so with a mission like JIMO may not be justified by the science return expected, as compared with a smaller, less expensive mission that does not use nuclear-reactor propulsion. NEP-class missions should not, in the committee's judgment, be perceived as a replacement for any of these mission lines, and funds should not be diverted from these smaller and less expensive lines to support much more expensive nuclear-electric missions. Further, the committee sees a need for a flagship class of missions, such as the Europa Geophysical Explorer and the Solar Probe, which are intermediate in cost relative to the New Frontiers and the super-flagship NEP-class missions. By making a wide range of measurements of a given body, system, or region of space, such large-scale missions should allow for serendipitous discoveries that would not be possible with less expensive, narrowly focused missions.

The development of nuclear propulsion systems is seen as having many possible advantages for future science missions. However, the associated cost may dramatically impact near-term mission capabilities. If NASA's science program is required to cover the development of systems, a substantial decline in expertise and capability will result, and the recovery from this decline will be slow and difficult.

> *Recommendation:* **The cost of developing advanced power and propulsion technologies, and of implementing missions employing such technologies, must not be allowed to compromise the diversity of the space science missions recommended by the decadal surveys, because these missions address the most important scientific questions in solar and space physics, solar system exploration, and astronomy and astrophysics and are thus essential to maintaining the long-term health and vitality of the entire space science enterprise. Given the level of resources required to implement NEP-class missions, these super-flagship endeavors will have to be extraordinarily capable of addressing a broad-based, cross-cutting range of truly interdisciplinary scientific activities, if such missions are to provide a science return commensurate with the investment made in them.**

Public Acceptance and Approval of Launch

> *Finding:* **Previous launches of nuclear-powered spacecraft have raised concerns among members of the public. If such concerns were to intensify, it could seriously affect any planned use of nuclear technology on space science missions.**

Another of the committee's initial concerns expressed in Chapter 1 was the degree to which issues have been raised relating to safety and the interagency launch-approval process. Although these issues are still a concern, the committee is less worried about them than it was at the outset. Nuclear power is used throughout the United States to provide electrical power to a significant portion of the population. Public opposition to the perceived risk of nuclear power plants and the associated production of long-lived radioactive waste, compounded by escalating costs, has led over the past three decades to a de facto cessation of the design and construction of new nuclear plants on U.S. soil. Plans for the construction of large, ground-based nuclear facilities (e.g., the Yucca Mountain high-level nuclear waste repository or the Ward Valley low-level waste facility) have also met with strong opposition by relatively large segments of the population in the vicinity of such sites. There are many indications that a significant fraction, if not the majority, of the U.S. public is resistant to the development of new nuclear systems.

The experience with the use of nuclear power in space systems, on the other hand, has been somewhat different. Opposition to the launch of spacecraft that carry a nonnegligible inventory of radioactive material, such as the RPS-powered Galileo, Cassini, and New Horizons, has been visible and vocal, but not necessarily widespread nor ultimately successful in preventing the launch of these systems. The larger public's interest in these, as well as Mars missions—e.g., the Mars Exploration Rovers—that carried smaller amounts of radioactive material onboard (in the form of radioisotope heater units) has been largely positive despite the missions' nuclear power underpinning. Thus, it could be argued that the negative public perception of nuclear power is selective and may be changing, especially when a visible demonstration of successful return can be claimed. Nevertheless, the potential for public opposition to nuclear power development exists and must be considered by NASA in planning the development of nuclear space power and propulsion systems.

Historically, public acceptance has been enhanced by openness during the technology design phase and full revelation of the technology development path, including a clear explanation of the benefits and challenges of the proposed developments. Denial of risk and neglect of impacts that are potentially visible for a given development have, on the other hand, been the curse, and often the demise, of otherwise potentially beneficial nuclear technology developments. Nuclear space reactor technology has seen very limited development in the United States or, for that matter, worldwide and undoubtedly poses a number of questions regarding reliability and safety that need to be fully understood and addressed by the technical and scientific community and made comprehensible to the public at large.

Missions powered or propelled by nuclear devices have to satisfy both environmental laws and launch-approval requirements (i.e., National Environmental Policy Act [NEPA] regulations and Presidential Directive NSC-25). Safety analyses and risk assessments to satisfy both types of requirements have been developed and applied successfully for past missions carrying RPSs. However, there is no past experience with applying these processes to obtain approval for the design and launch of missions carrying more complex and powerful devices such as a nuclear reactor. Also, although no specific national or international laws, regulations, or policies have been promulgated regarding safety and environmental issues beyond the Earth environment, the questions of safe disposal of reactor fuel and protection of planetary environments may eventually be raised and perhaps used, legally or politically, to oppose missions with nuclear reactors onboard.

In summary, it would be prudent to evaluate whether the current interagency (i.e., NASA/DOE) processes for NEPA and launch approval are sufficient to address potential public or international concerns about the safety and environmental impact of nuclear reactors for space missions, or whether some additional requirements are likely to have to be addressed in the future by different means.

Recommendation: **It is essential that NASA communicate clearly and openly with the public regarding the potential benefits of and challenges posed by the use of space nuclear power and propulsion systems. The agency and its partners must avoid the denial of risks and neglect of impacts, as well as the perception thereof. NASA should adopt a very proactive stance and role in the management and integration of current (e.g., National Environmental Policy Act and interagency launch-approval procedures) and future foreseeable processes of assessment and decision making that will undoubtedly influence public opinion about the general environmental and safety risks associated with the use of nuclear power and propulsion systems in space.**

Human Exploration Applications

Finding: **Fission reactors are likely to be useful in providing long-term power for human activities on the surface of the Moon and Mars. Surface power systems are, in practice, likely to be very different from shipboard reactors and will require separate development programs.**

The great distances, exposure to intense cosmic radiation, and physiological response to zero gravity all support the concept of using an advanced propulsion system to shorten the duration of human missions to Mars. Nuclear power and propulsion systems could also provide the large amounts of electricity necessary for life-support systems on human missions and for support of surface science and exploration activities. Surface and space power systems are likely to be different, however, and it is not clear that the NEP system currently under study by Project Prometheus is adequate for either application. NTP systems may provide better thrust for manned Mars missions. Nuclear reactor power and propulsion systems for human exploration missions must be qualified to a much higher level of reliability than power and propulsion systems for robotic missions, and will also need to be validated for reliable operation at full power and for the lifetime of the mission.

Applications of nuclear power for human exploration, especially NEP for piloted missions, may involve problems associated with reactor-generated radiation. Current systems, as illustrated by the JIMO/Prometheus Baseline (PB) 1 design, have neutron and gamma fluxes at the science platform that are far in excess of those considered safe for humans. The mass of shielding required to reduce exposure to safe levels may negate the propulsion advantages of NEP. Radiation is also a concern, although one more easily mitigated, for surface-based systems powering human-occupied stations. In the absence of containment systems on the scale of Earth-based generating systems, such power systems will have to be located at a remote site, possibly surrounded by a protective regolith berm, with power transmission cables to deliver the electric power to the crew station.

> ***Recommendation:*** **NASA should reexamine the technology goals of Project Prometheus to assess the benefits (in terms of cost, schedule, and performance) of using a technology that can support the propulsion requirements of both human and robotic missions.**

Launch and Assembly

> ***Finding:*** **NEP-class spacecraft are inherently massive and, as such, will require either in-space assembly following multiple launches of components on the largest launch vehicles currently available, or a single launch on a new heavy-lift booster.**

A heavy-lift launch capability would potentially enable new classes of space science missions. However, the added costs must be included when comparing JIMO-class missions using nuclear propulsion technologies to other mission options. In addition, development of a heavy-lift launch vehicle or the use of multiple launches followed by assembly in orbit would also have an impact on schedule, again negatively affecting already high cost estimates.

> ***Recommendation:*** **Studies of trade-offs comparing propulsion options should take into account the complexities and cost of launching NEP-class missions.**

Technology and Program Development

> ***Finding:*** **Attention has to be paid to a variety of technical and programmatic issues that can affect the scientific utilization of NEP-class missions. These issues include the fraction of a spacecraft's launch mass dedicated to the science payload; high-bandwidth communications; onboard data processing; the capacity of the Deep Space Network, Planetary Data System, and research and analysis programs to handle increasing volumes of data; the availability of radiation-hardened components and radiation-tolerant instruments; and mitigation of contamination. Failure to make allowance for some or all of these factors can lead to hidden costs that will impact the implementation of NEP-class missions.**

Considerations relating to these technical and programmatic issues include the following:

- *Fraction of launch mass for science.* On typical planetary missions flown over the last 30 years, the fraction of science payload mass to total mass has varied between 0.09 and 0.17. For example, the Cassini spacecraft, currently in orbit around Saturn, has a science payload to mass fraction of >0.1: that is, somewhat more than 600 kg is allocated to the science payload (body-mounted science instruments totaling approximately 300 kg, and an atmospheric entry probe of mass greater than 300 kg) on a spacecraft with an overall launch mass of less than 6,000 kg. By contrast, the JIMO spacecraft, for example, would have a launch mass in excess of 25,000 kg, with only 1,500 kg of that allocated to the science payload, yielding a science payload to mass fraction of <0.06. The much larger masses necessitated by large NEP systems should offer the opportunity for much larger science payloads.

- *The Deep Space Network and the Planetary Data System.* A selling point of NEP-class missions is that their abundant electrical power would enable a new generation of high-power, high-capability instruments that could collect unprecedented amounts of data. In Chapter 1 the committee expresses initial concerns about the ability of both the space science infrastructure—exemplified by the Deep Space Network and the Planetary Data System—and the data-analysis programs to accommodate such large data volumes. These concerns remain valid. In fact, using current capabilities, it is unlikely that the complete dataset collected by such missions could be transmitted back to Earth. Accommodating this high volume of data will require some combination of the following: advanced onboard processing to reduce the amount of data that must be sent back to Earth; high-bandwidth communications facilitated, in part, by greater transmitting power; and improvements to the Deep Space Network.

Advanced onboard processing is increasingly important. In fact, astrophysics missions are now being proposed that have substantial (~10 kW) power demands (see Table 7.1) driven by the need for data correlation and compression. Onboard processing does, however, have a significant drawback: the danger that potentially important serendipitous discoveries will be precluded because the telemetry stream is inadvertently biased toward results that are expected a priori. Therefore, increasing Earth-based receiving apertures, particularly if implemented using arrays of small antennas, may be the more flexible approach in that these receiving apertures could, for example, support several missions simultaneously. The Planetary Data System and other data repositories will have to be expanded so that the large volumes of data returned by NEP-class missions can be adequately archived and distributed to the scientific community. Appropriate data-analysis programs will have to be established and/or augmented to meet the needs of these future missions and ensure that the data returned are fully analyzed.

- *Radiation-hardened components and radiation-tolerant detectors.* The development of new, more capable, radiation-hardened electronic components, particularly processors, will enhance measurement capabilities. Similarly, the development of new detector materials, new detection concepts, and a better understanding of the detectors' response to and damage by radiation from advanced nuclear power and propulsion technologies would enhance, and in some cases enable, the scientific return of missions in these radiation environments.

- *Contamination mitigation for instruments I.* A spacecraft equipped with nuclear power and propulsion systems must accommodate a wide range of instrument types that are sensitive to local environmental conditions. Instruments that might benefit from power and/or propulsion from nuclear reactors will clearly be compromised or damaged by high-energy particles and photons from the reactor. In addition, the reactor and its power-conversion and radiator systems are likely to be sources of DC magnetic fields, electromagnetic interference over a wide range of frequencies, waste heat, vibrations, and outgassed effluents. The ion thrusters also contaminate the environment with plasma, magnetic fields, and electromagnetic interference, and can also erode exposed surfaces. Power and propulsion systems must be clean and stable in terms of transient magnetic and electric fields, chemical contamination, radiation and charged-particle levels, and vibration to allow characterization of, for example, planetary magnetic fields; planetary magnetic-field/solar-wind interactions; phenomena associated with local plasmas; useful ion and neutral mass spectrometer studies in upper atmospheres, near ring systems, and near small bodies; precision measurements of gravitational fields; and precise instrument pointing and stability. Sample-return missions must ensure that the samples are not altered by high neutron and gamma fluxes and fluences. If NEP systems are to enhance or enable space science objectives, their effects as sources of interference must be fully investigated and mitigating strategies developed that avoid to the maximum extent possible the use of heavy shielding.

- *Contamination mitigation for instruments II.* Nuclear reactors operating within Earth's magnetosphere are well established as causing significant interference to balloon-borne and orbiting gamma-ray observatories and hampering their ability to conduct astronomical measurements. This interference is caused by primary and secondary gamma rays and, in addition, electron-bremsstrahlung and positron-annihilation radiation. These difficulties are particularly problematic for reactors located inside Earth's magnetosphere, because of the long timescale (up to several minutes) for trapping of particles in the geomagnetic field. The interfering signals can have a duration ranging from a few seconds to many minutes and can also have highly variable amplitudes and rates.

The amplitude of the photon events depends simply on the location of the reactor relative to the detector, whereas the particle-induced event rates are more complicated to quantify because they also depend on the orientation and strength of geomagnetic field lines near the location where they were emitted, as well as on the time between emission and detection. All these effects have been well documented in data from the Gamma-Ray Spectrometer aboard the Solar Maximum Mission, which operated from 1980 to 1989 and which suffered from significant background of this type generated by the Russian Cosmos orbiting ~100-kW nuclear reactors.[4-7] These factors suggest that unless it can be demonstrated that this type of interference will not occur, nuclear reactors on future spacecraft should only be operated well outside Earth's magnetosphere.[b]

> ***Recommendation:*** **Determination of the cost of NEP-class missions should take into account the cost of necessary associated technologies and programs. Particular emphasis should be placed on studies of the means to maintain or, if possible, increase the fraction of launch mass allotted to science payloads above that typical for current space science missions.**

REFERENCES

1. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.
2. National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*, The National Academies Press, Washington, D.C., 2003.
3. G.R. Schmidt, R.L. Wiley, R.L. Richardson, and R.R. Furlong, "NASA's Program for Radioisotope Power System Research and Development," *Space Technology and Applications International Forum—STAIF-2005,* M.S. El-Genk, ed., American Institute of Physics, Melville, N.Y., 2005.
4. E. Reiger et al., "Man-Made Transients Observed by the Gamma-Ray Spectrometer on the Solar Maximum Mission Satellite," *Science* 244: 441, 1989.
5. G.H. Share et al., "Geomagnetic Origin for Transient Particle Events from Nuclear Reactor-Powered Satellites," *Science* 244: 444, 1989.
6. E.W. Hones and P.R. Higbie, "Distribution and Detection of Positrons from an Orbiting Nuclear Reactor," *Science* 244: 448, 1989.
7. O'Neill et al., "Observations of Nuclear Reactors on Satellites with a Balloon-Borne Gamma-Ray Telescope," *Science* 244: 451, 1989.

