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Visions into Voyages for Planetary Sciences in the Decade 2013-2022: A Midterm Review

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Committee on the Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences

Space Studies Board

Division on Engineering and Physical Sciences

A Consensus Study Report of
The National Academies of
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Preface

In spring 2011 the National Academies of Sciences, Engineering, and Medicine produced a report outlining the next decade in planetary sciences. That report, titled *Vision and Voyages for Planetary Science in the Decade 2013-2022*, and popularly referred to as the "decadal survey," has provided high-level prioritization and guidance for NASA's Planetary Science Division. Other considerations, such as budget realities, congressional language in authorization and appropriations bills, administration requirements, and cross-division and cross-directorate requirements (notably in retiring risk or providing needed information for the human program) are also necessary inputs to how NASA develops its planetary science program.

In 2016 NASA asked the National Academies to undertake a study assessing NASA's progress at meeting the objectives of the decadal survey. After the study was underway, Congress passed the National Aeronautics and Space Administration Transition Authorization Act of 2017 which called for NASA to engage the National Academies in a review of NASA's Mars Exploration Program. NASA and the Academies agreed to incorporate that review into the midterm study. That study has produced this report, which serves as a midterm assessment and provides guidance on achieving the goals in the remaining years covered by the decadal survey as well as preparing for the next decadal survey, currently scheduled to begin in 2020.

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, 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 thank the following individuals for their review of this report:

Robert D. Braun, NAE,[4] University of Colorado, Boulder,
Wendy M. Calvin, University of Nevada, Reno,
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Daniel J. Scheeres, NAE, University of Colorado, Boulder,
Amy Simon, NASA Goddard Space Flight Center,
Norman H. Sleep, NAS,[5] Stanford University, and
Jessica Sunshine, University of Maryland.

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 Marcia J. Rieke, NAS, University of Arizona. She was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the National Academies.

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Contents

Summary

This decade has been one of the most important and scientifically productive periods ever in the history of planetary science. New worlds have been explored and new discoveries have been made. Only 5 years ago Pluto was no more than a blurry smudge in the view of the most powerful telescopes, but today Pluto is known as a highly complex world. The atmosphere and magnetic forces of Jupiter have been explored in greater detail than ever before. The deep oceans of Enceladus and Europa have been identified, and the rings, moons, and atmosphere of Saturn have been revealed in new ways. A fleet of spacecraft is examining the atmosphere and the surface of Mars, uncovering mysteries like the possibility of water flowing just beneath the surface. Meanwhile, the most sophisticated rover ever built is currently sampling the rocks and soils of Mount Sharp, accompanied half a world away by the Opportunity rover, currently hunkered down on Mars amid a global dust storm, but hopefully still active 14 years after it made a bouncing landing on the red planet. Soon a new spacecraft will set down on Mars and begin listening for seismic rumbles deep underground. Because of the efforts of NASA and the United States' international partners, Mercury, Venus, Ceres, Vesta, comet 67P/Churyumov-Gerasimenko, asteroid Itokawa, and the Moon have all served up answers and new mysteries about their origins and compositions, and provided hints about the creation of the solar system.

These developments in many cases result from the strategic guidance and scientific prioritization provided by the two decadal surveys that NASA has asked the planetary science community to perform via the National Academies of Sciences, Engineering, and Medicine. The most recent planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, was released in March 2011. The decadal surveys, particularly *Vision and Voyages*, have served the planetary science community well in justifying a plan for planetary science that has been successful both in obtaining funding for missions and supporting research, and in protecting that plan from proposals and objectives that have not been vetted by the community-based decadal process.

NASA is required to conduct decadal surveys by law, and is also required to conduct midterm assessments of their progress toward meeting the goals of the decadal survey. In late 2016 NASA asked the National Academies to undertake a planetary midterm review. In spring 2017, after the passage of the NASA Authorization Act, the agency asked the National Academies to expand the scope of its midterm review to also include an assessment of the Mars Exploration Program (MEP), which is managed within the Planetary Science Division (PSD). This report assesses NASA's performance at achieving the goals of the decadal survey at its midterm, as well as specifically assessing the Mars Exploration Program (the statement of task is included in Appendix A). The report offers recommendations to NASA for achieving the goals of the decadal survey until the next decadal survey, and makes recommendations for preparing for the next decadal survey, currently planned to begin holding meetings in spring 2020.

Vision and Voyages fully recognized the possibility that both NASA budgets and development challenges could impact execution of their recommended program. To help address this possibility they provided three decision rules to be used for planetary science program de-scopes:

1. De-scope or delay a flagship mission;
2. Slip New Frontiers or Discovery missions only if flagship adjustments cannot solve the problem;
3. Place high priority on preserving research and analysis (R&A) and technology funding.

In response to the decadal survey's recommendations, NASA de-scoped both the Mars Astrobiology Explorer-Cacher (MAX-C) mission (which became Mars 2020) and the Jupiter Europa Orbiter (JEO; which became Europa Clipper). This was done because neither would have been affordable within the planned budget. NASA did not de-scope or delay a flagship mission in response to budget cuts.[1] It did slip both New Frontiers and Discovery missions. NASA did place high priority on preserving R&A and technology funding.

The decadal survey also recommended the following priorities if more funding than expected was made available for the planetary science program during the next decade (and assuming that the Uranus orbiter and probe mission was funded in addition to MAX-C and Europa orbiter):

1. An increase in funding for the Discovery program;
2. Another New Frontiers mission; and
3. Either the Enceladus Orbiter or the Venus Climate Mission.

The committee concluded that despite significant cuts to the Planetary Science Division's budget early in this decade, NASA has made impressive progress at meeting the decadal survey's goals. The agency has begun development of two of the decadal survey's top recommended large strategic (i.e., flagship) class missions, the Mars 2020 rover and the Europa Clipper.[2] It has also met or exceeded the decadal survey recommendations for funding both research and analysis (R&A) and technology research and development (R&D) programs. (See Figure S.1.)

At the same time, the committee also concluded that budgetary and policy decisions limited NASA's ability to achieve the recommended cadence for Discovery and New Frontiers mission announcements and NASA has conducted or begun planning for fewer announcements of opportunity for these missions than the recommended pace. NASA has indicated that it is planning on initiating a second New Frontiers announcement of opportunity within the decadal survey period, and the committee endorses this plan, but believes that it will be challenging to meet this schedule. Similarly, NASA will have to conduct several further Discovery mission selections to achieve the recommended cadence before the decadal period is finished.

In addition, for several years since the release of *Vision and Voyages*, NASA was precluded from beginning recommended technology development for conducting an eventual Mars sample return mission. The Mars 2020 rover will collect samples for eventual return to Earth, but the return portion of that effort will be technologically difficult, and *Vision and Voyages* recommended a technology development effort that did not begin until late 2017. The committee concluded that the Planetary Science Division's Mars sample return technology development plan is on the right track, and endorsed its proposed "lean Mars sample return" strategy. However, the committee is also concerned about the aging orbital infrastructure at Mars, which conducts valuable science, but is vital for communicating with rovers on the surface. The committee cautions that the loss of one or more of these spacecraft could make it difficult for NASA to communicate with its surface rovers, and reduce their science return.

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[1] The initial de-scoping of both MAX-C and the Jupiter Europa Orbiter were originally directed by the decadal survey.

[2] The two large strategic missions recommended in *Vision and Voyages* were the MAX-C rover and the Jupiter Europa Orbiter. They are being implemented as Mars 2020 and Europa Clipper, respectively.

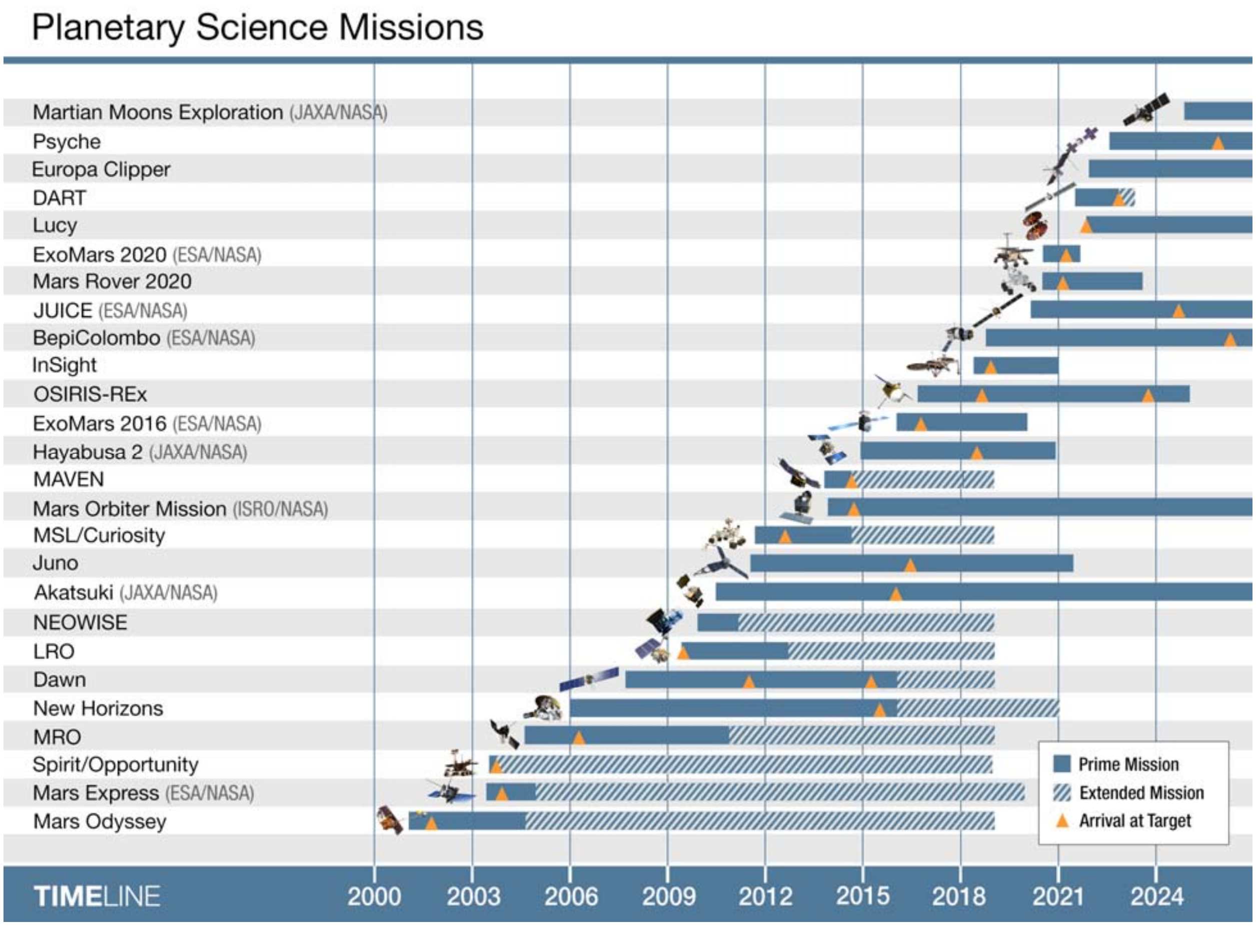

FIGURE S.1 Recent, current, and in-development NASA planetary science missions and international missions which NASA is participating. SOURCE: NASA.