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[b] The situation for NEP and NTP systems is somewhat different and has to be studied. The low thrust of the former means that an NEP system may spend a prolonged period (months to years) in the magnetosphere as it spirals out of Earth orbit. The high thrust of the latter means that an NTP system will likely make a rapid transit (minutes) through the magnetosphere as it boosts out of Earth orbit.

Appendixes

A

Past U.S. Space Nuclear Power and Propulsion Programs

The United States has a long history of developing space nuclear power and propulsion programs. The most common systems have been the various types of radioisotope power systems used for outer planet spacecraft such as Voyager and Cassini (see Table 1.2 for details). However, many other technologies have been studied and occasionally progressed to advanced testing or even launch.

ROVER AND NERVA (1955–1972)

Starting in the mid-1950s, the United States initiated a program to develop nuclear propulsion for spacecraft. The basic technology involved passing hydrogen through a very high temperature nuclear reactor, where it expanded and blasted out of the reactor at high velocity. Eventually NASA and the Atomic Energy Commission jointly ran two main programs, a reactor technology development program named Rover and a program to develop a flight-capable nuclear rocket engine known as NERVA.

Under the Rover program, nuclear reactors were built at the Los Alamos National Laboratory’s Pajarito Site and tested at very low power, and then shipped to the Nevada Test Site for higher-power tests. Laboratory work also included developing and testing the fuel elements that powered the reactors. Phase one of Project Rover was called Kiwi and entailed building and testing eight reactors between 1959 and 1964. Phase two, called Phoebus, involved advanced nuclear reactors.

NERVA began in 1961 and by the mid-1960s progressed to hardware development tests in the Nevada desert. The NERVA engine utilized a hot-bleed cycle in which a small amount of hydrogen gas is diverted from the thrust nozzle to drive the turbine that pumps fuel into the engine. NERVA reached an integrated system component demonstration readiness level. At various points NASA planned on using NERVA as a rocket upper stage, a space ferry for lunar missions, and a propulsion stage for human missions to Mars. However, after Apollo, none of these projects was approved, and NERVA therefore had no dedicated mission. Congress showed greater support for NERVA than did the White House, but the program was eventually canceled by 1972.

ORION (1955–1965)

The nuclear pulse drive was conceived by H-bomb designers Stanislaw Ulam and Cornelius Everett at Los Alamos in 1955 and sponsored primarily as a study project by the Atomic Energy Commission and then the U.S. Air Force under the name Project Orion.

Orion adapted nuclear explosives for space use: nuclear bombs would be ejected aft of a spacecraft and exploded some distance away. Propellant (water or wax) surrounding the bombs would be transformed into high-energy plasma and bounce off a pusher plate at the rear of the rocket and push it forward. Shock absorbers would reduce the substantial vibration caused by detonating nuclear weapons behind the craft approximately once every second. Although the plasma from the explosion would have a temperature of 80,000 K, the impulse would be brief and only a tiny layer of the ablative pusher plate would sublimate after each explosion. The vehicle would be ground launched from a remote location.

The Orion design theoretically allowed vast payloads to be hurled to the planets. A typical design had a payload of hundreds of tons, meaning no complex environmental recycling systems or lightweight structures or equipment would be needed. The pusher plate was typically about one-third of the weight of the craft. The project was transferred to the Air Force in 1957 and produced small-scale demonstration tests involving conventional explosives detonated under a model suspended from a crane. The 1963 Nuclear Test Ban Treaty banned atmospheric nuclear tests, essentially killing the program. Funding was eliminated entirely in 1965. Even Orion's designers had acknowledged that it was a difficult project with a limited chance of success.

SYSTEMS FOR NUCLEAR AUXILIARY POWER REACTOR (1959–1971)

The Air Force's Project RAND first proposed using nuclear reactors to power satellites in 1946. At the time there was no other way to provide sufficient power to an orbiting satellite. The Air Force funded low-level study efforts of space nuclear reactors over the next decade, but the eventual development of solar cells made nuclear reactors unnecessary. By the late 1950s the Atomic Energy Commission began the Systems for Nuclear Auxiliary Power (SNAP) program to develop fission reactors and radioisotope power systems for both terrestrial and space use. Radioisotope and reactor programs were given odd- and even-number designations, respectively. In 1965 the Air Force launched the SNAP-10A reactor into orbit. It operated for 43 days, producing 500 W of power until the failure of a voltage regulator caused it to shut down. The SNAP-10A reactor was a small zirconium hydride (ZrH) thermal reactor fueled by uranium-235.

RADIOISOTOPE POWER SYSTEMS (1961–PRESENT)

Radioisotope power systems (RPSs) convert heat generated by the natural decay of radioisotope fuel (typically plutonium-238 in the United States) into electricity through thermoelectric coupling. The first two RPS demonstration systems (called SNAP-3) were flown in 1961 and generated 3 W of power. Later ones were flown on several Earth-orbiting spacecraft. RPSs were used on Apollo 12, 14, 15, 16, and 17 to supply power to the Apollo lunar surface experiment packages. They were also used to provide primary power to Viking 1 and 2 (SNAP-19, 85 We total), Pioneer 10 and 11 (SNAP-19, 165 We total), Voyager 1 and 2 (each RPS provided 157 We), Galileo (300 We total, along with 120 lightweight radioisotope heater units), Ulysses (same as Galileo), and Cassini (three RTGs delivering 870 We, along with 117 lightweight radioisotope heater units). Many other systems, including all Mars rovers, have used lightweight radioisotope heater units to maintain appropriate temperatures for system electronics. Table A.1 gives a more complete list. These systems have been successfully deployed.

SP-100 (1978–1995)

In 1983, a triagency group (National Aeronautics and Space Administration, Department of Defense, and Department of Energy) began development of a 100-kilowatt-electric-class space nuclear reactor called the SP-100. The SP-100 was designed with a 2-MWt fast reactor unit and thermoelectric system delivering 100 kWe for a 7-year period. This reactor was intended to support a wide variety of deep-space exploration needs, defense applications, and planetary outpost power requirements. Because of high costs, schedule delays, and changing national space mission priorities, the SP-100 program was suspended in the early 1990s and later canceled.

TABLE A.1 Use of Radioisotope Power Systems on Spacecraft, 1961 to 2006

Power Source	Spacecraft	Mission Type	Launch Date	Status
SNAP-3B7	Transit 4A	Navigational	6-29-61	RPS operated for 15 years. Satellite now shut down but operational.
SNAP-3B8	Transit 4B	Navigational	11-15-61	RPS operated for 9 years. Satellite operated periodically after 1962 high-altitude test. Last reported signal in 1971.
SNAP-9A	Transit 5-BN-1	Navigational	9-28-63	RPS operated as planned. Non-RPS electrical problems on satellite caused satellite to fall after 9 months.
SNAP-9A	Transit 5-BN-2	Navigational	12-5-63	RPS operated for over 6 years. Satellite lost ability to navigate after 1.5 years.
SNAP-9A	Transit 5-BN-3	Navigational	4-21-64	Mission was aborted because of launch vehicle failure. RPS burned up on re-entry as designed.
SNAP-19B2	Nimbus-B-1	Meteorological	5-18-68	Mission was aborted because of range safety destruct. RPS heat sources were recovered and recycled.
SNAP-19B3	Nimbus III	Meteorological	4-14-69	RPSs operated for over 2.5 years.
RHU	Apollo 11	Lunar Surface	7-14-69	Radioisotope heater units for seismic experimental package. Station was shut down 8-3-69.
SNAP-27	Apollo 12	Lunar Surface	11-14-69	RPS operated for about 8 years until station was shut down.
SNAP-27	Apollo 13	Lunar Surface	4-11-70	Mission aborted on the way to the Moon. RPS re-entered Earth's atmosphere and landed in South Pacific Ocean. No radiation was released.
SNAP-27	Apollo 14	Lunar Surface	1-31-71	RPS operated for over 6.5 years until station was shut down.
SNAP-27	Apollo 15	Lunar Surface	7-26-71	RPS operated for over 6 years until station was shut down.
SNAP-19	Pioneer 10	Planetary	3-2-72	RPSs still operating. Spacecraft successfully operated to Jupiter and is now beyond orbit of Pluto.
SNAP-27	Apollo 16	Lunar Surface	4-16-72	RPS operated for about 5.5 years until station was shut down.
RPS	"Transit" (Triad-01-1x)	Navigational	9-2-72	Power system still operating.
SNAP-27	Apollo 17	Lunar Surface	12-7-72	RPS operated for almost 5 years until station was shut down.
SNAP-19	Pioneer 11	Planetary	4-5-73	RPSs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.
SNAP-19	Viking 1	Mars Surface	8-20-75	RPSs operated for over 6 years until lander was shut down.
SNAP-19	Viking 2	Mars Surface	9-9-75	RPSs operated for over 4 years until relay link was lost.
MHW-RTG	LES 8	Communications	3-14-76	RPSs still operating.
MHW-RTG	LES 9	Communications	3-14-76	RPSs still operating.
MHW-RTG	Voyager 2	Planetary	8-20-77	RPSs still operating. Spacecraft successfully operated to Jupiter, Saturn, Uranus, Neptune, and beyond.
MHW-RTG	Voyager 1	Planetary	9-5-77	RPSs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.
GPHS-RTG and LWRHU	Galileo	Planetary	10-8-89	RPSs operated through 9-17-03, when the spacecraft completed its mission.
GPHS-RTG	Ulysses	Planetary/Solar	10-6-90	RPS still operating. Spacecraft en route to solar polar flyby.
LWRHU	Mars Pathfinder	Mars Surface	12-4-96	LWRHU provided essential heat to Sojourner electronics for 84 days.
GPHS-RTG and LWRHU	Cassini	Planetary	10-15-97	RPS still operating. Cassini entered orbit about Saturn in July 2004.
LWRHU	Mars Exploration Rovers	Mars Surface	6-25-03 and 7-5-03	LWRHU provide essential heat to electronics.
GPHS-RTG	New Horizons	Planetary	1-19-06	RPS operating. Spacecraft en route to Pluto.

NOTE: An RPS is a generic name for a family of different technologies, including the RHU, RTG, MHW-RTG, and others. SNAP, Systems for Nuclear Auxiliary Power program; RPS, radioisotope power system; RTG, radioisotope thermoelectric generator; RHU, radioisotope heater unit; MHW-RTG, multi-hundred-watt RTG; GPHS-RTG, general-purpose heat source RTG; LWRHU, lightweight radioisotope heater unit.

TIMBERWIND (1987–1992)

The Timberwind space nuclear thermal propulsion program was initiated by the Strategic Defense Initiative Organization in November 1987. Timberwind was a highly classified program to develop technology for a very high acceleration nuclear-powered rocket to launch missile interceptors into space. The project was transferred to the Air Force in 1991 and terminated in 1992, at which point some of the material was declassified. The Project Timberwind concept was based on a particle-bed reactor using tiny uranium carbide pellets as fuel to heat hydrogen propellant. The exhaust would have been highly radioactive. Preliminary designs had been selected but no prototype components had been tested before the program was canceled. No system was ever launched.

TOPAZ-2 (1980s–1990s)

Launching dozens of nuclear reactors into space during the 1970s and 1980s, the Soviet Union had a far more active space nuclear power program than did the United States. Although full details remain inaccessible, the Soviet Union is known to have had several separate space nuclear reactor programs under development in the late 1980s. One of these projects, mistakenly labeled "Topaz-2" in the United States but actually known as "Enisey," was purchased by the U.S. Ballistic Missile Defense Organization in the early 1990s. (Two Soviet nuclear reactors known as Topaz were flown in orbit in the later 1980s but were an entirely different design.) Six Topaz-2 reactors and supporting equipment were flown from Russia to the United States, where several of the reactors were extensively ground tested by a joint team of U.S., British, French, and Russian engineers. The reactors' unique design allowed them to be tested without nuclear fuel. Topaz utilized a thermionic design for directly converting heat energy into electricity without using a circulating heat transfer fluid or turbine. Although the test program was considered highly successful and the United States retained several flight-capable reactors, no plans were pursued to actually use the equipment in any flight programs.

BIBLIOGRAPHY

Aftergood, Steven, "Background on Space Nuclear Power," *Science & Global Security* 1(1–2): 93–108, 1989.

Department of Defense Inspector General Audit Report, *The Timber Wind Special Access Program*, Report Number 93-033, December 16, 1992. See <http://www.fas.org/sgp/othergov/dod/tw.pdf> last accessed February 2, 2006.

Dewar, James A., *To the End of the Solar System: The Story of the Nuclear Rocket*, University Press of Kentucky, Lexington, Ky., 2003.

Dyson, George, *Project Orion: The True Story of the Atomic Spaceship*, Owl Books, 2003.

General Accounting Office, *Space Nuclear Propulsion: History, Cost, and Status of Programs*, T-NSIAD-93-2. See <161.203.16.4/d17t6/137492.pdf>.

General Accounting Office, *The SP-100 Nuclear Reactor Program: Should It Be Continued?*, T-NSIAD-92-15. See <161.203.16.4/t2pbat6/146124.pdf>.

General Accounting Office, *TOPAZ II Space Nuclear Power Program: Management, Funding, and Contracting Problems*, OSI-98-3R. See <161.203.16.4/paprpdf1/159668.pdf>.

Mondt, Jack F., "SP-100 Space Reactor Power System for Lunar, Mars and Robotic Exploration," IAF 92-0563, 43rd Congress of the International Astronautical Federation, August 28–September 5, 1992.

National Research Council, *Assessment of the Topaz International Program*, Aeronautics and Space Engineering Board, June 27, 1996.