The committee's findings and recommendations are summarized by category.

LARGE STRATEGIC MISSIONS (FLAGSHIPS)

Vision and Voyages devoted considerable attention to the large strategic missions (often referred to as "flagships"). It recommended the MAX-C rover and the Jupiter Europa Orbiter missions based upon their high science value, but also recommended that both missions be de-scoped in order to fit within available budgets. These missions have been implemented by NASA as the Mars 2020 rover and Europa Clipper.

The Europa Clipper concept currently in Phase B is reduced in cost and scope from the Jupiter Europa Orbiter mission that was proposed to *Vision and Voyages* and its cost appears to be within the guidelines established by the decadal survey. New funding has been allocated by Congress for this mission. This committee finds that the Europa Clipper mission addresses most of the recommendations laid out by *Vision and Voyages*. (This is further discussed in Chapter 3.) The committee also cautions that flagship-class missions pose the greatest potential danger to the overall planetary program if they experience significant cost overruns. Thus, they require careful monitoring and management.

Recommendation: NASA should continue to closely monitor the cost and schedule associated with the Europa Clipper to ensure that it remains executable within the approved life cycle cost (LCC) range approved at Key Decision Point-B (KDP-B) without impacting other missions and priorities

as defined by the decision rules in *Vision and Voyages* (p. 36). If the LCC exceeds this range, NASA should de-scope the mission in order to remain consistent with the *Vision and Voyages* decision rules. (Chapter 3)[3]

Recommendation: NASA's Planetary Science Division should implement an Independent Cost and Risk Review Process at Mission Definition/System Definition Review (Key Decision Point-B, or KDP-B) specifically for large planetary flagship missions to ensure that potential mission costs and cost risks are understood. (Chapter 3)

NASA is currently working to define the scientific goals, assess the feasibility of implementation, define the mission concept, and estimate the cost of a Europa lander. A lander was not prioritized or discussed in detail in *Vision and Voyages,* where it was referred to as a "far term" mission. It also did not undergo a cost and technical evaluation like other large missions prioritized in the decadal survey.[4] Given its cost and its potential impact on the rest of the planetary science program, the committee concluded that the mission should be vetted within the decadal survey process.

Recommendation: As a prospective flagship mission, the results of the NASA Europa lander studies should be evaluated and prioritized within the overall PSD program balance in the next decadal survey. (Chapter 3)

The third prioritized flagship-class mission in *Vision and Voyages* was an ice giants mission.[5] Such a mission to either Uranus or Neptune has not yet been initiated by NASA. Exoplanet discoveries further enhance the importance of an ice giants mission. The notional ice giants mission described in *Vision and Voyages* would address a broad range of ice giant science objectives using mature instrumentation. The objectives of the mission concept described in a NASA-sponsored 2017 ice giants study have been changed significantly from the original *Vision and Voyages* science objectives. The committee found that the scientific payload proposed in the study carries significant risk of failing to make the measurements proposed in *Vision and Voyages*. New objectives were proposed in the ice giants study. A Doppler imager, not mentioned in *Vision and Voyages* for this mission and not yet flown on a spacecraft, has been added to the payload to make measurements of planetary oscillations that may not be detectable. If this component of the mission were not successful scientifically, a large part of the revised science objectives would be degraded or lost.

Recommendation: NASA should perform a new mission study based on the original ice giants science objectives identified in *Vision and Voyages* to determine if a more broad-based set of science objectives can be met within a $2 billion cost cap. (Chapter 3)

DISCOVERY AND NEW FRONTIERS

The committee found that NASA's decision to eliminate Phase E (operations) funding and launch vehicle cost from the Discovery announcement of opportunity (AO) has been enabling for missions to the

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[3] KDP-B refers to Key Decision Point-B, when a mission has reached an advanced design stage but prior to KDP-C, when a mission begins full-scale development.

[4] All space science decadal surveys follow a cost and technical cvaluation (CATE) process, using an independent contractor in response to a legally mandated requirement. The CATE process varies slightly for each decadal survey, but is used to determine the technical maturity of a mission concept and its approximate cost. One value of the CATE process is to enable a decadal survey to determine the overall affordability and viability of its recommended program. The five flagship-class missions prioritized in *Vision and Voyages* all underwent a CATE.

[5] A Uranus orbiter and probe mission was recommended by Vision and Voyages due primarily to trajectory concerns, but both ice giants were considered equally scientifically interesting by the decadal survey.

outer solar system. This was recommended in *Vision and Voyages* and is another example of NASA successfully following the decadal survey.

Although two Discovery missions were selected from the 2014 AO, the next AO will not be issued until 2019. NASA will not have met the *Vision and Voyages* goal of a Discovery AO release every 24 months unless three missions are selected from the two potential future AOs.

Recommendation: NASA should issue Discovery announcements of opportunity (AOs) at the *Vision and Voyages* recommended cadence of ≤24 months, recognizing that an AO that selects two missions would count as two AOs for the purpose of meeting the *Vision and Voyages* recommendation. To approach meeting the *Vision and Voyages* recommendation, NASA should select three missions from AOs issued in 2019 and 2021. (Chapter 3)

New Ocean Worlds targets were introduced into the New Frontiers 4 call. This addition to the list of allowed New Frontiers missions was made outside the decadal survey process. While the Outer Planets Assessment Group (OPAG) supported the addition, the Lunar Exploration Analysis Group (LEAG), Small Bodies Assessment Group (SBAG), Venus Exploration Analysis Group (VEXAG), and Mars Exploration Analysis Group (MEPAG) did not support this change (as per presentations to this committee). Such a process could undermine the scientific priorities of the decadal survey and community support for them. The Space Studies Board's Committee on Astrobiology and Planetary Science (CAPS) was not authorized to express a formal position on this change to the NF4 call at the time, but is now able to produce letter reports regarding issues relevant to the decadal survey at NASA's request and provides a method for evaluating proposed changes to the decadal survey.

Recommendation: If scientific discoveries or external factors compel NASA to reassess decadal survey priorities, such as the list of New Frontiers missions, NASA should vet these changes via CAPS, and allow for input from the community via assessment and analysis groups as time permits. (Chapter 3)

The committee also found that the pace of New Frontiers class missions is significantly behind the recommended cadence of two per decade, with only one mission likely this decade. Given the current cadence for New Frontiers, the New Frontiers 5 call may occur while the next decadal survey is under way, but both Lunar Geophysical Network and Io Volcanic Observer were recommended by *Vision and Voyages* for New Frontiers 5, and the committee believes they still remain valid missions for New Frontiers 5.

Recommendation: NASA should issue the New Frontiers 5 announcement of opportunity as soon as possible, but at a minimum release the announcement of opportunity no later than five years after the issuance of the New Frontiers 4 announcement of opportunity (i.e., December 2021). (Chapter 3)

THE NASA MARS EXPLORATION PROGRAM (MEP)

Vision and Voyages recommended that NASA begin technology development to enable the next steps toward sample return from Mars. During the first several years of the period covered by the decadal survey, NASA did not do this. However, by fall 2017 the Planetary Science Division began technology demonstration tests and had developed a "lean and rapid" architecture for returning samples from Mars. Although NASA has considerable work to do to make this a reality, the committee was impressed and encouraged by these new developments.

Recommendation: NASA should continue planning and begin implementation of its proposed "lean and rapid" architecture to return samples from the Mars 2020 mission to achieve the highest-

priority decadal survey flagship-class science for consideration by the next decadal survey. (Chapter 5)

NASA currently operates Mars Odyssey, Mars Reconnaissance Orbiter (MRO), and Mars Atmosphere and Volatile Evolution mission (MAVEN) around Mars, all of which have exceeded their design lifetimes. In addition to performing science, these missions also provide vital telecommunications support to surface assets.[6] There is a risk that ongoing and soon-to-be landed assets on Mars will be left without telecommunications support because of the aging orbiters. The system is fragile and aging. The loss of even one of the three U.S. orbiters capable of relay communications would create tactical challenges for continued operation of current and planned landed missions beyond 2021, and compromise the ability of the Mars Exploration Program to continue its science return.

Recommendation: NASA should ensure the longevity of the telecommunications infrastructure at Mars to support the science return from current and planned landed assets (e.g., MSL, InSight, ExoMars, Mars 2020), to mitigate the risks associated with the existing aging assets. This should not be accomplished by sacrificing the science being conducted by existing orbiters. (Chapter 5)

Missions to Mars being led by non-U.S. entities (including ExoMars, Trace Gas Orbiter, Mars HOPE, and Mars Moon Explorer) benefit and significantly augment the U.S. Mars Exploration Program and lead to a broader scientific exploration of Mars.

Recommendation: NASA should immediately work to reinvigorate international cooperation to help implement Mars exploration more effectively and affordably. This could involve international contributions of instruments, other hardware, or whole missions that complement what the United States is providing or leading, as suggested in *Visions and Voyages* and as proposed in the "lean and rapid" concept for Mars Sample Return. (Chapter 5)

There are strong arguments for continuing Mars exploration through a *program* rather than as a series of independent, unconnected missions. Although the current MEP has a broad focus across most areas of Mars as a system, the program going forward beyond Mars 2020 is focused entirely on sample return. There is currently no vision for a program beyond sample return, either for scientific investigation or to prepare for future human exploration.