National Research Council, *Thermionics Quo Vadis? An Assessment of the DTRA's Advanced Thermionics Research and Development Program*, National Academy Press, Washington, D.C., 2001.

B

The Interstellar Observatory

MISSION CONCEPT

The Interstellar Observatory—so named to distinguish the mission developed here from past interstellar-probe concepts—is envisaged as being equipped with instruments never before flown on missions to the outer solar system (Table B.1). As such, it will address a highly cross-disciplinary scientific agenda (see below) and be capable of making important new observations in planetary science, heliospheric physics, and astrophysics throughout its journey to some 200 AU from the Sun. A more complete description of a possible implementation of the Interstellar Observatory concept can be found in Box 4.1.

The Interstellar Observatory will begin to make fundamental new scientific observations shortly after launch as it moves through the solar system with advanced, highly sensitive instrumentation acquiring data at a high time resolution with high accuracy. This mission embodies the concept of exploration and will redefine the frontier of modern space science as it is propelled beyond our solar system to explore the local interstellar medium.

SCIENCE OBJECTIVES

The Interstellar Observatory concept is designed to address scientific issues in the following general areas:

- Space physics and the heliosphere;
- Zodiacal dust and the Kuiper Belt;
- The edge of the solar system;
- Cosmic infrared background radiation;
- Search for organic molecules;
- Composition and ionization state of interstellar matter;
- Cosmic rays and modulation by the solar magnetic field; and
- Cosmic rays and the energy density of the galaxy.

Each of these topics is discussed in detail below.

TABLE B.1 Instruments for the Interstellar Observatory

Instrument	Measurement or Objective
In Situ Package	
Magnetometer	Magnetic fields of heliosphere and interstellar medium
Plasma and radio wave detector	Interaction of solar wind and interstellar medium
Solar-wind plasma ion and electron detector	Thermal ion composition and charge state; ion and electron distribution functions
Interstellar medium plasma ion and electron detector	Thermal ion composition and charge state; ion and electron distribution functions
Pickup and interstellar ion mass spectrometer	—
Interstellar neutral atom mass spectrometer	Density, composition of neutral species in the interstellar medium
Suprathermal ion mass spectrometer	—
Anomalous and galactic cosmic ray element/isotope spectrometer	—
Molecular analyzer for organic material	Organic material in outer heliosphere and interstellar medium
Dust composition analyzer	—
Suprathermal ion charge states detector	—
Gamma-ray burst detector	Complement long-baseline grid to locate gamma-ray bursters accurately
Imaging Package	
Infrared spectrometer—scans via spin	Structure of solar system dust disk; cosmic infrared background radiation
Energetic neutral atom imager	Structure and dynamics of heliosphere
Ultraviolet spectrometer (Lyman alpha)	Backscatter from neutrals in the interstellar medium; heliospheric structure

Space Physics and the Heliosphere

The heliosphere is a large and complicated structure whose dimensions are not definitively known. Recent measurements suggest that the Voyager 1 spacecraft may have crossed the “termination shock” of the solar wind and passed intermittently into the interstellar medium (Figure B.1). Although the interpretations of the observations are controversial, it is quite certain that this region is unlike anything ever sampled previously. Continued tracking of the two Voyager spacecraft should provide the size of our heliospheric cavity within the next several years.[1]

The solar wind continually rams into the local interstellar medium, and through complex interactions forms the large-scale outer boundaries of our solar system. The latter has three distinct components:

- The termination shock where the solar wind is abruptly slowed and heated prior to being deflected by the interstellar medium;
- The heliopause that separates the solar wind from the interstellar medium; and
- The bow shock or bow wave where the interstellar flow is slowed, heated, and deflected by the solar wind.

Between these boundaries that separate layers of solar wind from the interstellar medium, this “interstellar interaction” generates an approximate factor-of-two enhancement of neutral hydrogen (the “hydrogen wall”) in the upstream direction—the direction from which interstellar material is moving toward the Sun at ~25 km/s. Understanding the structure and dynamics of the interstellar interaction and our solar system’s outer boundaries is a primary goal of heliospheric science, and it is also relevant to understanding how other stars interact with the interstellar medium.

A variety of indirect measurements have provided only limited information on the nature of the interstellar interaction. These indirect techniques include measurements in the inner heliosphere of interstellar neutral atoms

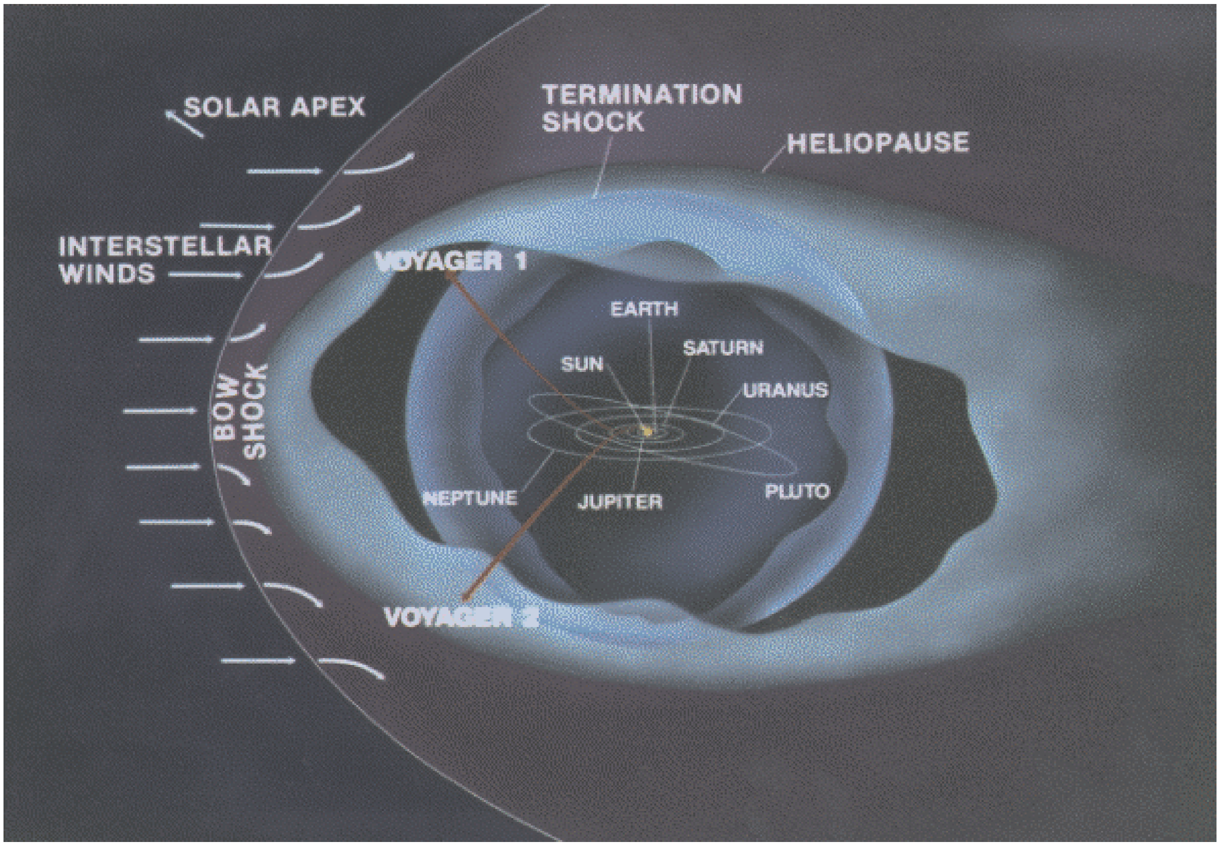
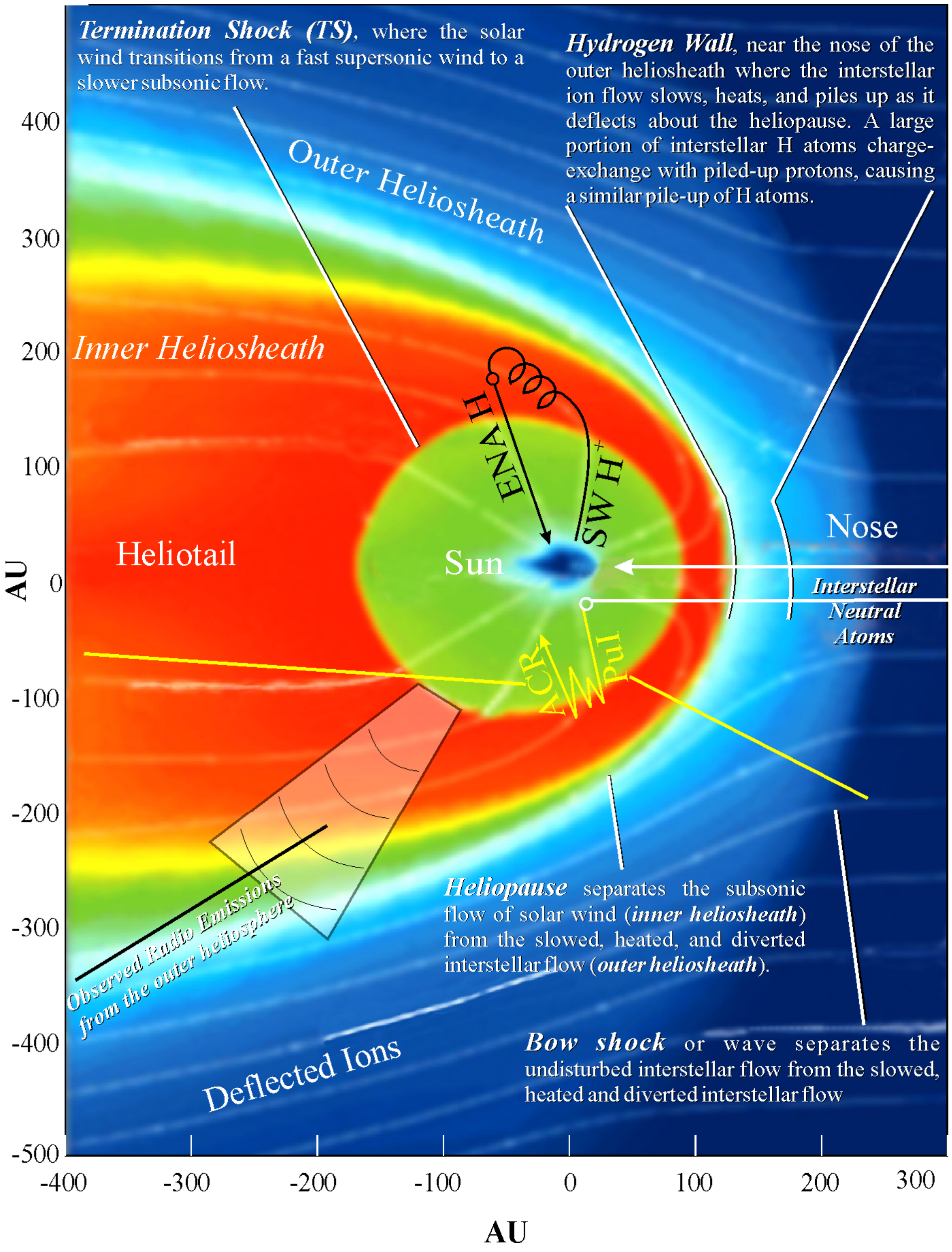


FIGURE B.1 A sketch of the heliosphere and its major features indicating the location of the planets of the solar system and the trajectories of Voyagers 1 and 2.

and pickup ions produced by charge exchange between interstellar neutral atoms and solar wind ions. In the outer heliosphere, indirect tracers of the interstellar interaction include measurements of anomalous cosmic rays and radio emissions at very low frequencies, apparently from the heliopause (Figure B.2). There is also now a promising technique to image globally the interstellar interaction through measurements of so-called energetic neutral atoms—i.e., direct products of the interstellar interaction formed through charge-exchange between the hot solar wind beyond the termination shock and the inflowing interstellar neutral atoms (Figure B.3).

Zodiacal Dust and the Kuiper Belt

The Kuiper Belt, a remnant of our solar system's formation, is a region that extends beyond the orbit of Pluto with bodies ranging in size from minute dust grains to small boulders and small planetary-sized objects. It is believed that the Kuiper Belt is continually eroded through collisions and may feed much of the dust-grain population throughout the solar system. To advance understanding of the formation and evolution of the solar system, greater understanding is needed of the inner parts of the solar system's zodiacal dust cloud, the Kuiper Belt, and the extended dust disk beyond the Kuiper Belt. However, the structure of our solar system's dust cloud beyond 3 AU cannot be studied remotely from vantage points near Earth because of the much larger emissions from the dust inside 3 AU.



Termination Shock (TS), where the solar wind transitions from a fast supersonic wind to a slower subsonic flow.

Hydrogen Wall, near the nose of the outer heliosheath where the interstellar ion flow slows, heats, and piles up as it deflects about the heliopause. A large portion of interstellar H atoms charge-exchange with piled-up protons, causing a similar pile-up of H atoms.

Heliopause separates the subsonic flow of solar wind (***inner heliosheath***) from the slowed, heated, and diverted interstellar flow (***outer heliosheath***).

Bow shock or wave separates the undisturbed interstellar flow from the slowed, heated and diverted interstellar flow

FIGURE B.2 A simulation of the heliosphere showing interactions between the solar wind and the interstellar medium. Simulation courtesy of Gary Zank, University of California, Riverside.