There are no plans at present to replace the site characterization and monitoring capabilities of MRO that have proven so important for landing-site certification and strategic planning of landed science. The Mars Exploration Program has not yet put forward a complete architecture and attendant strategic plan that addresses the long-term goals of Mars exploration and optimizes science return across the spectrum of past, current, and future missions.

Recommendation: NASA should develop a comprehensive MEP architecture, strategic plan, management structure, partnerships (including commercial partnerships), and budget that address the science goals for Mars exploration outlined in *Visions and Voyages*. The architecture and strategic plan should maximize synergy among existing and future domestic and international missions, ensure a healthy and comprehensive technology pipeline at the architectural (vs. individual mission) level, and ensure sustenance of foundational infrastructure (telecommunications, imaging for site certification, etc.). This approach of managing the MEP as a *program*, rather than just as a series of missions, enables science optimization at the architectural level. This activity should include assurance that appropriate NASA/MEP management structure and international partnerships are in place to enable Mars Sample Return. (Chapter 5)

[6] The European Space Agency (ESA) also operates two Mars orbiters that have additional telecommunications capabilities. One of these spacecraft is also significantly beyond its planned lifetime.

TELESCOPES AND PLANETARY SCIENCE

Not all planetary science is or can be conducted at planetary bodies. Significant discoveries have been made by space and ground-based telescopes. For example, the Arecibo observatory is uniquely important for radar studies of asteroids, including characterization of potentially hazardous asteroids. The loss of the unique capabilities of the Hubble Space Telescope (HST) in the next decade will leave fewer opportunities for space-based telescope time allocated to solar system targets in the visible and ultraviolet (UV) wavelengths. The James Webb Space Telescope (JWST) will obtain limited observations of solar system targets but will not have the spectral coverage of HST.

Recommendation: NASA should conduct an assessment of the role and value of space-based astronomy, including newly emerging facilities, for planetary science. This assessment should be finished before the next decadal survey is significantly under way. (Chapter 3)

RESEARCH AND ANALYSIS

Vision and Voyages stressed the importance of a strong research and analysis program in planetary science and recommended an increase to the overall budget devoted to it. The committee determined that R&A spending levels have risen 32 percent relative to fiscal year (FY) 2011 spending levels, the year for which *Vision and Voyages* had budget information. This well exceeds the *Vision and Voyages* recommendation. The committee found that analyzing R&A budget levels was difficult because the Planetary Science Division does not track spending on R&A and technology in the way the decadal survey defined them. This can create misunderstandings within the science community.

Recommendation: NASA is largely following or exceeding the *Vision and Voyages*-recommended levels of R&A and technology spending. It should continue to make these critical investments. (Chapter 3)

Recommendation: The next decadal survey committee should work with NASA to better understand the categorization and tracking of the budget for each of the R&A program elements, specifically providing insight into the budget for (1) principal investigator (PI)-led, competed, basic research and data analysis; (2) ground-based observations; (3) infrastructure and management; and (4) institutional or field center support. Also, the next decadal survey should be unambiguous when stipulating programs and recommended levels of spending. (Chapter 3)

A subject that is repeatedly raised within the community is the selection rates for R&A programs, and this will logically be part of the future discussion.

TECHNOLOGY RESEARCH AND DEVELOPMENT

The committee found that the Planetary Science Division has to-date met and is expected to continue to fully meet the decadal survey's technology investment recommendation. Since the decadal survey, the Department of Energy (DoE) has restarted production of Pu-238, which the committee considers a welcome development.

Recommendation: NASA should continue to work closely with the DoE to ensure that the schedules for Pu-238 and clad production and the development of the Multi-Mission Radioisotopic Generators are maintained. It is also important that NASA continue the longer-term developments of advanced energy conversion techniques. (Chapter 4)

NASA created the PICASSO and MatISSE programs to provide a sustained, broad-based science instrument technology development through technology readiness level (TRL) 6 as recommended by *Vision and Voyages*. The high number of proposals submitted to these programs, relative to the funding available, shows a strong community demand for these programs.

The Planetary Science Division has embraced the decadal survey's technology recommendations, and they have constructed a rational and comprehensive technology portfolio that can enable new and more challenging planetary science missions in the future. *Vision and Voyages* recommended investing 6-8 percent of the Planetary Science Division budget in technology R&D, and NASA has essentially done that, which the committee applauds.

Recommendation: NASA should continue investment in development of the mission-enabling technologies at the 6-8 percent level. (Chapter 4)

INFRASTRUCTURE AND LABORATORY SUPPORT TO PLANETARY SCIENCE

The 2014 Discovery AO and 2017 New Frontiers AO require early planning and coordination for sample return missions. The actual costs for all aspects of curation, from planning through distribution and storage, including all required laboratory construction or modification, are required to be borne by the mission from inception to two years following sample return. Therefore, curation activities (and their associated costs) during phases A-D fall under the AO cost cap and activities during phase E fall under the PI-managed mission cost (but not the AO cost cap). Whereas long cruise missions can defer such costs to phase E, this situation penalizes short missions that have to include curation and laboratory costs in phases B-D.

Recommendation: NASA should consider the budget for curation by sample return missions, as developed in the AO-required Curation Planning documents, a phase E cost, regardless of the phase in which the costs are actually incurred. This would ensure that sample return missions are on equal footing with other mission proposals and discourage unrealistically low budgets for sample curation. (Chapter 3)

Recommendation: NASA should ensure that all constituencies relating to sample return missions, both competed and directed, be coordinated through the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) to optimize communication, avoid duplication of effort, and maximize existing expertise. (Chapter 3)

The committee also notes that the Deep Space Network (DSN) is vital to the success of planetary missions and is concerned that changes made to the DSN could impact current and future missions. The recommendation for Ka-band uplink and downlink at all stations has not yet been met. Ka-band downlink is available at all three stations (U.S., Spain, Australia), but Ka-band uplink is available only at Goldstone. The plan is to incorporate Ka-uplink at all stations in the next few years, but this is not yet a committed capability that missions in development can count on, as it is not listed in the Space Communications and Navigation (SCAN) catalog.

Recommendation: The committee endorses the *Vision and Voyages* recommendation that all three DSN complexes should maintain high-power uplink capability in the X- and Ka-bands, and downlink capability in the S-, X-, and Ka-bands. (Chapter 3)

EDUCATION AND PUBLIC OUTREACH

The intent of the *Vision and Voyages* endorsement of 1 percent of mission budgets going toward education and public outreach activities was to have scientists who are involved in NASA's missions directing and participating in public education and outreach activities. Currently, the STEM Activation program is not uniformly engaging NASA missions; some missions are not being engaged at all. Furthermore, the STEM Activation program is not utilizing the mission scientists to define or provide science content; therefore, the critically important connections between the mission scientists and these education programs have been greatly reduced. While NASA center-managed public engagement efforts are connecting with some missions, in other cases there is no direct tie between missions that are producing results for the programs and the work of the NASA education program.

Recommendation: In order to enable the excitement of space exploration to be fully communicated to the broader public, the STEM Activation program should work with all NASA planetary missions to define science content and program implementation. NASA's Planetary Science Division should link education and outreach activities directly to the missions that are providing the science content for them, interfacing through the PIs for competed missions, and through the project scientists for directed missions. Education experts within the STEM Activation program should work directly with the mission scientists and engineers (subject matter experts, or SMEs) to ensure a strong connection to NASA's mission results. NASA had previously provided funds equal to 1 percent of the overall project budget to support these activities. New funding at this level would provide robust support for project engagement in these education and outreach activities. (Chapter 3)

PREPARING FOR THE NEXT DECADAL SURVEY

With less than two years left before the next decadal survey begins, there is a very limited amount of time to conduct new mission concept studies to assist the next decadal survey committee. During the last decadal survey mission concept studies were being conducted during the survey itself, placing great strain on the volunteers and staff, as well as the NASA budget that supported the studies. This committee concluded that it is important to avoid such a rushed process during the next decadal survey. To date, NASA has conducted only the ice giants study (which this committee has recommended be redone), and started Ceres lander and Venus studies. The committee believes that numerous additional studies are still required.

Recommendation: NASA should sponsor 8 to 10 mission concept studies based on the list produced by the Committee on Astrobiology and Planetary Sciences, prioritized with input from the assessment and analysis groups, prior to the next decadal survey. Mission concept studies for flagship-class missions should include options as described in the National Academies report *Powering Science—NASA's Large Strategic Science Missions*. (Chapter 6)

The recently launched InSight mission to Mars includes two planetary CubeSats, a technology capability that did not exist when *Vision and Voyages* was written. NASA is undertaking numerous studies of additional CubeSat and smallsat missions in order to determine their viability for planetary science. Aside from requirements derived from the competitively selected SIMPLEx missions and PSDS3 mission concepts, there is not a clear pathway for prioritizing development of the key CubeSat and SmallSat technologies or planetary deployment and operational architectures that would enable operations beyond the Earth-Moon environment. These include, but are not limited to, destination delivery approaches, propulsion, telecommunications, and deployable elements to provide power generation or instrument aperture.

Recommendation: In preparation for the next decadal survey, NASA should consider priorities and pathways for advancing the state of the art of CubeSats and SmallSat technology, and how science-driven planetary small mission concepts that leverage emerging capabilities are identified and possibly implemented for flight. (Chapter 6)

NASA operates two “virtual institutes” for supporting planetary science research. The committee was briefed about both of them, but notes that the last evaluation of either institute was conducted a decade ago and the virtual institutes are not well addressed in *Vision and Voyages.*

Recommendation: A formal assessment by NASA of how well the program structure and funding of the virtual institutes are aligned with the Planetary Science Division’s science goals should be conducted on a regular basis, appropriately phased to the cycle of decadal surveys and midterm reviews. (Chapter 6)

The committee notes that there have been substantial developments in communications and computer technology, such as the emergence of “cloud computing.” These are impacting many areas of science, including planetary science.

Recommendation: The next decadal survey committee should assess NASA’s ability to respond to new needs for data archiving and interoperability from spacecraft, laboratories, and publications. (Chapter 6)

Chapter 1 of this report explains the background of both the decadal survey and this report. Chapter 2 outlines some—but by no means all—of the substantial planetary science discoveries made in the past few years. Chapter 3 evaluates NASA’s progress at meeting the goals of *Vision and Voyages*, and provides recommendations for further progress. Chapter 4 addresses NASA’s technology development program. Chapter 5 assesses the Mars Exploration Program. Last, Chapter 6 addresses preparations for the next planetary science decadal survey.

1

Background on the Decadal Survey and Midterm Assessment

The planetary sciences decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, was released in March 2011. The report provided guidance for NASA to structure its planetary science program for the coming decade. It was produced in response to a request that included the following tasks:

- An overview of planetary science—what it is, why it is a compelling undertaking, and the relationship between space- and ground-based planetary science research;
- A broad survey of the current state of knowledge of the solar system;
- An inventory of the top-level science questions that should guide flight programs and supporting research programs;
- Recommendations on the optimum balance among small, medium, and large missions and supporting activities;
- An assessment of National Science Foundation (NSF)-supported infrastructure;
- A discussion of strategic technology development needs and opportunities;
- A prioritized list of major flight investigations in the New Frontiers and larger classes recommended for initiation over the decade 2013-2022;
- Recommendations for supporting research required to maximize the science return from the flight investigations; and
- A discussion of the opportunities for conducting science investigations involving humans in situ and the value of human-tended investigations relative to those performed solely robotically.

The decadal survey process relied heavily on five supporting panels that were specific to particular kinds of bodies (inner planets, Mars, giant planets, satellites, and primitive bodies, respectively) coordinated by a steering group. Community input was sought in the form of white papers as well as presentations to the panels and the steering committee. The survey also developed detailed technical studies that were commissioned for specific mission concepts. Independent cost and technical evaluations (CATEs) were obtained from The Aerospace Corporation for a limited set of these technical studies, and they played a very significant role in the prioritizations reached late in the survey.[1]

DECADAL SURVEY RECOMMENDATIONS

The final report lays out the compelling case for a sustained planetary program. Four criteria were used for selecting and prioritizing missions. The first and most important was science return per dollar. Science return was judged with respect to the key science questions identified by the planetary science community. The second criterion was programmatic balance—striving to achieve an appropriate balance

[1] The CATE process was developed by the National Academies and modified for each of the decadal surveys. It attempts to produce a cost estimate that also takes into account the technical maturity of a mission concept as well as external threats (like inadequate budgets) to development. It is not the same as an independent cost estimate.

among mission targets across the solar system and an appropriate mix of small, medium, and large missions. The other two criteria were technological readiness and availability of trajectory opportunities within the 2013-2022 time period.

Small Missions

The survey concluded that there is much compelling science that can be addressed by small (Discovery class) missions, and recommended continuation of the Discovery program at its then current level, adjusted for inflation, with a cost cap per mission that is also adjusted for inflation from the current value (i.e., to about $500 million in fiscal year [FY] 2015, excluding launch vehicle). The survey also recommended a cadence of ≤24 months for release of Discovery announcements of opportunity (AOs) and for selection of new missions. The survey also supported the European Space Agency (ESA)-NASA Trace Gas Orbiter small mission that was subsequently successfully placed into Mars orbit in 2016.

Medium Missions

At the time of the survey, two medium (New Frontiers) missions were under way (New Horizons to Pluto and beyond, and Juno to Jupiter; OSIRIS-REx was selected in May 2011—after the decadal survey was delivered—and launched to the asteroid belt in 2016). (See Figures 1.1, 1.2. and 1.3.) The survey proposed modest but significant changes to the cost cap for this class of mission and two mission opportunities were advocated for 2013-2022. The survey also proposed to cap New Frontiers missions at $1.0 billion excluding the launch vehicle. The survey chose five candidates for the New Frontiers 4 opportunity

- Comet Surface Sample Return,
- Lunar South Pole-Aitken Basin Sample Return,
- Saturn Probe,
- Trojan Tour and Rendezvous, and
- Venus In-Situ Explorer.

This list was subsequently augmented for the second (New Frontiers 5) opportunity, adding

- Io Observer, and
- Lunar Geophysical Network.

An “Ocean Worlds Program” was not addressed by the decadal survey committee, but has subsequently garnered interest within the scientific community due to discovery of candidate Europa plumes, hydrothermal activity on Enceladus, a Titan subsurface ocean, and related discoveries.[2] NASA added—without a formal Academies endorsement—two Ocean Worlds concepts (Titan, Enceladus) to the New Frontiers 4 list.

[2] There is a misconception within the scientific community that Congress mandated that Ocean Worlds concepts be added to the New Frontiers mission line. The NASA Appropriations Act of 2015 called for the creation of a NASA Ocean Worlds Program, but did not direct that it be incorporated into the New Frontiers program line.

FIGURE 1.1 The OSIRIS-REx spacecraft undergoing final preparations prior to launch. OSIRIS-REx will return samples from an asteroid to Earth. SOURCE: NASA, "OSIRIS-REx Readied for Encapsulation," https://www.nasa.gov/content/osiris-rex-images; courtesy of NASA.

FIGURE 1.2 New Horizons being placed into its launch shroud. The spacecraft flew past Pluto in summer 2015, returning data that revealed Pluto to be a complex world in the far reaches of our solar system. SOURCE: NASA Kennedy Space Center, https://mediaarchive.ksc.nasa.gov/#/Image/4980/S.

FIGURE 1.3 The Juno spacecraft with solar array arm outstretched in testing. Juno began orbiting Jupiter in 2016. In addition to making new scientific discoveries, Juno has demonstrated the use of solar power at Jupiter distances from the Sun. SOURCE: NASA, "Packing Juno's Power," PIA14172, https://photojournal.jpl.nasa.gov/; courtesy of NASA/JPL-Caltech/KSC.

Large Missions

The large mission (flagship) category was the most difficult challenge presented to the survey because all of the options under consideration proved to be higher cost than originally anticipated. The highest priority was a Mars rover (then called MAX-C, now called Mars 2020; see Figures 1.4, 1.5, 1.6); a first step in the return of samples from Mars, but with a mission architecture that has heritage from the Mars Science Laboratory/Curiosity mission (see Figure 1.7). This choice was contingent on reducing the cost to $2.5 billion FY 2015 (the original CATE estimate was $3.5 billion). This mission was conceived to have significant scientific return in addition to being the first step in a campaign to return samples, but it also meant an implicit commitment beyond the time frame of the decadal survey.

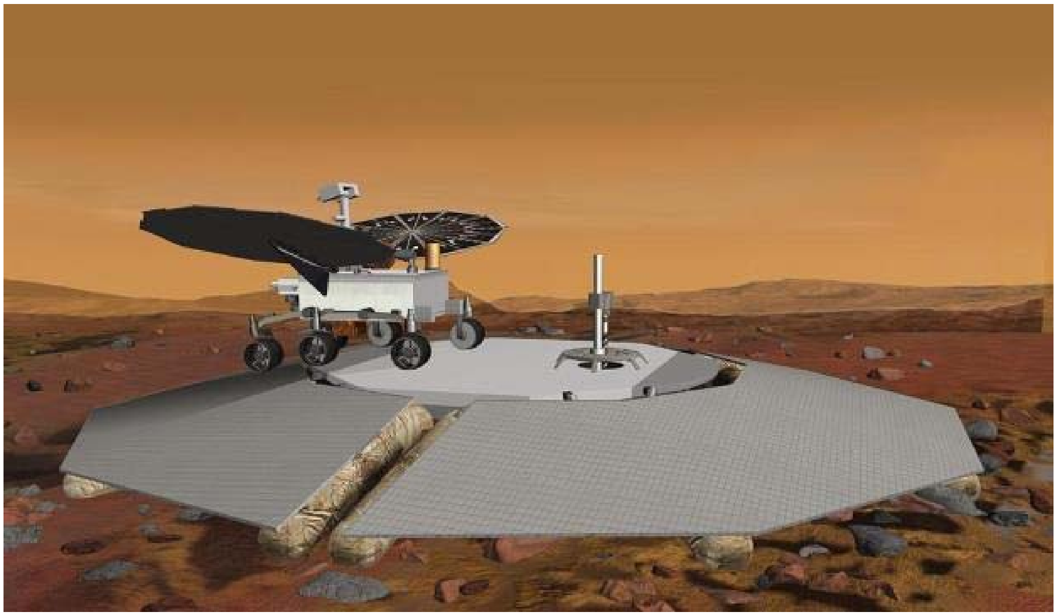

FIGURE 1.4 Computer-generated concept image of the MAX-C rover on its pallet after landing. SOURCE: "2018 MAX-C Rover Pallet Lander Drill Scene," http://www.fourth-millennium.net/mission-artwork/max-c-rover-home.html; courtesy of NASA JPL/Corby Waste.

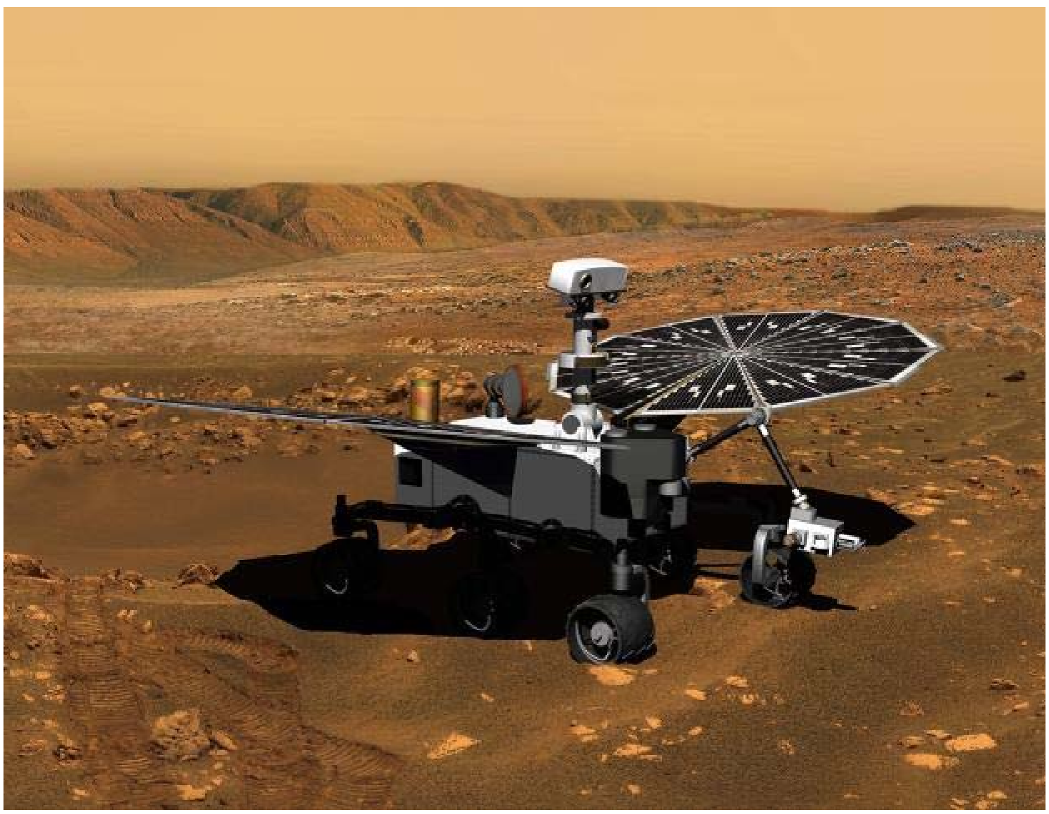

FIGURE 1.5 The MAX-C rover on Mars. MAX-C was one of the concepts evaluated by the decadal survey and recommended as a future mission. MAX-C was eventually implemented as the Mars 2020 rover. SOURCE: "2018 MAX-C Rover Scene," http://www.fourth-millennium.net/mission-artwork/max-c-rover-home.html; courtesy of NASA JPL/Corby Waste.