The Interstellar Observatory will map the structure of the solar system's dust cloud, the outer zodiacal cloud, using the infrared emissions from interplanetary dust. In situ instruments will study the composition of both interstellar and interplanetary dust grains to provide clues to their origin. The Interstellar Observatory's measurements of dust in the Kuiper Belt will probe the collisional evolution of the solar system, leading to a greater understanding of the evolutionary progression from dense protostellar disks to debris disks like those around Beta

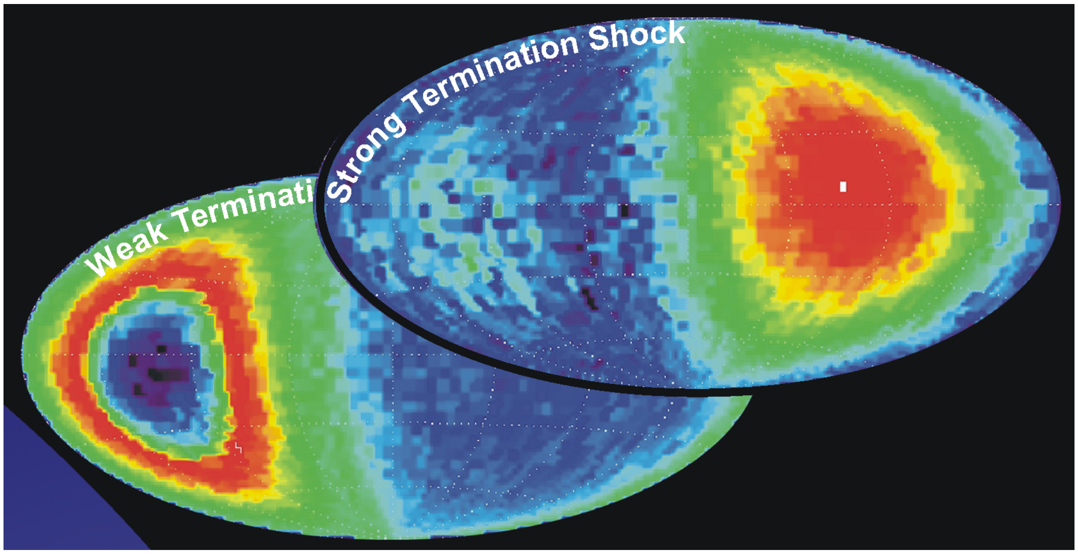


FIGURE B.3 Simulation of the relative intensity of energetic neutral atoms seen across the entire sky at 1 AU produced at the termination shock. The intensities and patterns differ depending on the shock strength.

Pictoris, and Alpha Lyrae, and finally to pristine systems like our own. Greater knowledge of dust in the solar system from this mission will enhance understanding of dust disks and the formation and evolution of planetary systems around other stars.

The Interstellar Observatory would make the first observations of predicted structures in the zodiacal dust cloud such as a heliocentric ring of dust at Mars orbit, dust associated with Jupiter's Trojan asteroids, and structure in the Kuiper disk associated with dust trapped in mean-motion resonances with Neptune. All of these structures are expected to have direct analogs in debris disks around other stars. Figure B.4 shows submillimeter-wavelength observations of a dust debris disk around the nearby (~10 light-years) solar-type star Epsilon Eridani; the structure of the disk is thought to be evidence of a planet around this star. Thus, the mission will make fundamental contributions to the goals of NASA's Origins program, since understanding our own zodiacal emission is key to understanding the structures of dust around other stars, and eventually to searching through the haze of both local and extrasolar zodiacal clouds for planets around other stars.

The Edge of the Solar System

Recent measurements of Kuiper Belt objects (KBOs) have shown a steep drop-off in the density of material in the outer solar system beyond the orbits of Neptune and Pluto. Is this the edge of the solar system, or only an "inner" edge? Various models attempt to explain the observed drop-off, such as a close encounter with another star in the early history of the solar system (unlikely in the local stellar environment) or an inefficient accretion process at large heliocentric distances, with smaller bodies spiraling in due to gas drag. It is also possible that the Kuiper Belt formed closer to the Sun and migrated outward ~10 AU with Neptune early in early solar system history.

Depending on how the solar system evolved, there remains the possibility that the density of circumsolar material will increase again at distances greater than 100 AU and return to the level predicted by extrapolation of the $r^{-1.5}$ curve fit to the material within 50 AU (see Figure B.5). A mission to the interstellar medium would measure such an increase, if present, and thereby enhance our understanding of the evolution of the solar system, a central goal of both planetary and origins-related science.

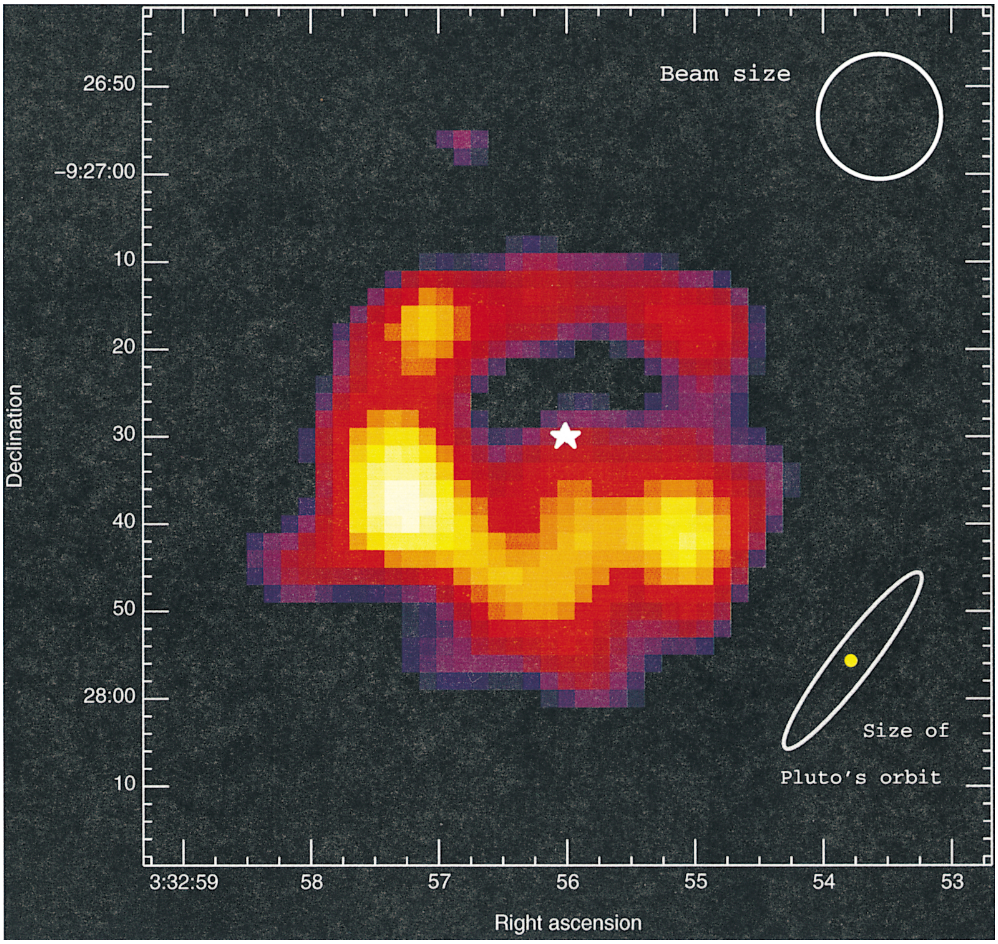


FIGURE B.4 Submillimeter-wavelength radio observations of a dust debris disk around Epsilon Eridani; the structure of the disk is thought to be evidence of a planet in orbit around this star.

The dust, particles, waves, and magnetic fields in the little-explored region of the outer heliosphere provide interaction sites for energetic particles, the sources of energetic neutral atoms, and pickup ions. How Kuiper Belt objects, grains, and the solar-wind populations in the outer heliosphere have interacted over time remains a subject of current and active research. Resolution of many of the questions about these populations will require the type of in situ measurements that only the Interstellar Observatory can provide.

Cosmic Infrared Background Radiation

Once the Interstellar Observatory has traveled some 5 to 10 AU from the Sun, the cosmic infrared background (CIRB) radiation will become visible as background uncontaminated by emissions from zodiacal dust. With a suitably cooled and shielded infrared detector, the Interstellar Observatory would enable measurement, for the first time, of the spectrum of the CIRB between 3 and 100 μm. These wavelengths correspond to highly redshifted (z ~7 to 10) rest-frame ultraviolet/optical wavelengths emitted by very distant objects formed early in the history of the universe. The CIRB contains information about the formation and evolution of galaxies and can be used to address questions relating to the following topics:

- When did stars and galaxies form?
- Did stars form before galaxies?
- Were early galaxies dusty? (If so, they could be unobservable in the optical but visible in the infrared.)

Thus, observations of the CIRB from a mission to the interstellar medium can be used to test fundamental hypotheses of modern-day cosmology.

Search for Organic Molecules

Organic material is found in the solar system—e.g., in asteroids, comets, meteorites, and interplanetary dust grains—and in the interstellar medium. Important questions relating to these materials include the following:

- Do the nonterrestrial organic materials have similar origins?
- Amino acids have been found in meteorites and tentatively identified in the interstellar medium in Sagittarius B2, but do they exist in the local interstellar medium as well?
- Did extraterrestrial organic material that reached Earth play a role in the emergence of life on our planet?

These questions can only be answered with in situ measurements in the outer heliosphere and the local interstellar medium. A suitable instrument on the Interstellar Observatory would search for and analyze organic material in the outer solar system and in the nearby interstellar medium to determine the nature and chemical evolution of this organic material.

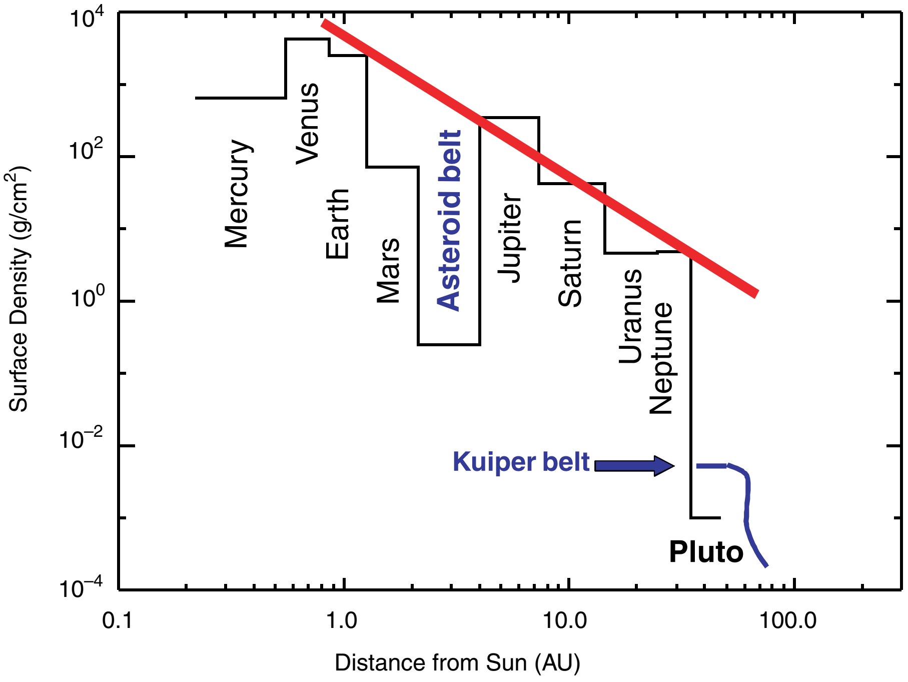


FIGURE B.5 Mass density in the solar system showing the observed edge of the solar system at about 50 AU. Beyond 100 AU, the mass density may increase dramatically up toward the level expected from extrapolation of the solid curve. Courtesy of Michael Brown, California Institute of Technology.

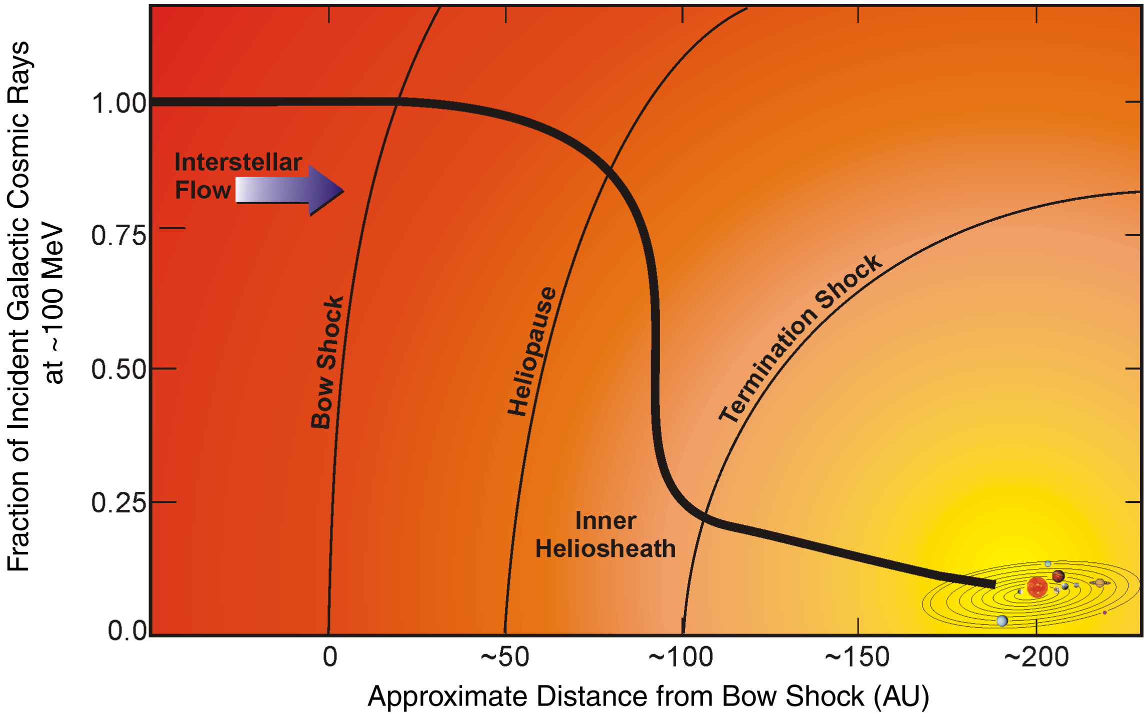


FIGURE B.6 A schematic showing the reduction of galactic cosmic rays reaching the inner heliosphere due to filtering provided by the interaction of the heliosphere and the local interstellar medium. Understanding time variations of this population is important for the safety of astronauts on interplanetary voyages.

Composition and Ionization State of Interstellar Matter

The chemical composition of the interstellar medium changes continually as it becomes enriched with material processed and reprocessed from stars, and then is released through stellar winds, novas, and supernovas. Understanding how the interstellar medium changes with time is the key to understanding the chemical evolution of our galaxy and the universe. By in situ sampling of interstellar matter, the Interstellar Observatory will determine directly how elements are distributed between solid (dust), neutral (gas), and plasma (ionized) states, as well as the ionization state of the interstellar medium, and how the isotopic composition of the present-day interstellar medium compares with that in the solar system. The current chemical inventory of our solar system has been established through the study of comets, asteroids, meteorites, Earth, the Moon, other planets, the Sun, and the solar wind. Analysis of the material brought back by the Genesis spacecraft will greatly enhance knowledge of the solar chemical inventory.

How does the composition of the interstellar medium compare with that of the Sun and solar system? While the interstellar medium has evolved chemically over the last 4.6 billion years, the chemical inventory of the Sun and solar system has remained largely unchanged, and so is a record of the composition of the interstellar medium 4.6 billion years ago when the solar system was formed.

What will this tell us about the chemical evolution of the galaxy? The abundances in the local interstellar medium that will be found by the Interstellar Observatory will be compared to solar abundances and those from more distant galactic regions. In the context of cosmogenic and nucleosynthetic models, the local interstellar abundances found by the Interstellar Observatory will improve our understanding of how stars process matter and how the galaxy evolves, and it will improve our knowledge of the age of the universe.

Cosmic Rays and Modulation by the Solar Magnetic Field

In the heliosheath—the region beyond the termination shock, where the solar wind is heated and slowed—models show the formation of a large magnetic barrier that filters out the majority of the low-energy galactic cosmic rays (<100 MeV/nucleon) from the interstellar medium. In addition, the solar wind's magnetic field—i.e., the interplanetary magnetic field—and its embedded large-scale magnetic disturbances exclude more galactic cosmic rays from the inner solar system over the ~2- to 4-year period when the Sun is most active during the 11-year solar cycle.

Highly penetrating galactic cosmic rays are one of the most serious hazards for astronauts on long-duration missions beyond the protection of Earth's magnetic field (Figure B.6). By directly passing through and sampling the heliosheath, measuring both galactic cosmic rays and the heliosheath's magnetic field, the Interstellar Observatory will study directly how the solar system is shielded from the majority of galactic cosmic rays.

Cosmic Rays and the Energy Density of the Galaxy

The spectrum of interstellar cosmic rays is not known because particles with energies <100 MeV/nucleon are excluded from the heliosphere. Only a spacecraft such as the Interstellar Observatory that travels to the interstellar medium can determine the full cosmic-ray energy spectrum and its contributions to the energy density and ionization state of the interstellar medium. These measurements will allow further study of astrophysical processes such as the acceleration of cosmic rays by supernova shocks, galactic radio and gamma-ray emissions, recent nucleosynthesis, and the heating of the interstellar medium. Finally, the Interstellar Observatory's direct measurements of the cosmic-ray energy spectrum will determine how the cosmic-ray pressure in the local interstellar medium affects the size and shape of the solar system's outer boundaries.

REFERENCE

1. National Research Council, *Exploration of the Outer Heliosphere and the Local Interstellar Medium*, The National Academies Press, Washington, D.C., 2004.

C

Additional Solar System Exploration Mission Concepts

RPS-ENHANCED OR RPS-ENABLED MISSIONS ENVISIONED BY 2020

Additional Long-Lived Lander Concepts

In addition to the Venus Long-Lived Lander described in Chapter 4, other examples of long-lived landers enhanced or enabled by radioisotope power systems (RPSs) are, in heliocentric order, as follows:

- *Mercury Polar In Situ Explorer.* Radar reflectivity measurements of polar craters on Mercury indicate that a reflective material, believed to be ice, exists locally. Because the craters of interest lie near the poles and may be in permanent shadow, RPSs will be needed to enable surface and shallow subsurface sampling, to distinguish between surface volatile deposits and bedrock or regolith.
- *Mars Deep Driller.* The Mars Exploration Rovers have revealed clear evidence for near-surface (several to tens of meters) stratigraphy on Mars, which contains fundamental information about the history of Mars and the history of water within those regions of Mars that were once wet. Drilling can potentially reach depths of up to 1 km, sampling layers that are largely unmodified by near-surface chemical processes, and may reach layers that are not exposed for view anywhere on the surface. The speed and depth of drilling need to be matched to available power sources. Slow, shallow drilling may be within the capabilities of an RPS, but deeper, faster drilling may require power from a small nuclear reactor. An RPS-powered mission of this type has been studied for launch sometime in the next decade.[1]
- *Mars Polar Profiler.* A desire to understand long-term climatic variations would lead to analysis of the depth structure of a polar cap, with in situ down-hole instrumentation perhaps augmented with retrieval of cored material to the surface for detailed analysis.
- *Io In Situ Explorer.* Io is probably the most volcanically and tectonically active body in the solar system. Io's atmosphere is uniquely affected by ubiquitous and time-variable volcanism, which adds to the atmospheric inventory through plumes and affects the surface temperature and composition. Monitoring of Io's volcanism over a significant period (at least several months) would allow study at a range of resolutions and timescales of the volcano-tectonic processes on this highly active body. The extreme temporal variability of Io requires a high data rate to adequately monitor surface changes. Development of radiation-hardened electronics and instruments would be required to allow a surface package to endure for a sufficient length of time to monitor activity in Jupiter's harsh radiation environment.

- *Europa Astrobiology Lander.* The harsh radiation from the jovian magnetosphere breaks all chemical bonds in the top tens of centimeters of Europa's surface, making it desirable that an astrobiology lander be capable of deriving material from a depth of at least 50 cm to analyze it for signatures of biological precursors or activity.
- *Icy Satellite Deep Driller.* A study of ice cores from the tectonically active icy satellites will shed light both on the history and the chemical composition of any possible subsurface oceans. The deep driller should be capable of drilling down to, and analyzing samples (cores or well logs) taken from, depths of tens of meters. The challenge for such a mission is the fabrication of a remotely operated deep drill, which would require substantial operating power (several hundred watts). The drill could be installed on a mobile platform (like a rover) to provide multiple measurements from different geological regions. Deep/fast drilling capability may require power from a nuclear reactor.
- *Comet Nucleus and KBO Surface laboratories.* Primitive bodies are diverse, ranging from asteroids in the main-belt and near-Earth space, to comets passing through the inner solar system, to Kuiper Belt objects. Before the return of a cryogenic sample from a comet nucleus back to Earth, much information could be collected about the nature of cometary ices and volatiles through in situ sampling of the ices. The low surface gravity of these bodies and the unknown nature of the surface materials would make developing such a laboratory a challenge.

Additional Rover Concepts

Rover concepts enhanced or enabled by RPS technology are, in heliocentric order, as follows:

- *Venus Mobile Laboratory.* Such a mission would couple the challenge of building a rover that could investigate a larger area than allowed by a simple lander with the challenge of operating any equipment in such a hostile environment.
- *Lunar Polar Rover/Driller.* Permanently shadowed craters at the lunar poles are believed to contain concentrations of hydrogen or its compounds, which may provide a resource for human use. To assess the scientific and resource potential of these deposits will require three-dimensional investigations within permanently shadowed craters. Long-lived rover and drilling missions require moderate amounts of power (hundreds of watts) for operation, which would be difficult to obtain from solar cells alone at the basin's location near the Moon's south pole. RPSs, on the other hand, could provide long-term thermal and electric power and, thus, enable a rover equipped with a 1- to 2-m coring device to range over distances of ~10 km and operate continuously through the long, cold lunar night.
- *Mars Advanced Science Laboratory.* It is possible to envisage more elaborate versions of NASA's planned Mars Science Laboratory equipped with, for example, more capable analytic instruments and the ability to drill beneath Mars's thin, hostile near-surface layer. These capabilities, plus extended range and endurance, are significantly enhanced by the availability of power at a level of hundreds of watts or greater from RPSs. A somewhat similar concept, the Astrobiology Field Laboratory, has been studied for possible launch to Mars sometime in the next decade.[2]
- *Titan Surface Laboratory.* The heliocentric distance of Titan, coupled with its dense atmosphere, makes the use of an RPS power source critical for any exploration on the surface. The images returned by the Huygens probe and Cassini's radar system indicate that significant parts of Titan's surface have the kind of muted relief that is ideally suited for long-range rover operations. A Mars Exploration Rover (MER)- or Mars Science Laboratory (MSL)-class rover, powered by an RPS, might be a less complex and risky approach to the exploration of Titan than the aerobot concepts discussed below and elsewhere in this report.

Additional Global Network Concepts

In addition to the Long-Lived Mars Network described in Chapter 4, other examples of network missions enhanced or enabled by RPSs are, in heliocentric order, as follows:

- *Mercury and Lunar Long-Lived networks.* These missions are similar in concept to the networks that could be deployed on Mars or Venus, except that the payload would emphasize measurement of seismic activity and heat-flow information. The heat-flow probes should be implanted under the surface using a drill or other means.

- *Icy Satellite Long-Lived Networks.* Seismic and magnetic sounding and measurements of geothermal heat flow are required to understand the internal structures and the states of the icy moons. The icy satellites of the solar system are some of the coldest places visited by spacecraft, and Galilean satellite surfaces are also exposed to the harsh radiation emanating from the jovian magnetosphere. Therefore, surface geophysical observatories require protection from these cold and harsh radiation environments. To obtain useful information about the interior, measurements from several landing sites over a period of several weeks to months would be required. The heating and long-term power requirements can be met through the use of RPS and radioisotope heater unit (RHU) technologies.

Additional Sample-Return Concepts

In addition to the Cryogenic Comet Sample Return, other examples of sample-return missions enhanced or enabled by an RPS are, in heliocentric order, as follows:

- *Mercury Sample Return.* Returning a sample from the surface would allow Mercury to be placed within the context of solar system chemistry and would provide clues to formation processes in the inner solar system.
- *Venus Selected Sample Return.* Sample return allows detailed geochemical analyses (e.g., of rare-earth elements and various isotopic systems) that constrain models for crustal and mantle evolution. Since Venus is essentially Earth's twin but has clearly undergone a very different history, studying its petrology, mineralogy, and trapped volatiles is important to understanding both Venus and Earth.
- *Mars Cryogenic Sample Return.* This mission would extract one or more cores of material (>10 m) from a polar cap or from subsurface ice deposits, and would maintain them in a sealed, refrigerated state for return to Earth. The preservation of samples of volatile materials at cryogenic temperatures is significantly enhanced by the availability of RPSs.

Additional Aerobot Concepts

Possible aerobot concepts enhanced or enabled by RPSs are, in heliocentric order, as follows:

- *Venus Aviator.* An aerial platform with maneuvering capability within the atmosphere of Venus would uniquely allow measurement of the three-dimensional composition and dynamics of the atmosphere. Measurements of expected volcanic gases by this vehicle would allow pinpointing and monitoring of volcanic emissions, if present. Flights at altitudes of less than 1 km would allow for high-resolution infrared mapping of the surface.
- *Titan Aerobot Explorer.* This mission would involve an RPS-powered lighter-than-air vehicle navigating in Titan's atmosphere.[3] Investigations would include high-resolution imaging of the surface from a variety of altitudes, possible subsurface sounding, measurement of weather phenomena, and, ideally, some analysis of surface material, either remotely or by a tethered sample collector.

NEP-ENHANCED OR NEP-ENABLED MISSIONS ENVISIONED BY 2020

In addition to the Jupiter Icy Moons Orbiter (JIMO), the Titan Express/Interstellar Pioneer, and the Neptune-Triton System Explorer discussed in Chapter 6, other examples of missions enabled by NEP-propulsion capabilities are, in heliocentric order, as follows:

- *Saturn System Multiple Rendezvous.* This concept is for a JIMO-like mission performing a tour of the saturnian system, including orbiting several of the saturnian satellites. If the NEP system's thrust is sufficient, "hovering" above the ring-plane may be possible. Delivery of (and provision of communications support to) subspacecraft such as landers, Saturn probes, and so on may also be a feature. It is important to note that the saturnian radiation environment is less severe than Jupiter's; thus the lifetime limitation for JIMO does not apply at Saturn. Transit time, spacecraft cleanliness, and maneuverability are significant concerns. NASA has already completed a detailed study of such a mission.[4]

- *Main-Belt, Trojan Asteroid, and Centaur Multiple Rendezvous.* This mission concept could employ the versatile capabilities of nuclear power and propulsion to explore the diversity of main-belt asteroids and trace the compositional gradient of solar system small bodies to the jovian Trojan asteroids and beyond to the Centaurs. Using high-resolution spectral and spatial imagery, radio science, and instrumentation to determine surface composition and subsurface structure, this mission would open an entirely new window on understanding of the nature and origins of primitive bodies. By exploring the region from the asteroid belt to the Centaurs, this mission would investigate compositions ranging from those similar to the early Earth, to primitive material from the jovian accretion region of the nebula, to objects that might be dynamically evolved from the Kuiper Belt.