FIGURE 1.6 Construction work on descent stage for Mars 2020. The Mars 2020 spacecraft is heavily based on the successful Mars Science Laboratory/Curiosity rover mission that landed on Mars in 2012. SOURCE: NASA Jet Propulsion Laboratory, "JPL Tech Works Mars 2020 Descent Stage," PIA22342, courtesy of NASA/JPL-Caltech.

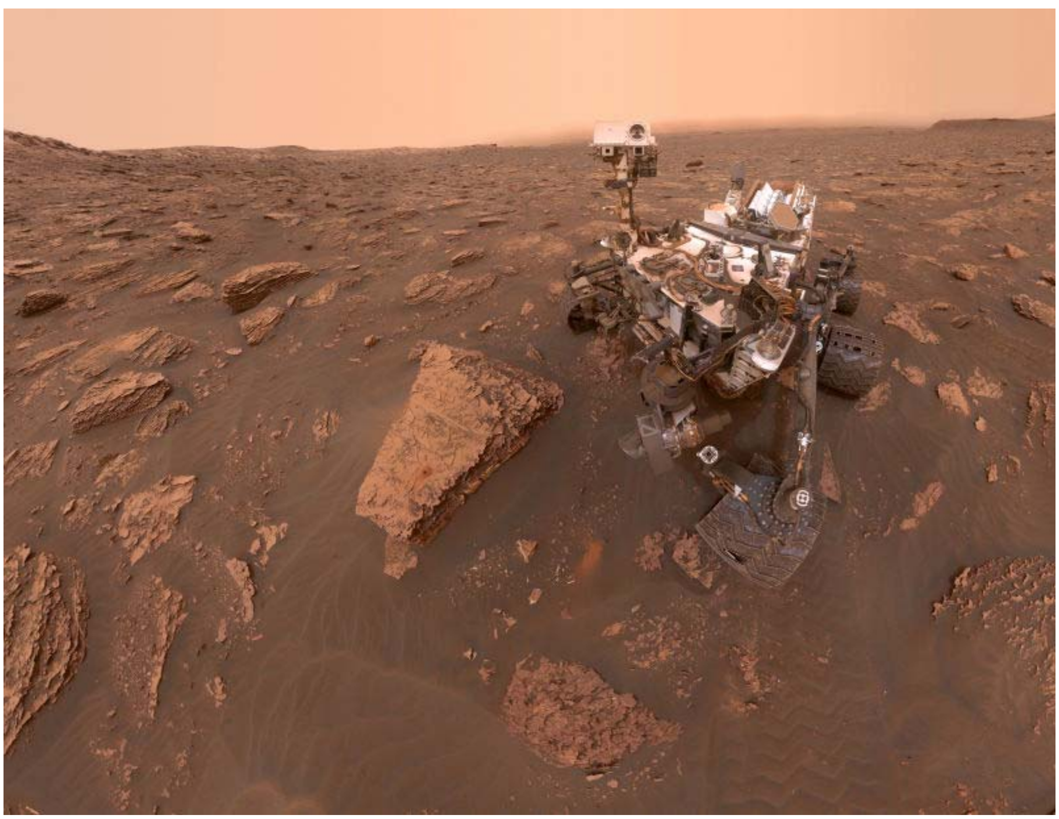

FIGURE 1.7 Self-image taken by the Curiosity rover during a global dust storm on Mars in June 2018. SOURCE: NASA Jet Propulsion Laboratory, "Curiosity's Dusty Selfie," PIA22486, courtesy of NASA/JPL-Caltech/MSSS.

The second priority flagship was a Europa orbiter (referred to as the Jupiter Europa Orbiter, or JEO, mission), but here too, the choice was contingent on the development of a mission design that was much reduced in cost from the original concept, which the CATE estimated at $4.7 billion. This has now become the Europa Clipper, which achieves many but not all of the science goals identified for the Jupiter Europa Orbiter.

The third large mission proposed was the Uranus Orbiter and Probe mission. The choice of Uranus over Neptune was for practical reasons (trajectories, flight times, and cost), as opposed to scientific ones—the decadal survey committee stated that both ice giants and their moons are equally scientifically interesting. The survey concluded that it should be possible to initiate this mission in the current decade, even with both the Mars and Europa missions in place, although it recognized that a constrained budget might cause delay and offered the same cautionary guidelines on budget that applied to Mars and Europa.

With respect to Europa, since *Vision and Voyages*, there has been congressional interest in a Europa lander. The decadal survey committee addressed the potential scientific significance of a "far term" Europa lander mission as part of the search for life, stating that "A key future investigation of the possibility of life on the outer planet satellites is to analyze organics from the interior of Europa. Such analysis requires either a lander in the far term or the discovery of active Enceladus-style venting, which would allow analysis from orbit with a mission started in the next decade**.**" A Europa lander was not in the prioritized list of missions in the *Vision and Voyages* recommendations for this decade, and no mission concept for a lander was evaluated or subjected to the CATE process like the other flagship-class missions. (See Figure 1.8.)

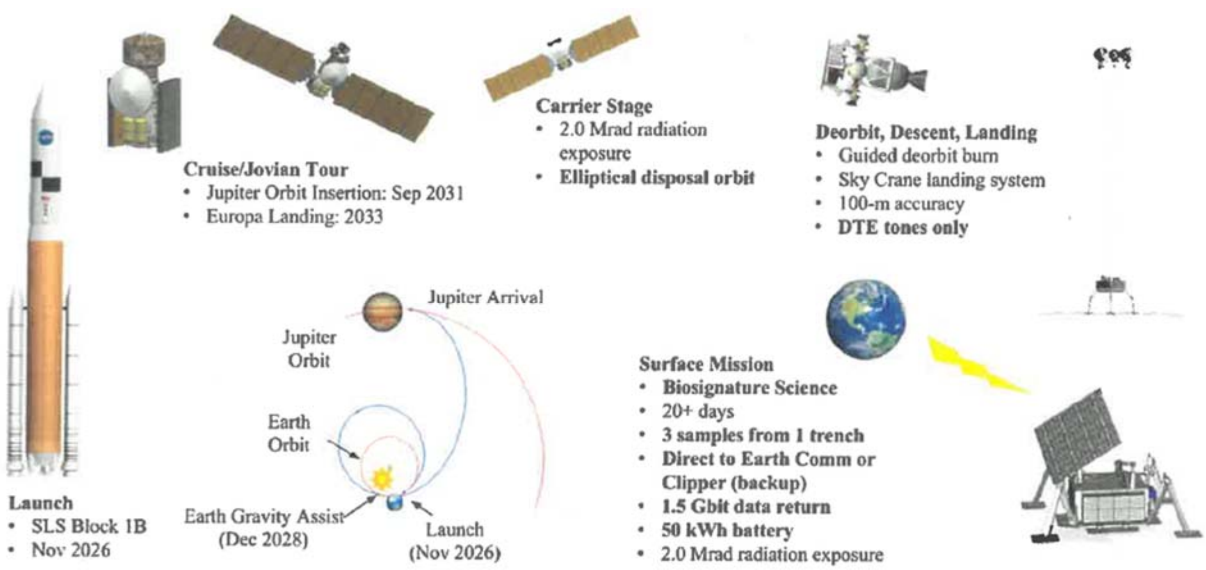

FIGURE 1.8 Mission concept for a Europa lander. A Europa lander was not prioritized in *Vision and Voyages.* This is a revised concept for the lander. SOURCE: NASA.

NASA's Planetary Research and Analysis Programs

The survey found that the research and analysis programs are heavily oversubscribed and recommended that NASA

- Increase the R&A budget for planetary science by 5 percent above the total finally approved FY 2011 expenditures in the first year of the coming decade, and;

- Increase the budget by 1.5 percent above the inflation level for each successive year of the decade.

NSF-Funded Research and Infrastructure

The survey recognized that the ground-based observational facilities supported wholly or in part by the National Science Foundation are essential to planetary astronomical observations, both in support of active space missions and in studies independent of (or as follow-up to) such missions. They concluded that their continued support is critical to the advancement of planetary science.

Technology Needs

The survey offered many specific examples of coming challenges in technology, but also provided a summary of the core needs:

- Reduction of mass and power requirements for spacecraft and their subsystems;
- Improved communications capabilities yielding higher data rates;
- Increased spacecraft autonomy;
- More efficient power and propulsion for all phases of the missions;
- More robust spacecraft for survival in extreme environments;
- New and improved sensors, instruments, and sampling and sample preservation systems; and
- Mission and trajectory design and optimization.

Since the future of planetary science depends on a well-conceived, robust, stable technology investment program, the survey strongly recommended that a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources. They concluded that this program should be consistently funded at approximately 6 to 8 percent of the total NASA Planetary Science Division budget. (See Figure 1.9.)

FIGURE 1.9 Beginning the Radioisotope Thermoelectric Generator (RTG) installation for Cassini. Pu-238 production for RTGs ceased in the 1980s and is only now being restarted. SOURCE: NASA JPL,

“Installing a Radioisotope Thermoelectric Generator (RTG),” October 9, 1997, https://saturn.jpl.nasa.gov/resources/7513/installing-a-radioisotope-thermoelectric-generator-rtg/.

Humans in Space

For the foreseeable future, humans can realistically explore only the surfaces of the Moon, Mars, Phobos and Deimos, and some asteroids. The Apollo experience suggests that robotic missions to targets of interest will undoubtedly precede human landings. The survey observed that the objectives of human exploration precursor measurements focus mainly on issues regarding health and safety and engineering practicalities, rather than science. Although there are a number of examples where the interests intersect—for example, finding a resource like water—the motivation and ultimate data applications of the two goals are typically quite different. The survey expressed concern that human spaceflight programs can impact space science programs and endorsed previous recommendations for budgetary firewalls. (See Figure 1.10.)

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FIGURE 1.10 Artist depiction of a human mission on Mars based on a late 1960s NASA concept. SOURCE: Artist Drell-7.

Recommended Program De-scope Options

The decadal survey fully recognized the possibility that both NASA budgets and development challenges could impact execution of its recommended program. To help address this possibility, the survey provided the following decision rules to be used for planetary science program de-scopes:

- Increased funding for planetary exploration could make even more missions possible. If funding were increased, the committee’s recommended additions to the plans presented above would be, in priority order:
  - An increase in funding for the Discovery program;
  - Another New Frontiers mission; and
  - Either the Enceladus Orbiter or the Venus Climate Mission.
- It is also possible that the budget picture could turn out to be less favorable than the committee assumed. This could happen, for example, if the actual budget for solar system exploration is smaller than the projections the committee used. If cuts to the program are necessary, the

committee recommends that the first approach should be de-scoping or delaying flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to flagship missions cannot solve the problem. And high priority should be placed on preserving funding for research and analysis programs and for technology development.

THE COMMITTEE'S CHARGE AND TASKS

NASA is at the midpoint of the 10-year horizon of the decadal survey (which covers the years 2013-2022). At NASA's request (and as required by the NASA Authorization Act), the National Academies of Sciences, Engineering, and Medicine convened an ad hoc committee to conduct a midterm assessment of NASA's planetary science program.

The midterm study was assigned the following tasks:

1. Describe the most significant scientific discoveries, technical advances, and relevant programmatic changes in planetary sciences over the years since the publication of the planetary decadal survey (*Vision and Voyages*).
2. Assess the degree to which NASA's current planetary science program addresses the strategies, goals, and priorities outlined in *Vision and Voyages* and other relevant National Research Council (NRC) and National Academies reports, and assess NASA progress toward realizing these strategies, goals, and priorities, and effectiveness in maintaining programmatic balance.
3. With respect to the Mars program within the planetary science program, the committee's assessment will include:
    a. The Planetary Science Division's Mars exploration architecture and its responsiveness to the strategies, priorities, and guidelines put forward by the National Academies' *Vision and Voyages* and other relevant National Academies Mars-related reports;
    b. The long-term goals of the Planetary Science Division's Mars Exploration Program and the program's ability to optimize the science return, given the current fiscal posture of the program;
    c. The Mars exploration architecture's relationship to Mars-related activities to be undertaken by foreign agencies and organizations; and
    d. The extent to which the Mars exploration architecture represents a reasonably balanced mission portfolio.
4. Recommend any actions that could be taken to optimize the science value of the planetary science program, including how to take into account emergent discoveries since the decadal survey in the context of current and forecasted resources available to it.
5. Provide guidance about implementation of the decadal survey's recommended mission portfolio and decision rules for the remaining years of the current decadal survey, but do not revisit or redefine the scientific priorities or mission recommendations from *Vision and Voyages*.
6. Recommend any actions that should be undertaken to prepare for the next decadal survey, such as community discussion of science goals, potential missions, and programmatic balance, and NASA support of potential mission concept studies.

THE COMMITTEE'S REVIEW PROCESS

The midterm assessment committee, comprised of planetary mission principal investigators (PIs), other scientists, experts in technology and programmatic issues, as well as individuals who served on the decadal survey committee, conducted its review, deliberations, and assessment over the course of five meetings.[3] The *Vision and Voyages* report provided the recommendations and priorities against which the current NASA planetary program was assessed. The committee formulated questions to NASA Science Mission Directorate (SMD) and Planetary Science Division (PSD) leadership, mission team leadership, mission support infrastructure experts, and program cost analysts, who then briefed the committee on their programs and responded to the questions. They provided briefing charts as well as written responses to follow-up questions.

Consistent with the charge, the committee's review covered not only missions envisioned at the time of the decadal survey but also new mission concepts that have emerged since the decadal survey, such as possible use of CubeSats, as well as commercial and entrepreneurial interest in planetary exploration.

The committee deliberations leading to the findings and recommendations in this report focused on assessing the briefings and follow-up questions in terms of how well the Planetary Science Division's program is following the recommendations in the *Vision and Voyages* report.

ORGANIZATION OF THIS REPORT

The findings and recommendations of the midterm assessment are provided in this report. They address the committee's review tasks as follows:

- Chapter 2 addresses tasks 1 and 4—recent scientific discoveries and their impact on the current program.
- Chapter 3 responds to task 2—the assessment of how well the current NASA planetary science program (with the exception of the Mars Exploration Program, which is found in Chapter 4) meets the intent of the recommendations provided in the *Vision and Voyages* report.
- Chapter 4 addresses task 3, technology.
- Chapter 5 addresses task 4, the strategic vision, architecture, content, and overall balance of the Mars program.
- Chapter 6 addresses task 5 and provides recommendations for mission studies in preparation for the next decadal survey as well as process-improvement recommendations for science program management.

There have been many impressive planetary science mission accomplishments and scientific discoveries since the publication of *Vision and Voyages*. NASA landed the Curiosity rover on Mars in 2012, and flew the New Horizons spacecraft past Pluto in 2015. The Cassini spacecraft ended its long and distinguished exploration of the Saturn system in 2017, and Juno began its exploration of Jupiter's atmosphere and magnetosphere. (See Figure 1.11.) MESSENGER completed its exploration of Mercury, and Dawn has explored Vesta and continues to observe Ceres. Spacecraft such as Mars Reconnaissance Orbiter, Odyssey, and the Lunar Reconnaissance Orbiter are in their extended mission phases and continue making important scientific discoveries. NASA has also contributed instruments and provided other support to foreign partner missions, such as the European Space Agency's highly successful Rosetta mission, which carried two U.S. instruments.

While this report was in its final stages, the Opportunity rover experienced its five-thousandth sunrise on Mars, but had gone to sleep during a massive Mars-wide dust storm, hopefully to awaken again soon and continue its extraordinary mission.

[3] These meetings were held in May, July, August, and late November 2017, and in February 2018. Shortly before the committee's first meeting, the Mars assessment task was added to the statement of task, enlarging both the scope of the study and the size of the committee. During the August 2017 meeting, NASA unveiled a new architecture for accomplishing the Mars sample return, which further expanded the issues that the committee needed to address. As a result, the committee adjusted its plans for delivery of its final report.

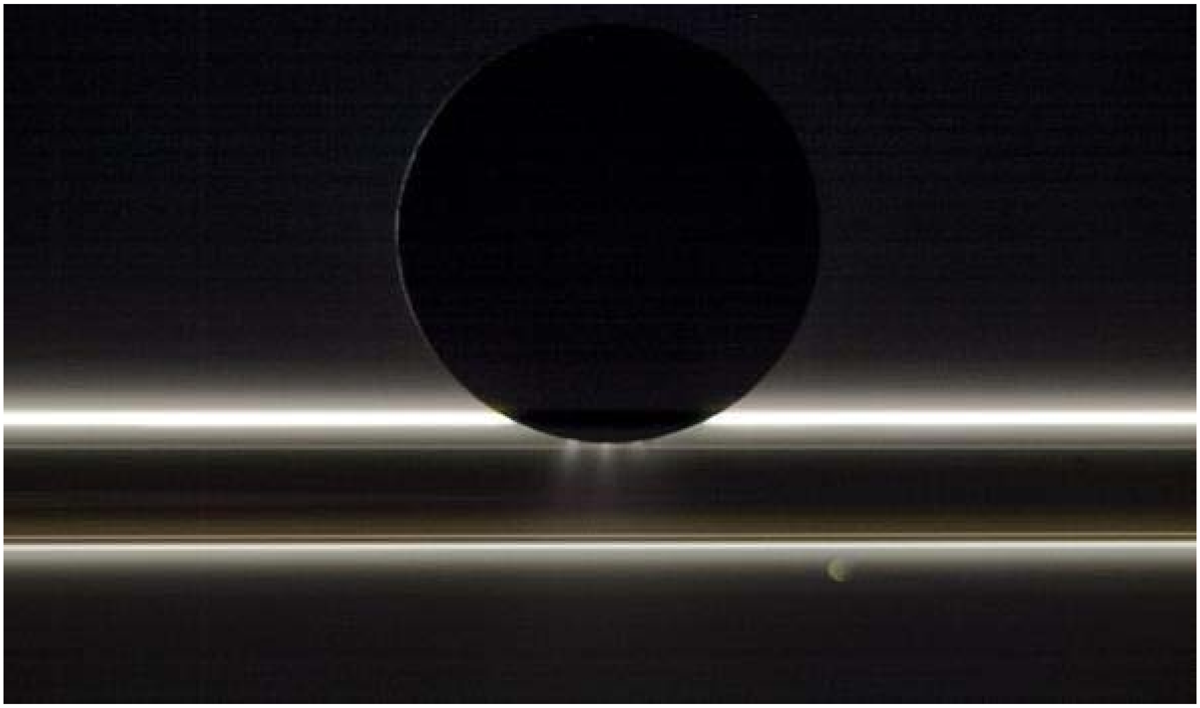

FIGURE 1.11 Enceladus jets and rings of Saturn in same illuminated plane. The Cassini mission came to an end in 2017, but Cassini's revelations about Saturn, its rings, and its moons will occupy scientists for years to come and inspire further missions. SOURCE: NASA Jet Propulsion Laboatory, "A Song of Ice and Light," PIA17144, https://photojournal.jpl.nasa.gov/; courtesy of NASA/JPL-Caltech/Space Science Institute.

2

Recent Scientific Discoveries

Since the publication of *Vision and Voyages*, planetary science has made many significant advances, including acquiring results from several highly successful missions. This chapter outlines some of the highlights, ordered according to the panels of the decadal survey: Inner Planets (Mercury, Venus, Moon); Mars; Giant Planets (Jupiter, Saturn, Uranus, Neptune); Satellites (Europa, Titan, Enceladus); and Primitive Bodies (asteroids, comets, Kuiper Belt Objects). This chapter is not intended to be comprehensive, and there are many other worthy scientific discoveries of the past few years.