NEP-ENHANCED OR NEP-ENABLED MISSIONS ENVISIONED AFTER 2020

Missions Deferred for Scientific Reasons Until After 2020

Although certain missions are clearly enabled by nuclear power and/or propulsion systems, scientific arguments can be made for delaying their launch until after 2020. Examples of such missions include the following:

- *Titan Surface Sample Return.* This mission is envisioned to include acquisition of Titan surface materials (including organics and ices) and their return to Earth in cryogenic condition. Titan ascent/descent may be performed by non-nuclear means, but sample return would require an advanced propulsion system. An in situ Titan exploration would define the goals of this mission and would be a likely precursor to a sample-return mission, hence providing the rationale for likely consideration after 2020.
- *Uranus System Explorer.* The ice-giant Uranus is unique in two key respects. First, all of the solar system's giant planets except Uranus have measurable amounts of heat emerging from their interiors. Second, Uranus is the only giant planet that spins on its side—i.e., at an obliquity of 98°. Whether this unique feature has anything to do with the low-heat flux is not known, but clearly this radical obliquity defines Uranus as an extremum for studies of suites of giant-planet models. The uranian system also has an unusual magnetic field, a ring system characterized by dark, narrow, and in some cases eccentric rings, plus five major icy satellites as well as a plethora of smaller moons. A Uranus-system mission should be comprehensive and relatively long term, and its objectives should span the planet, rings, magnetosphere, and satellites. These two goals would be strongly enabled by nuclear technologies, specifically power for the breadth and diversity of instrumentation, and propulsion for crafting a suitable system tour; however, reasonable transit times must be obtained. Geometric considerations suggest flight of this mission after 2020. Current observations of Uranus suggest that its atmosphere undergoes significant seasonal changes as the planet approaches equinox. Voyager 2 flew past Uranus at almost precisely its southern summer solstice (pole pointing at the Sun and Earth). A Uranus System Explorer should be targeted to arrive at the planet near equinox, the more interesting season, i.e., 2007 + 42 years, or 2049. A 10-year flight puts launch in the late 2030s.
- *Multiple Kuiper Belt Object Rendezvous.* This mission concept envisages a spacecraft capable of long-term orbital operations among the most remote and most primitive regions of the solar system. Through exploration of the Kuiper Belt, fundamental new insights are expected in planetary formation and accretion processes. Using the propulsion maneuverability and power of the nuclear systems, a mission trajectory could target multiple Kuiper Belt objects selected for their diversity in size, composition, and single or binary configuration. Apart from addressing basic questions concerning the objects' origin, composition, and morphology, detailed science investigations will be formulated that incorporate results from the first reconnaissance of Pluto and the Kuiper Belt by the New Horizons mission. Incorporating these mission results into the scientific planning and execution of a nuclear-enabled Multiple Kuiper Belt Object Rendezvous mission provides the rationale for launch in 2020 or beyond.

Missions Deferred for Technical Reasons Until After 2020

Examples of post-2020 missions enabled by Prometheus-derived propulsion include, in heliocentric order, the following:

- *Icy Moons Subsurface Sample Return.* Large icy, airless moons have surfaces that are greatly altered by external processes (e.g., bombardment by magnetospheric particle and micrometeorites, and ultraviolet chemistry and textural alteration). At a depth of centimeters to meters, the ice is less altered by these processes and contains information on the evolution of the body and possibly the conditions of origin. The specific goals vary from moon to moon. In the special case of Europa, there is likely to be a particularly high science return if the near-surface ice contains little modified material delivered from a subsurface ocean or melting event. This mission has very high technology demands because of the need to provide energy on the surface, as well as the need to deliver material out of Jupiter's gravity well and cryogenically back to Earth's surface. Meeting these demands would draw on nuclear propulsion and RPS capabilities of the type being developed by Project Prometheus.
- *Main-Belt, Trojan Asteroid, and Centaur Multi-Sample Return.* Performing the first detailed laboratory studies of the solar system's compositional gradient is the primary science goal of this mission concept. With nuclear power and propulsion, sampling a broad range of solar system bodies and returning those samples to Earth would become a newly enabled capability. Key to this study is characterization of the volatile inventory of the solar system, with the goal to understand the source of the life-enabling volatiles on Earth.

REFERENCES

1. See, for example, S. Miller, J. Essmiller, and D. Beaty, "Mars Deep Drill—Explore Active Hydrothermal Habitats," Jet Propulsion Laboratory, Pasadena, Calif., 2004. Available online at <http://mepag.jpl.nasa.gov/Advanced_Mission_Studies/index.html>, last accessed February 2, 2006.
2. See, for example, R. Diehl, "Astrobiology Field Laboratory—2013 Biosignature Detection," Jet Propulsion Laboratory, Pasadena, Calif., 2004. Available online at <http://mepag.jpl.nasa.gov/Advanced_Mission_Studies/index.html>, last accessed February 2, 2006.
3. J.L. Hall, V.V. Kerzhanovich, A.H. Yavrouian, J.A. Jones, C.V. White, B.A. Dudik, G.A. Plett, J. Mennella, and A. Elfes, "An Aerobot for Global In Situ Exploration of Titan," *Advances in Space Research*, in press.
4. Team Prometheus, NASA/DOE, *Saturn/Titan—JIMO Follow-On Mission Study, Final Report*, NASA, Washington, D.C., July 9, 2004.

D

Details of Selected Astronomy and Astrophysics Mission Concepts

INTERSTELLAR SCATTERING AND THE LONG-BASELINE RADIO INTERFEROMETER

Radio (λ >1 mm) interferometry on interplanetary baselines appears, at first glance, to be an ideal application of the ability of nuclear power and propulsion systems to deploy astronomical assets at great distances from Earth. However, the scattering of radio waves by the interstellar medium blurs radio images to angular sizes much greater than the resolution of a radio interferometer with a baseline of >1 AU.

The "warm, ionized" phase of the interstellar medium contains electron density fluctuations on a range of size scales, from smaller than $\sim 10^8$ m to greater than $\sim 10^{13}$ m. Evidence implies that the spectrum of density fluctuations is close to the Kolmogorov spectrum, familiar from characterizations of neutral turbulence. These fluctuations scatter radio waves from cosmic sources, causing frequency-dependent phase deviations that ultimately result in interference in the observer plane. This results in a variety of observed phenomena, including amplitude variations in time and frequency, akin to the twinkling of stars due to density inhomogeneities in Earth's atmosphere. Multipath scattering makes point sources of radio emission appear to have finite angular extent, of full width half maximum (FWHM) θ_s, a result of averaging over short-time-scale image wander. The size of the scattering "disk" varies inversely with ν^2 and depends strongly on the line of sight.

The greatest scattering is seen toward the galactic center: Sag A* has an apparent angular extent of 1.3 arcseconds at 1 GHz. Lines of sight perpendicular to the galactic plane show the least scattering, typically ~5 milliarcseconds at 1 GHz. Out of the plane, given the frequency dependence of θ_s, it is not hard to show that regions for which $\nu < 50$ to 150 B (where ν is in hertz and B is the interferometer baseline in meters) have $\theta_s > \lambda/B$, the effective interferometer resolution. This region is shown in Figure 8.1; radio interferometry with $B \geq 1$ AU is clearly uninteresting.

TERRESTRIAL INTERFERENCE AND THE FARSIDE RADIO OBSERVATORY

The impact of natural and human radio emissions on radio astronomy is enormous. The entire radio spectrum from ~30 MHz is strongly affected by interfering manmade signals. The region above 300 MHz—even those bands that have long been allocated specifically for radio astronomers—continue to experience tremendous pressure for commercial use. Moreover, Earth's ionosphere absorbs and refracts radiation below ~30 MHz. Additionally, natural sources of interference on Earth—such as auroral kilometric radiation, which produces very intense radiation in the frequency range from 50 to 750 kHz, or lightning, which produces strong interference in the range from 1 to 30 MHz and above—preclude observations below 30 MHz (the very low frequency [VLF] range) except under exceptional circumstances, or at special locations and for limited amounts of time.

A variety of astronomical phenomena are expected to emit radiation at the wavelengths affected by terrestrial radio noise. These include non-thermal emission from the Milky Way galaxy, pulsars, interstellar scintillation, active galactic nuclei, and clusters of galaxies, as well as the Sun and Jupiter. Much higher up in frequency, neutral atmospheric gases—particularly atmospheric water vapor—attenuate cosmic radiation increasingly strongly above 10 GHz, with attenuation peaking around 22 GHz. Strong oxygen lines attenuate heavily near 60 and 120 GHz, and water lines around 183 GHz.

OBSERVING WITH A 5-AU OPTICAL/NEAR-INFRARED OBSERVATORY

For observations at $\lambda \approx 0.2$ to 3 μm, sunlight scattered by zodiacal dust grains is the dominant source of diffuse background emissions and can, hence, be the dominant noise source for observations of faint sources. Observations from Pioneer 10[1] and Helios 1 and 2[2] spacecraft suggest that zodiacal brightness declines with heliocentric distance as $I_z \propto r^{-2.3}$ or $I_z \propto r^{-2.5}$. An observatory at 5 AU could have ≈ 50× lower zodiacal background than current or planned ultraviolet/optical/infrared observatories in Earth-trailing or L2 orbits. Reducing the zodiacal background further is of limited use, as diffuse galactic emission and the mean extragalactic flux are $\approx 10^{-2}$ of the 1-AU zodiacal background near 800 nm.

Point Sources

For background-limited observations of unresolved sources of specific flux f_ν, the signal-to-noise (S/N) ratio acquired in time *T* from a diffraction-limited telescope of diameter *D* scales as:

$$(S/N)^2 \propto (T f_\nu^2 D^4 / I_z)(\Delta\nu/\nu).$$

The last factor is the bandwidth of the observation. The lowered zodiacal background at 5 AU could increase observing efficiency by a factor of 50. This gain is realized only when the diffuse background is the dominant noise source. For brighter sources, shot noise in the source photons is dominant. For 2-meter-class visible telescopes at 1 AU, such as the Hubble Space Telescope (HST) or the proposed Supernova/Acceleration Probe, any source brighter than $V \approx 29$ mag is brighter than the diffuse background—nearly every star within 10 kpc, for example. The zodiacal brightness in the near-infrared is similar to that in the visible and drops precipitously into the ultraviolet, so it is unlikely that observing beyond 1 AU would be of use in observations of stars in the Milky Way.

Study of stars beyond the Milky Way, for example in elliptical galaxies, requires reaching $V > 29$ mag. But such observations also require very high angular resolution, much better than that afforded by the HST, to eliminate crowding of stars and resolve the population. Hence an increase in *D* to improve resolution (and S/N) would be much more useful than a reduction in I_z. There is hence little S/N incentive to move beyond L2 for the observation of point sources at ultraviolet, optical, and infrared wavelengths.

A major thrust of the astronomy and astrophysics (AAp) decadal survey[3] and NASA's exploration initiative is the detection and study of extrasolar planets. For such observations, there is little S/N incentive to reducing the solar zodiacal background by going to >1-AU orbits, because most of the targets will be embedded in a dust disk about their host stars that is a significantly larger and unavoidable source of background photons. Thus, the first reconnaissance and characterization of extrasolar planets will be done from a near-Earth vantage point.

Resolved Sources

Once the telescope is large enough to resolve the astronomical source, the S/N for objects with surface brightness fainter than the zodiacal background becomes

$$(\mathrm{S/N})^2 \;\alpha\; (Tf_\nu{}^2D^2/\mathrm{I}_z)(\Delta\nu/\nu).$$

A glance at the Hubble Ultra Deep Field shows that most of the faint, high-redshift galaxies in the universe are resolved by 2-m telescopes and are fainter than the zodiacal background in the visible. For observations of these very interesting sources, operation at 5 AU can perhaps be equivalent to a 50-fold increase in telescope area (or 7-fold increase in diameter). For a nuclear propulsion system to be useful, its cost and weight would have to be such that placing a 2-m telescope at 5 AU would be much cheaper than placing a 15-m telescope (or 50 2-m telescopes) at L2. Otherwise, one would choose the L2 observatories, which would offer superior S/N for other observations, as well as resolution.

Furthermore, a large telescope is only worth deploying at 5 AU if its purpose is limited to obtaining ultraviolet/optical/infrared spectra of high-redshift galaxies. A 0.1-arcsecond-diameter galaxy with surface brightness 10 times lower than the 1-AU zodiacal light will deliver only $\approx 10^{-3}$ photons per second to a 6-m aperture in a spectral element with $R = \Delta\nu/\nu \approx 1{,}000$. Hence a measurement with $S/N = 20$ would take 400,000 s—even assuming no deleterious effects of detector noise or radiation events. Imaging observations ($R \approx 10$) could more readily profit from the lower zodiacal background at 5 AU.

In terms purely of S/N, therefore, the value of nuclear power systems to ultraviolet/optical/infrared astronomy depends on the cost of the 5-AU location versus the cost of larger apertures at 1 AU, and in any case the S/N gains are likely to be limited to imaging of faint resolved galaxies. Certainly, the priorities of the ultraviolet/optical/infrared community will be served first by building a larger collecting area near 1 AU.

COOLING THE 5-AU FAR-INFRARED OBSERVATORY

A space telescope located 1 AU from the Sun will have an ambient temperature of approximately 300 K. Observations at wavelengths longer than 1 μm will be strongly background limited by the telescope's own thermal emissions. Cooling the telescope's optical system is clearly highly advantageous. Small, 1-meter-class telescopes can achieve operating temperatures of order of between 4 and 8 K by the use of onboard expendable cryogens. Applying such a cooling strategy to a large astronomical telescope is more problematic. The 6.5-m James Webb Space Telescope (JWST) will use a multilayer sunshield to passively achieve an operating temperature of 40 K at the Sun-Earth L2 point. This temperature is low enough to allow background-limited performance at $\lambda < 20$ μm, but for observations at longer wavelengths, still lower temperatures will be required. Current models for the proposed Single Aperture Far-Infrared Observatory (SAFIR) mission—envisioned as a colder, somewhat larger (~10-m-class), far-infrared version of JWST—indicate total residual heat loads of ~1 W for a telescope at 5 to 10 K. Such a heat load could, in principle, be addressed with expendable cryogens, although this approach would require some 30 liters of liquid helium per day. Such a consumption rate would lead to unreasonable masses of cryogen, and active cooling with onboard refrigerators is considered to be the best way to ensure long observatory lifetime. As described below, SAFIR is taken to be representative of the requirements for a class of large thermal-infrared space telescopes.

Space-qualified cryocoolers have been developed for both infrared and x-ray applications. Such low-temperature refrigeration systems do not rely on consumables and can be understood to provide a failure-limited observatory lifetime. These systems do, however, have substantial power requirements, and nuclear power sources can be considered as potentially enabling for such missions. For the low temperatures required by SAFIR, cryocooler efficiency is low, and a ratio of compressor input power to cooling power on the order of 1,500 is expected. Using the residual heat load referred to above, this would require on the order of 1.5 kW of electric power to maintain SAFIR at optimal temperature, which would mean that these cryocoolers would dominate the power budget of the observatory.

To supply just the cryocooler power budget for SAFIR at 1 AU, at least five Cassini-class RPS units (see Table 1.2) would be required. The power needs can also be met, however, by ~4 m^2 of solar panels, which are substantially smaller than the ~100 m^2 sunshield required for the observatory and are much less expensive than the RPSs. This sunshield would maintain an orientation perpendicular to the Sun, which is the orientation that is also most efficient for the solar panels. Thus, both the solar panels and the sunshield could be conveniently engineered together as part of an observatory structure. The advantages of solar panels relative to RPSs for SAFIR are multiplied by the more favorable power-to-mass ratio of solar panels. Although RPSs would not be as deployment-dependent as solar panels, they would add to the weight of the observatory about twice the weight that the solar panels would add.