MERCURY

After four years on orbit at Mercury, the MESSENGER mission ended in April 2015. Key results of the MESSENGER mission include the following:

- Mercury's core, expected to fill a large fraction of its interior, is even larger than expected, which implies that instead of pure Fe and Ni, it must contain light elements. There is a solid inner core, a liquid outer core, and possibly an outer layer of solid FeS (Hauck et al., 2013). Proposed explanations of the large size of the core include impact stripping of the outer silicate layer, ablation of the silicate layer, or segregation of metal from silicate in the solar nebula, none of which is strongly supported by geologic and chemical evidence (Smith et al., 2012; Hauck et al., 2013). Instead, Mercury's accretion in a highly reduced environment may have led to an enrichment in iron and a depletion in silica that was removed in a vapor phase (Ebel and Alexander, 2011).
- Comparison of observed crater populations to impactor flux models suggests that large volcanic deposits were emplaced by 3.5 Ga (Byrne et al., 2016). The composition of the volcanic materials varies across the surface from iron-poor komatiite to basaltic andesite (Vander Kaaden et al., 2015; Izenberg et al., 2014).
- Compressional structures (lobate scarps and wrinkle ridges) formed by horizontal shortening in response to cooling and contraction of the planet's interior dominate Mercury's tectonics. Mercury contracted by as much as 7 km in radius, substantially more than previously expected (Byrne et al., 2014). Surprisingly, extensional structures also occur, inside large impact basins and over buried craters where intra-basin processes and compaction dominated the stress field (Fassett et al., 2012; Klimczak et al., 2012).
- Mercury's magnetic field is offset northward along the planetary spin axis by 20 percent of the planet's radius. (See Figure 2.1.) The internal field is 100 times weaker than Earth's and barely holds off the solar wind at the subsolar point. The interaction of the planetary field with the solar wind induces a response in the core that generates an external magnetic field of magnitude similar to or larger than the planetary field (Anderson et al., 2012, 2014; Johnson et al., 2012; Winslow et al., 2014) and modifies the global scale of the magnetosphere (Jia et al., 2015). The inductive response remotely sounds the core-mantle boundary (Johnson et al., 2016). Detection of a crustal

remanent magnetic field indicates that a dynamo field at ~3.7-3.9 Ga must have been comparable to, or up to 100 times larger than Mercury's present field (Johnson et al., 2015).

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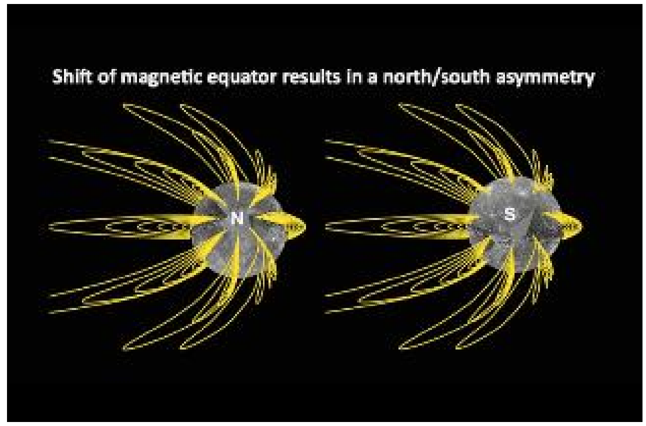

FIGURE 2.1 Measurements from MESSENGER's Magnetometer established that Mercury's magnetic equator is offset north of the center of figure by 484 km (the mean planetary radius is 2439 km). This shift creates asymmetric magnetospheric cusps, with a larger surface area in the south exposed directly to the solar wind. SOURCE: *Left:* B.J. Anderson, C.L. Johnson, H. Korth, M.E. Purucker, R.M. Winslow, J.A. Slavin, S.C. Solomon, R.L. McNutt Jr., J.M. Raines, and T.H. Zurbuchen, The global magnetic field of Mercury from MESSENGER orbital observations, *Science* 333(6051):1859-1862. *Right:* NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

Mercury's magnetosphere is highly dynamic because of the planet's small magnetic field and the properties of the solar wind at its radial distance from the Sun. The inner conducting boundary required to form a magnetosphere is not an ionosphere but is provided by the large iron core. Reconnection of the interplanetary and planetary magnetic field produces small structures called "flux transfer events" whose frequency of formation is so large that circulation of magnetic flux in the magnetosphere occurs 100 times faster than at Earth (DiBraccio et al., 2013; Gershman et al., 2013). These dynamics promote intense particle precipitation to the surface in regions of both open and closed magnetic field, so space weathering should be more intense on Mercury than on the Moon (Korth et al., 2014; Raines et al., 2014; Slavin et al., 2014).

Mercury is a volatile-rich planet with high contents of Na, K, Cl, S, and C in the crust. The formation environment of the planet was so oxygen-poor that normally volatile elements occur in refractory forms—for example, S occurs as Mg and Ca sulfides (Nittler et al., 2011; Peplowski et al., 2011; Evans et al., 2012). Carbon occurs as graphite that accounts for the planet's low albedo, and is highest in concentration in the remnants of a graphite flotation crust that was stirred by impacts into overlying volcanics. Remnants of the primordial crust are exposed by large basins, and locally in the oldest terrains (Murchie et al., 2015; Peplowski et al., 2016).

Radar-bright deposits in permanently shadowed polar terrain are rich in H (Lawrence et al., 2013). They consist mostly of water ice, but ice is exposed only in the coldest areas close to the poles. Slightly equator-ward they are covered by an organic-rich lag (Neumann et al., 2013), implicating a cometary source of volatiles (Delitsky et al., 2017). Hollows, which may form by removal of volatile materials, are small-scale, shallow, irregular depressions that produce a surface that resembles the Swiss cheese terrain in the CO_2 veneer on Mars's southern polar cap.

VENUS

Exciting Venus work has continued since the publication of *Vision and Voyages*; two areas highlighted here are continent-like plateaus and atmospheric dynamics.

Continent-Like Plateaus

Tesserae are intensely deformed terrains that have been proposed to be analogs to Earth's continents based on their planform, shallow, isostatic compensation and stratigraphically old age (Campbell and Taylor, 1983). On Earth, subduction and remelting of the original basaltic crust in the presence of water formed the huge volume of felsic (silica-rich, iron-poor) crust that comprises the continents. Continents are lower density than basaltic seafloor and they do not readily subduct. Although originally designed for observing a comet (not Venus), the VIRTIS instrument on Venus Express was able to observe the surface near 1 micron through a transmission window in Venus's CO_2 atmosphere. The VIRTIS data cover about half of the southern hemisphere, including one of Venus's six tessera plateaus, with reasonable precision. The derived surface emissivity data show that Alpha Regio is felsic (iron-poor) compared to the basaltic plains (see Figure 2.2), consistent with the interpretation of tesserae as continental analogs (Gilmore et al., 2015). Although water is not stable on the surface today, Venus Express data showed that Venus continues to lose significant amounts of water via erosion from the upper atmosphere by solar wind stripping (Curry et al., 2015). Pioneer Venus showed that Venus has lost a shallow ocean's worth of water (Kumar et al., 1984), but the timing of this water loss is not clear. The evidence for felsic crust at Alpha Regio suggests that the other tesserae terrains, comprising 7 percent of the surface, may also be felsic, and provide evidence of the role of interior or past surface water in shaping the evolution of Venus.

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FIGURE 2.2 VIRTIS radiance anomaly at 1.02 microns overlaid onto Magellan radar image. Alpha Regio appears in blue, indicating lower emissivity and iron content compared to the surrounding basaltic plains. SOURCE: Modified from Gilmore et al. (2015).

Venus as an Analog for Early Earth

Venus is of great interest as an analog for early Earth and for understanding the conditions needed for plate tectonics, which may be a key to understanding planetary habitability. Numerous potential subduction locations on Venus have clear morphologic, mechanical, and gravity field similarities to terrestrial subduction zones (e.g., Schubert and Sandwell, 1995) and there is much ongoing research seeking to identify the likely initiation process for these features, possibly involving plumes. The high lithospheric temperature on Venus today due to its greenhouse make it a good analog for Earth billions of years ago, when terrestrial plate tectonics began. Davaille et al. (2017) show that three dimensional (3D) laboratory simulations of plume-induced subduction predict previously unexplained features of venusian subduction zones, such as partial arcs of subduction, and that current conditions on Venus are ideal for the initiation of subduction on rocky planets.

Atmospheric Dynamics

The Japanese mission Akatsuki observed for the first time dramatic planetary-scale standing gravity (buoyancy) waves at the cloud tops (see Figure 2.3) that are tied to specific topographic features and local time (Fukuhara et al., 2017; Kouyama et al., 2017). These bow-shaped, 10,000-km-long standing waves form each evening, in locations tied to Venus's largest topographic highlands. Large waves were observed in the atmosphere previously, but they were not standing waves and instead rotated along with the super-rotating atmosphere. Venus's atmosphere rotates at an astounding 100 m/s at the cloud-top altitude of ~70 km. This super-rotation is a fundamental characteristic of Venus's atmospheric dynamics that remains challenging to fully understand and model. The discovery of the gravity waves indicate much more coupling of the atmosphere with surface topography than previously known. The waves may transfer momentum from the lower atmosphere to the cloud-top levels, and help fuel super-rotation. Further modeling is required to explain how the cloud layer, time of day, and temperature affect these waves. It is likely that the atmospheric dynamics cause variations in the spin rate of Venus on the time scale of years to decades, but the Venus Express data do not clearly demonstrate a change (Mueller et al., 2012). A more complete understanding of atmospheric dynamics from modeling the gravity waves may provide constraints on the coupling of atmospheric and interior dynamics.