Because of the high minimum power (~0.5 to 1 MWt) required for reactors with competitive power-to-mass ratios, fission systems appear a poor choice to power an observatory that would otherwise require only a few kWe. Dumping most of the thermal power from an onboard fission generator into free space would be difficult to do without adding large heat loads to the observatory itself. In addition, the strong gamma-ray flux from the fission system would seriously affect the performance of the observatory sensors.

Under what circumstances might nuclear power systems offer value to cryogenic infrared observatories? Although the power needs for such telescopes seem to be met economically by solar arrays at 1 AU, telescopes at larger heliocentric distances might benefit. Large heliocentric distances offer lower zodiacal background and increased operational efficiency. While both cooling power requirements (which are determined largely by solar insolation) and photovoltaic-power generation together decrease with distance, the benefit equation changes when the distance is large enough that active cooling no longer dominates the observatory power budget. In addition, communication power requirements rise even faster with distance for a given bandwidth. For such cases (at, for example, 3 to 5 AU) RPS power might be highly enabling. For the reasons noted above, however, onboard fission systems would remain problematic.

REFERENCES

1. M.S. Hanner, J.L. Weinberg, D.E. Beeson, and J.G. Sparrow, "Pioneer 10 Observations of Zodiacal Light Brightness Near the Ecliptic—Changes with Heliocentric Distance," pp. 29–35 in *Interplanetary Dust and Zodiacal Light: Proceedings of the IAU Colloquium No. 31*, Springer-Verlag, Berlin and New York, 1975.
2. C. Leinert, I. Richter, E. Pitz, and B. Planck, "The Zodiacal Light from 1.0 to 0.3 A.U. as Observed by the Helios Space Probes," *Astronomy and Astrophysics* 103: 177–188, 1981.
3. Board on Physics and Astronomy–Space Studies Board, National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

E

Glossary, Acronyms, and Abbreviations

Accretion, accretion disk: Astronomical objects as diverse as protostars and active galaxies may derive their energy from the gravitational power released by the infall, or accretion, of material onto a central object. The combined effects of gravity and rotation often force the accreting material into an orbiting accretion disk.

ACE: Advanced Composition Explorer.

Active cooling: Cooling achieved by power-consuming heat-management techniques such as the use of Stirling coolers or other refrigeration systems.

Active galactic nuclei (AGN): A term that refers to the existence of energetic phenomena in the nuclei, or central regions, of galaxies that cannot be attributed clearly and directly to individual stars.

Active galaxy: Certain galaxies emit far more energy than can be accounted for by their stars alone. The central regions of these galaxies harbor a compact, solar-system-sized object capable of outshining the rest of the galaxy by a factor of 100. The ultimate energy source for active galaxies may be the accretion of matter onto a supermassive black hole. Active galaxies can emit strongly across the entire electromagnetic spectrum, from radio waves to gamma rays.

Aerobot: A robotic aerial vehicle that can be used to remotely investigate planetary surfaces.

Aerocapture: The technique by which an incoming spacecraft uses a single, precisely determined passage through a planet's atmosphere to shed sufficient excess velocity to enter a predetermined orbit about that planet.

Alloy: A combination of two or more elements, at least one of which is a metal, and where the resultant material has metallic properties.

Altimetry: Determination of the altitude of an object or surface with respect to a fixed level, like sea level.

Anomalous cosmic rays (ACRs): Cosmic rays that originate from the interstellar space beyond the heliopause and differ from other types of cosmic rays in that they are singly charged, contain more helium than protons, and contain more oxygen than carbon.

Arcsecond: A unit of angle corresponding to 1/3600th of a degree; 1/60th of an arcminute. An arcsecond is approximately the size of a dime viewed from a distance of 1 mile.

ARISE: Advanced Radio Interferometry between Space and Earth.

ASEB: Aeronautics and Space Engineering Board.

Astrobiology: Study of the origin, evolution, and distribution of life in the universe.

Astronomical unit (AU): A basic unit of distance equal to the separation between Earth and the Sun, about 150 million km.

Aurora: A glow in a planet's ionosphere caused by the interaction between the planet's magnetic field and charged particles from the Sun.

Baseline: The separation between telescopes in an interferometer. The largest baseline determines the finest detail that can be discerned with an interferometer.

Bow shock: Also, "bow wave," where the interstellar flow is slowed, heated, and deflected by the solar wind. In a planetary magnetosphere, the bow shock is the boundary at which the speed of the solar wind abruptly drops as a result of its approach to the magnetopause.

Brayton power conversion: An open-cycle power-conversion system that uses a thermodynamic cycle featuring heat addition and rejection at constant pressure. This cycle represents the idealized behavior of the working fluid in a gas turbine engine.

Bremsstrahlung: Electromagnetic radiation produced by the acceleration of a charged particle, such as an electron, when deflected by another charged particle, such as an atomic nucleus.

C3: The energy per unit mass of a spacecraft once it gets away from Earth's gravitational field. If $C3 > 0$, the launch vehicle sends the spacecraft directly to its destination—outside Earth's sphere of influence. If $C3 < 0$, the launch vehicle sends the spacecraft into Earth orbit, and the spacecraft then has to use its own propulsion to leave Earth's sphere of influence. The units of C3 are km^2s^{-2}.

Celestial mechanics: A term for the application of physics, historically Newtonian mechanics, to astronomical objects such as stars and planets.

centiSievert (cSV): One-hundredth of a Sievert, the SI unit of radiation dose equivalent, which indicates what dose of x-rays or gamma rays produce the equivalent damage.

Chirality: The right- or left-handedness of an asymmetric molecule. Absence of symmetry on reflection.

CIRB: Cosmic infrared background radiation.

COBE: The Cosmic Background Explorer, a NASA mission launched in 1989 to study the cosmic background radiation from the Big Bang.

Corona: The luminous “atmosphere” of the Sun extending millions of kilometers into space.

Coronal mass ejection (CME): A disturbance of the Sun’s corona involving eruptions from the lower part of the corona and ejection of large quantities of matter into the solar wind. These ejecta sometimes have higher speed, density, and magnetic field strength than is typical for the solar wind. If their speeds relative to the background solar wind are high, they can produce shocks in the plasma that precede them as they move outward.

Cosmic accelerator: The process by which matter can be accelerated to speeds far above those available in Earth-based particle accelerators.

Cosmic microwave background (CMB) radiation: The radiation left over from the Big Bang explosion at the beginning of the universe. As the universe expanded, the temperature of the fireball cooled to its present level of 2.7 degrees above absolute zero (2.7 K). Blackbody radiation from the cosmic background is observed at radio, millimeter, and submillimeter wavelengths.

Cosmic radiation: Atomic nuclei, accelerated to extremely high energies by unknown processes in space, which continually bombard Earth from all directions.

Cosmogonic: Relating to the creation or origin of the planets.

CR: Cosmic ray (see *Cosmic radiation*).

Cryogenic: Of or relating to the production of very low temperatures.

Cryostat: An apparatus for maintaining a constant very low temperature.

CSSR: Comet Surface Sample Return.

Cyclotron radiation: The characteristic electromagnetic radiation emitted when nonrelativistic charged particles spiral around magnetic field lines.

Dark energy: An as-yet-unknown form of energy that pervades the universe. Its presence was inferred from the discovery that the expansion of the universe is accelerating, and these observations suggest that about 70 percent of the total energy density of the universe is in this form. The remaining 30 percent is composed of visible matter (4 percent) and dark matter (26 percent). Such an acceleration would be predicted if the cosmological constant that Einstein included in his general theory of relativity were non-zero.

Dark matter: Approximately 87 percent of the matter in the universe may have so far escaped direct detection. The presence of this unseen matter has been inferred from motions of stars and gas in galaxies, and of galaxies in clusters of galaxies. Candidates for the missing mass include brown dwarf stars and exotic subatomic particles. Dark matter was called “missing mass” for many years. However, because it is the light, not the mass, that is missing, astronomers stopped using that term.

Decalcification: The removal or loss of calcium or calcium compounds (as from bones or soil).

Delta-V: The change in velocity needed by a spacecraft to switch from one trajectory to another.

Diurnal: Recurring every day; or of, or relating to, occurring in the daytime.

DSN: Deep Space Network.

Dynamo: An electromagnetic process in which the movement of conductive material gives rise to a magnetic field.

Eccentricity: A measure of how much an orbit's shape deviates from a circle.

Ecliptic: The plane of Earth's orbit around the Sun.

Einstein rings: A gravitational lens effect in which the image of a remote background point source of radiation, such as a quasar, is distorted into a ring by the gravity of a foreground galaxy.

Electromagnetic spectrum: Radiation can be represented as electric and magnetic fields vibrating with a characteristic wavelength or frequency. Long wavelengths (low frequencies) correspond to radio radiation; intermediate wavelengths, to millimeter and infrared radiation; short wavelengths (high frequencies), to visible and ultraviolet light; and extremely short wavelengths, to x-rays and gamma rays. Most astronomical observations measure some form of electromagnetic radiation.

Emission line: A bright line in the spectrum of a luminous object caused by the emission of light at a particular wavelength. Emission lines may appear on their own, as in the spectrum of a nebula energized by radiation from a nearby hot star, or they may be superimposed on an absorption spectrum, as happens when a star is surrounded by hot gas.

Energetic neutral atom (ENA) imaging: ENA production mechanisms in space plasmas are charge-exchange reaction with atmospheric/exospheric gases, sputtering of planetary atmospheres, backscattering from the planetary atmospheres (ENA albedo), sputtering from planetary surfaces, ion neutralization/sputtering on dust particles, and recombination (CMI). In contrast to charged particles, ENAs are no longer influenced by electromagnetic fields and propagate on straight paths from the source to the observer. Directional detection of ENAs yields a global image of the interaction and by complex inversion techniques properties of the source populations can be deduced.

eV: An electron volt, a measure of energy equal to that gained by an electron passing through a potential difference of 1 volt; also a unit of particle mass when divided by the speed of light (c) squared. Electrons have a mass of about 0.511 MeV/c^2 (million electron volts); protons have a mass of about 938 MeV/c^2 (billion electron volts).

Event horizon: The "surface" of a black hole. It is a one-way membrane, allowing matter or signals to flow in but not out.

EXIST: Energetic X-ray Imaging Survey Telescope.

Fast neutron: A free neutron with a kinetic energy level close to 1 MeV (speed of 14,000 km/s), produced by nuclear processes such as nuclear fission.

Field programmable gate arrays (FPGAs): Electronic components of digital circuits that use a grid of logic gates that can be programmed by the consumer (rather than the manufacturer).

Fission: A process whereby a large nucleus such as uranium is split into two smaller nuclei.

Formation flying: Multiple spacecraft maintaining a constant distance from each other to high precision.

Full width half maximum (FWHM): A term commonly used in statistics and telecommunications that refers to the value of the width of a function at which the dependent variable is at half its maximum value.

Gamma ray: Electromagnetic radiation with wavelengths less than 0.00001 micron, more energetic than x-rays.

Gamma-ray burst (GRB): Burst of gamma rays from cosmic sources observed by detectors on satellites. Several hundred are detected per year, and they range in duration from fractions of a second to several seconds. Most gamma-ray bursts come from objects at cosmological distances.

Gardening (of the regolith): The process of mixing surface materials by impact.

GLAST: Gamma-ray Large Area Space Telescope.

Gravitational lensing: A consequence of Einstein's general relativity theory is that the path of light rays can be bent by the presence of matter. Astronomers have observed that the light from a distant galaxy or quasar can be "lensed" by the matter in an intervening galaxy to form multiple and often distorted images of the background object.

Gravitational wave: According to the theory of general relativity, a ripple in the geometry of space-time propagating as a wave.

Gravity assist: Also known as the sling-shot effect, an important spaceflight technique, already used successfully on a number of interplanetary missions including Voyager, Galileo, and Cassini, whereby the gravitational field of a planet is used to increase the speed and alter the course of a spacecraft without the need to expend fuel.

Ground truth: Facts that are found when a location is studied in situ, as opposed to information obtained from remote-sensing observations.

Hall fields: A phenomenon thought to play a critical role in changing the large-scale structure of magnetic fields (at Earth, on the Sun, and elsewhere in the cosmos).

HCIPE: High Capability Instruments for Planetary Exploration program.

Heliosheath: Where the solar wind is heated and slowed beyond the termination shock.

Heliosphere: The region of space dominated by the Sun's magnetic field. It includes the Sun itself as well as the corona and the solar wind, and extends beyond the orbit of Pluto to distances in excess of 50 AU.

HEMT: High Electron Mobility Transistor.

HEO: High Earth orbit

Hot atom: Atom released from a molecule when a nuclear reaction takes place. Such particles are likely to be moving very fast, enabling them to break other bonds and induce further chemistry when they collide with other atoms or molecules. This may induce reactions that could not occur under thermal conditions, leading to production of unusual species that cannot otherwise be generated.

HST: Hubble Space Telescope.

IMAGE: Imager for Magnetopause-to-Aurora Global Exploration.

Inclination: Angle between the plane of the object's orbit and the ecliptic.

Interferometer: An optical system in which radiation from multiple sources is combined and the resulting interference pattern is used to provide information on the nature and configuration of the sources.

Interplanetary Monitoring Platform (IMP)-8: The last of a series of NASA probes, managed by the Goddard Space Flight Center, designed to study Earth's magnetosphere and plasma (ionized gas) in interplanetary space.

Interplanetary shock: The abrupt boundary formed at the front of a plasma cloud (e.g., from a coronal mass ejection) moving much faster than the rest of the solar wind, as it pushes its way through interplanetary space.

Interstellar medium (ISM): The material between the stars, consisting of gas, dust, and cosmic rays (high-energy charged particles moving at nearly the speed of light).

Interstellar Observatory: A mission detailed in this report that uses nuclear power and propulsion to directly explore interstellar space beyond the heliopause.

Interstellar scintillation: An apparent twinkling of the signals from distant point-like radio sources that is due to changes in the density of the interstellar medium through which the signals have passed on their way to Earth.

Iogenic: Originating from Io.

Ionosphere: The part of the atmosphere that is kept partially (up to 0.1 percent) ionized by ultraviolet light and x-rays from the Sun. It lies immediately above the stratosphere, roughly between altitudes of 50 and 500 km from Earth.

IPSTDT: NASA's Interstellar Probe Science and Technology Definition Team.

IRAS: Infrared Astronomical Satellite.

ISO: The European Space Agency's Infrared Space Observatory.

JGA: Jupiter Gravity Assist.

JIMO: Jupiter Icy Moons Orbiter.

JPL: Jet Propulsion Laboratory.

JWST: James Webb Space Telescope.

KBOs: Kuiper Belt objects (see *Kuiper Belt*).

Kolmogorov spectrum: A concept arising in the theory of turbulence describing how energy is distributed among eddies of different sizes.

kpc: Kiloparsec, which is $3.08568025 \times 10^{19}$ meters.

Kuiper Belt: A region of the solar system containing icy planetesimals distributed in a roughly circular disk some 40 to 100 AU from the Sun. Pluto is believed to circumscribe the innermost region of the Kuiper Belt.

kW: Kilowatt, a unit of power.

kWe: Kilowatt-electric, a unit of electrical power (e.g., the total amount of electrical power produced by a nuclear reactor, which is substantially less than the total thermal power because of the inefficiencies in converting thermal energy to electrical energy).

L1/L2: Sun-Earth Lagrangian points. L1 and L2 are approximately 1.5 million km from Earth. L1 is located between the Earth and the Sun. L2 is located on the far side of the Earth from the Sun.

Lagrangian point: One of five locations in space around a rotating two-body system (such as the Earth-Moon or Earth-Sun) where the pulls of the gravitating bodies combine to form a point at which a third body of negligible mass would be stationary relative to the two bodies.

LEO: Low Earth orbit.

Liquid metal coolants: Molten metal used as a reactor coolant.

LISA: Laser Interferometer Space Antenna.

Lithium hydride: A lightweight, high-temperature alloy of lithium that is effective as a neutron shield and can also be used as a liquid metal coolant.

Lithosphere: The rigid outer crust of rock of a planetary body.

Local Group galaxies: A collection of more than 40 galaxies, spread across a volume of space some 10 million light-years in diameter, of which our own Milky Way Galaxy and the Andromeda Galaxy are the dominant and central members.

Magnetopause: The boundary between a planet's magnetosphere and the magnetic field of the solar wind.

Magnetosphere: The region exterior to a planet in which its magnetic field plays the dominant part in controlling the physical processes that take place there.

Magnetotail: The part of a planet's magnetosphere that is elongated away from the Sun by the solar wind.

MAO: Mars Upper Atmosphere Orbiter.

Maser: A natural or artificial source of very intense, narrow-band, coherent microwave radiation. "Maser" stands for "microwave amplification by stimulated emission of radiation."

Mass spectrometer: Instrument that produces and measures, usually by electrical means, a mass spectrum. It separates ions according to the ratio of their mass to charge, allowing scientists to determine the abundances of each isotope.

Mass wasting: Loss of material from a slope due to gravity-driven processes.

Maunder minimum: The period from approximately 1645 to 1715 during which there was a substantial reduction in the number of sunspots visible on the solar disc. This phenomenon was first identified by the British astronomer Edward W. Maunder (1851–1928).

Metrology: The study of precise measurements.

MIDEX: Midsize Explorer; a continuing series of highly focused and relatively inexpensive (less than $180 million in total cost to NASA) astrophysics and space physics missions.

MMRTG: Multi-mission radioisotope thermoelectric generator.

Moore's law: An empirical observation, made in 1965 by Gordon Moore, Intel cofounder, that the number of transistors per integrated circuit exhibits exponential growth over time, resulting in an approximate doubling of transistors per circuit every 18 months.

MSL: Mars Science Laboratory.

Nebula: A cloud of gas and dust in space.

NEP: Nuclear-electric propulsion, a nuclear propulsion system that uses electricity from a space nuclear reactor to power an electric propulsion system, such as an ion engine.

NEPA: National Environmental Policy Act.

NERVA/Rover: U.S. nuclear thermal rocket technology program conducted from 1955 to 1973.

Neutrino: One of a family of subatomic particles with little or no mass. These particles are generated in nuclear reactions on Earth, in the centers of stars, and during supernova explosions and can give unique information about these energetic processes. Because neutrinos interact only weakly with matter, they are difficult to detect.

New Horizons: A NASA mission to explore Pluto and the Kuiper Belt, launched in January 2006.

NGST: Next Generation Space Telescope, the original name for the James Webb Space Telescope.

Noble gases: The chemical series of elements (found in group 18 of the periodic table) that includes helium, neon, argon, krypton, xenon, and radon. These gases are relatively unreactive, due to their full outer electron shells, and were historically referred to as "inert gases" or "rare gases."

Nova: An extreme example of the cataclysmic variable phenomenon in which a star's brightness suddenly increases by a factor of a million and then fades over a period of weeks. Novas occur in binary systems of one normal and one white dwarf star, where the normal star transfers matter to the dwarf via an accretion disk. The accreted matter accumulates until such time that it spontaneously ignites in a thermonuclear outburst on the white dwarf's surface.

NRC: National Research Council.

NTP: Nuclear-thermal propulsion, a nuclear propulsion system that converts the thermal energy produced by a nuclear reactor directly into thrust, for example, by heating hydrogen, which is then exhausted through a propulsion nozzle.

Nucleon: Neutron or proton.

Nucleosynthesis: The process by which heavy elements such as helium, carbon, nitrogen, and iron are formed out of the fusion of lighter elements, such as hydrogen, during the normal evolution of stars, during supernova explosions, and in the Big Bang.

Obliquity: The angle between the orbital plane of an object and the plane of its rotational equator.

Occultation: The disappearance of the light of a celestial body owing to the intervention of another body of larger apparent size across the line of sight.

Outgassing: The emanation of gases from within an object.

Parallax: The apparent shift in position of a nearby object relative to a more distant object, as the observer changes position. Using basic trigonometry, it is possible to derive the distance of a star from its parallax as observed from opposite points on Earth's orbit.

PDS: Planetary Data System.

Petrology: Field of geology that focuses on the study of rocks and the conditions by which they form.

Photovoltaic: A photovoltaic cell is a device that turns light into electrical energy.

Planetesimals: The planetary bodies that formed the building blocks of all the solar system's planets and satellites.

Plasma waves: Periodically interacting electromagnetic waves and particles common in ionized plasmas such as the solar wind.

Positron: Antiparticle of the electron.

Prebiotic: Not yet alive; a chemical system or environment that is a precursor to life.

Project Prometheus: A NASA initiative to develop nuclear technology for power and propulsion in space exploration, announced in January 2003.

Protostellar disk: The disk of gas, dust, and matter from which planets are formed around other stars.

PUI: Pickup ions, produced by charge exchange between interstellar neutral atoms and solar-wind ions.

Pulsar: A spinning neutron star that emits radiation in a beam. The sweeping action of the beam causes the object to pulse regularly when viewed by an observer, just as with a lighthouse.

Quantum gravity: Quantum gravity is the study of theories that incorporate known gravitational and quantum phenomena in a unified mathematical framework.

Quasi-stellar object (QSO): Together with active galactic nuclei, quasi-stellar objects form the group of objects known as active galaxies.

Radioisotope: An atom with an unstable nucleus that spontaneously undergoes radioactive decay by emitting gamma ray(s) and/or subatomic particles.

Radioisotope power system (RPS): A system that produces electrical power utilizing the nuclear decay of radioactive isotopes, typically plutonium-238 (^{238}Pu).

Radiolysis: Molecular decomposition of a substance as a result of the action of radiation.

Rankine power conversion: A closed-cycle power-conversion system commonly found in power generation plants. Heat is added at constant pressure in a boiler, which converts the working fluid (e.g., water) to superheated steam. The steam expands through a turbine at constant entropy before being exhausted at a lower pressure into a condenser, where the steam is cooled. The resulting condensate is compressed at constant entropy so that it can be returned to the boiler.

Reactor coolant: A gas or fluid circulated through a heat exchanger, radiator, or other cooling device to maintain the core of a nuclear reactor at the desired temperature.

Redox: Chemical reactions in which there is a loss of an electron by a molecule or atom (oxidation) and an uptake of an electron by another molecule or atom (reduction). Such reactions are essential to biological energy exchange and thus to life on Earth.

Redshift: Radiation from an approaching object is shifted to higher frequencies (to the blue), while radiation from a receding object is shifted to lower frequencies (to the red). A similar effect raises the pitch of an ambulance siren as it approaches. The expansion of the universe makes objects recede so that the light from distant galaxies is redshifted. The redshift is parameterized by z, where the wavelength shift is given by the factor (z) times the wavelength in the rest frame.

Refractory alloy: An alloy with an extremely high melting point, which makes it suitable for use in construction of reactor cores and other high-temperature applications.

Regolith: The layer of fragmented, incoherent rocky debris on the surface of a planetary body.

Relativistic: Systems with particles moving with velocities close to the velocity of light.

RF: Radio frequency.

RHESSI: Reuven Ramaty High Energy Solar Spectroscopic Imager.

RHU: Radioisotope heater unit.

R_J: Distance measure, radii of Jupiter.

RTG: Radioisotope thermoelectric generator.

SAFIR: Single Aperture Far-Infrared Observatory.

SDO: Solar Dynamics Observatory.

Shannon's theorem: A fundamental concept in information theory relating the maximum rate at which data can be transmitted in a communications system to the system's bandwidth and background noise.

Shot noise: Shot noise consists of random fluctuations in a signal (electrical or optical) caused by the discrete nature of the signal carriers (i.e., electrons or photons, respectively). The strength of this noise increases with growing magnitude of the average current or intensity of the light.

Signal-to-noise ratio (S/N): The ratio between the magnitude of a signal and the magnitude of background noise.

Small Explorer (SMEX): A continuing series of highly focused and relatively inexpensive (less than $120 million in total cost to NASA) astrophysics and space physics missions.

SOHO: Solar and Heliospheric Observatory.

Solar Coronal Cluster: A mission of four clustered spacecraft near the Sun that provide basic understanding of the physical drivers of space weather and radiation, as detailed in this report.

Solar-electric propulsion: Reaction system that utilizes solar energy to power an ion engine.

Solar energetic particles (SEPs): Atoms that are associated with solar flares. SEPs are a type of cosmic ray.

Solar flux: A unit of radio emission from the Sun, used as a measured index for solar activity.

Solar sail: A device that uses the pressure of sunlight to propel a spacecraft in the same way that a sailing ship uses wind.

Solar System Disk Explorer: A mission to explore the outer heliosphere and the disk of dust in the Kuiper Belt and beyond.

Solar wind: The stream of charged particles and atoms (mainly ionized hydrogen but actually a mixture of all atoms in the Sun) moving outward all the time from the Sun with low velocities in the range of 300 to 500 kilometers per second.

Space Infrared Telescope Facility (SITRF): Now known as the Spitzer Space Telescope, it was launched in August 2003 and detects the infrared energy, or heat, radiated by objects in space between wavelengths of 3 and 180 microns.

Specific impulse (I_{sp}): Total thrust provided by an engine divided by the mass flow rate of the propellant used to provide that thrust. In other words, it is the length of time that unit weight of propellant can provide unit thrust.

Spectroscopy: A technique whereby the light from astronomical objects is broken up into its constituent colors. Radiation from the different chemical elements that make up an object can be distinguished, giving information about the abundances of these elements and their physical state.

Sputtering: The process in which atoms on the surfaces of airless planetary bodies are knocked free by high-speed atomic particles in the solar wind; much-higher-energy cosmic rays can also sputter surface materials.

SRG: Stirling radioisotope generator.

SSB: Space Studies Board.

STDT: Solar Probe Science and Technology Definition Team.

STEREO: Solar-Terrestrial Relations Observatory.

Stirling power conversion: A closed-cycle power-conversion system that features isothermal (constant temperature) expansion of a gas in a cylinder, followed by an isochoric (constant volume) cooling, followed by isothermal compression back to the original volume and isochoric heating back to the original temperature.

Stratigraphy: The study of the relationships between stratified rocks.

String theory: A new physical theory that is described as being both a consistent quantum theory of gravity and a unified theory of all particles and forces.

Sublimation: Phase transformation directly from the solid to gaseous state.

Supernova: A star that, due to accretion of matter from a companion star or exhaustion of its own fuel supply, can no longer support itself against its own weight and thus collapses, throwing off its outer layers in a burst of energy that outshines an entire galaxy. In 1987 a star in the Large Magellanic Cloud was observed as a dramatic supernova called Supernova 1987A.

Systems for Nuclear Auxiliary Power (SNAP): A program of experimental radioisotope thermoelectric generators (RTGs) and space nuclear reactors flown during the 1960s.

Telemetry: Data received electronically from a spacecraft during flight.

Termination shock: Where the solar wind is abruptly slowed and heated prior to being deflected by the interstellar medium.

Thermoelectric power conversion: Direct, static conversion of heat energy into electric power through the use of special materials that produce a voltage differential when parts of the material or system are maintained at different temperatures.

Time-of-arrival triangulation: A method of calculating the location of an object or event (e.g., a gamma-ray burst) by using the difference in detection times at a minimum of three different, widely separated detectors.

Torus: A doughnut-shaped surface of revolution generated by revolving a circle about an axis coplanar with the circle.

TPF: Terrestrial Planet Finder.

Transverse velocity: The component of the velocity of an object, such as a star, that is at right angles to the observer’s line of sight; also known as tangential velocity.

Van Allen belts: A donut-shaped region in Earth’s magnetosphere that contains a high density of energetic charged particles trapped in the dipole field of the planet.

VISE: Venus In Situ Explorer.

Volatiles: Elements that condense from or exist as a gas at low temperatures.

Waveband: A band of adjacent frequencies.

WMAP: Wilkinson Microwave Anisotropy Probe.

Zodiacal dust cloud: A lenticular-shaped dust cloud surrounding the Sun and maintained by fine material from asteroidal collisions and cometary activity.

Zodiacal light: A faint glow of light scattered off the zodiacal dust; it can sometimes be seen under very dark sky conditions, along the horizon, either just after dusk or before sunrise.