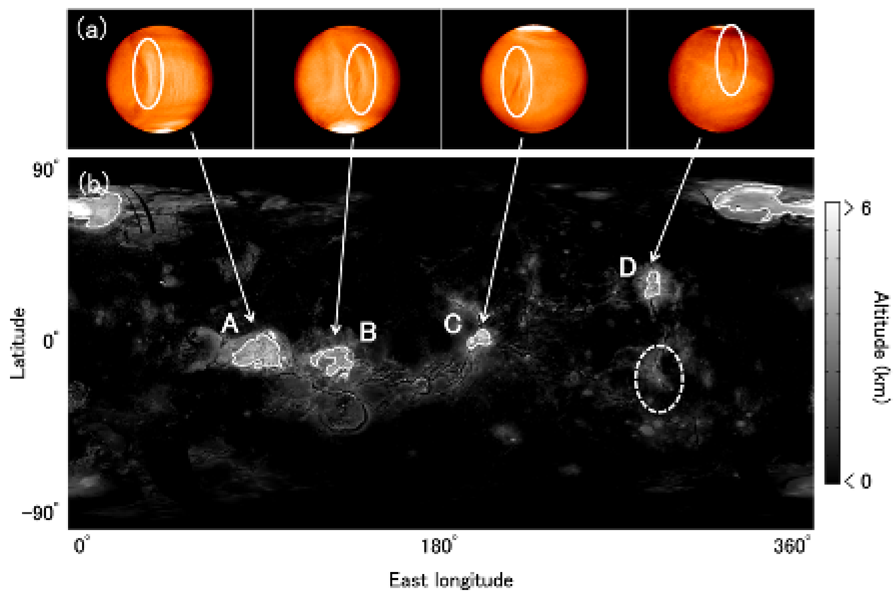

FIGURE 2.3 The Akatsuki spacecraft revealed for the first time large stationary gravity waves at the cloud tops of Venus. (a) Examples of large stationary gravity waves seen in brightness temperature images of the Venus disk taken by the Longwave Infrared Camera; and (b) the four highland locations surrounded by 3 km altitude lines (after 3 degree smoothing) on a Venus altitude map. Phoebe Regio, where a standing wave was also observed, is indicated by a dashed ellipse. The altitude range from 0 to 6 km is enhanced. SOURCE: T. Kouyama, T. Imamura, M. Taguchi, T. Fukuhara, T.M. Sato, A. Yamazaki, M. Futaguchi, et al., Topographical and local time dependence of large stationary gravity waves observed at the cloud top of Venus, *Geophysical Research Letters* 44:12,098-12,1052017, ©2017 American Geophysical Union.

THE MOON

The relative accessibility of the Moon has led to its selection as the objective of a number of both NASA and non-NASA missions. Additional motivation has been provided by the growing awareness that the Moon is not as dry as once thought, which has increased interest in its formation and evolution. The Moon is also a likely target for future human exploration.

The Lunar Reconnaissance Orbiter (LRO) was launched in 2009 and continues to collect important data. (See Figure 2.4.) Evidence for widespread OH or water on the surface has been inferred from spectral data (Banfield et al., 2018), building on earlier results obtained from the Indian spacecraft Chandrayaan-1 (Pieters et al., 2009). The different forms of water now identified from the lunar interior, across the lunar surface, and sequestered at the poles have become areas of intense active research and are now known to represent different fundamental processes active on the Moon and other silicate bodies of the inner solar system (e.g., Hurley et al., 2017; Pernet-Fisher et al., 2017). The distribution of polar hydrogen deposits has led to the recognition of true polar wander arising from changes in the internal mass distribution of the Moon, most likely associated with lunar mare volcanism (Siegler et al., 2016).

NASA's Lunar Atmosphere and Dust Environment Explorer (LADEE) orbited the Moon to gather detailed information about the structure and composition of the thin lunar atmosphere, and confirmed that there is a dust cloud surrounding the Moon over time, which is sustained by the continual bombardment of interplanetary dust particles (Horanyi et al., 2015).

Gravity Recovery and Interior Laboratory (GRAIL; a pair of spacecraft that provided very accurate gravity and topography) provided many new results for lunar structure (Zuber et al., 2013), including confirmation of the existence of a small core, global mapping of the crustal thickness (less than thought) and crustal density (lower than thought) (Wieczorek et al., 2013). (See Figure 2.5.) Ancient igneous intrusions were identified, indicating an early phase of expansion of the Moon by a few kilometers (Andrews-Hanna et al., 2013). Mass anomalies on a new and increasingly precise level of spatial resolution were identified, and the circum-Procellarum fracture network was identified in the gravity gradient map (Andrews-Hanna et al., 2014). The mass anomalies are important for lunar geology, and for models of interior dynamics and volcanic processes. Topography and gravity suggest frozen-in bulges from both early faster rotation and tidal heating, together with possible true polar wander (a large reorientation of the Moon's polar axis; Garrick-Bethell et al., 2014).

The Moon was included in the Inner Planets theme of *Vision and Voyages*. Priorities for spacecraft missions to the Moon, Mars, and other solar system bodies were treated in a unified manner. Lunar science addresses numerous cross-cutting investigation themes identified in *Vision and Voyages*, particularly the accretion, accretion timing, water supply, chemistry, and differentiation of their inner planets, the role of early bombardment, and current volatile composition and distribution. Significant progress has been made in fundamental lunar science since 2011. LRO continues to make fundamental discoveries about the Moon. Many Gravity Recovery and Interior Laboratory (GRAIL) results were published in 2011-2013 time frame. The LADEE mission (2013-2014) characterized the Moon's environment and surface-bound exosphere. And sample research continues on Apollo samples and meteorites.

FIGURE 2.4 NASA's Lunar Reconnaissance Orbiter captured a unique view of Earth from the spacecraft's vantage point in orbit around the Moon. SOURCE: NASA, "NASA Releases New High-Resolution Earthrise Image," December 18, 2015, courtesy of NASA/Goddard/Arizona State University.

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FIGURE 2.5 Crustal thicknesses on the Moon determined by GRAIL. Near side shown on the left; far side on the right. The gray circle at the bottom of the far side image delineates the south pole-Aiken Basin. SOURCE: NASA.

Lunar Interior

Although the GRAIL mission occurred prior to *Vision and Voyages*, most of the important results came out after *Vision and Voyages* was drafted. The existence of a small core, crustal thickness (less than thought) and density (lower than thought) (Wieczorek et al., 2012), and mass anomalies on a new and increasingly precise level of spatial resolution, including the identification in the gravity gradient map of the circum-Procellarum fracture network (Andrews-Hanna et al., 2014), are important for lunar geology, including models of interior dynamics and volcanic processes. GRAIL and LRO results yield definitive definition of the lunar inventory of impact basins (Neumann et al., 2015). Detailed laboratory measurements now possible with carefully prepared samples allow the character of the ancient lunar dynamo to be identified and constrained to be active from 4.25 and 3.56 billion years ago (Ga) (Garrick-Bethell et al., 2016; Tikoo et al., 2017), and age of crustal components to be determined, including a FAN age of 4360 +/– 3 million years, which requires either that the Moon solidified significantly later than most previous estimates or that the long-held assumption that FANs are flotation cumulates of a primordial magma ocean is incorrect (Gaffney and Borg, 2014) and the formation of the urKREEP at 176Lu-176Hf and Sm-Nd urKREEP ages, 4368 ± 29 Ma, representing the time at which the magma ocean crystallized (Boyet, 2015; Carlson, 2014).

Lunar Surface

The Moon has a stunningly diverse array of volcanic landforms: large shield volcanoes, spatter cones, pyroclastic deposits, mare basalt provinces, and silicic volcanics—some of it occurring within the last 1 billion years of lunar history (Lawrence et al., 2013; Boyce et al., 2017; Braden et al., 2014; Whitten et al., 2015). Global inventory of structures shows that the rate of tectonics due to cooling and solidification of core and seismic activity is associated with Earth tidal forces (Waters et al., 2016). Reexamination of both samples and lunar geologic relationships from high-resolution imaging have shown that the big basin chronology of the Moon is not as well as was once thought (Spudis et al., 2011; Fassett et al., 2012; Robbins et al., 2014; Norman et al., 2016), which has enormous implications for important issues such as the late heavy bombardment that drives dynamical models of the early solar system (e.g., Morbidelli et al., 2012). Discoveries continue to be made about the diversity of the lunar crust using the high spatial and spectral resolution of M3 and the SELENE spectral suite data, including new detections of ilmenite, silica-rich mineralogies, spinels, pyroxene varieties, and nearly pure anorthosite (Yamamoto et al., 2013; other references). Exciting new science has enabled identification of surface mineralogy, with first global UV bands (LROC) and thermal data (Diviner).

Lunar Volatiles

Visions and Voyages barely had time to incorporate the emerging knowledge of lunar volatiles. White papers were due: just 3 months into the LRO mission; before LCROSS impact; months after publication of M3 3µm hydration observations. Results from LADEE, LRO, LCROSS, M3/Deep Impact/Cassini, ARTEMIS, Chang'e-3, and Kaguya have significantly contributed to the understanding of lunar volatiles (see reviews by Anand et al., 2014, and Denevi, 2017). The different forms of water now identified from the lunar interior, across the lunar surface, and sequestered at the poles have become areas of intense active research and are now known to represent different fundamental processes active on the Moon and other silicate bodies of the inner solar system (e.g., Hurley et al., 2017; Pernet-Fisher et al., 2017). LRO characterization of the polar environment, including surface and subsurface temperatures (Diviner) and illumination conditions (LROC), and the possibility of surface frosts (LAMP, LOLA) restricted to locations that never get warmer than 110 K, the cold-trap temperature above which water-ice sublimes (Gladstone et al., 2012; Lucey et al., 2014; Pernet-Fisher et al., 2017). Analyses of volatiles in lunar basalts and crustal rocks have confirmed the presence of small but significant amounts of water in the lunar magma ocean. The approximate constancy of volatile depletion in the Moon relative to Earth is explained by assuming that both acquired volatiles from a similar source or by a similar mechanism, but Earth was more efficient in acquiring the volatiles. The H2O, F, and S concentrations in the primitive lunar mantle source are similar to or slightly lower than those in terrestrial MORB mantle (Hui 2013; Chen et al., 2015).

Lunar Environment

Extensive further analysis of lunar orbital data sets from LADEE and LRO, theoretical modeling, and laboratory simulation of the lunar environment has led to tighter constraints on environmental (charged particles, fields, regolith, dust, exosphere, surface volatiles) dynamics, including the volatile sources, sinks, and transport. The LADEE neutral mass spectrometer (NMS) detected argon, mapping out how argon moves over the course of a lunar day. The NMS findings indicate that a very thin layer of argon sticks to the surface on the cold night side of the Moon (much like frost is deposited during the night on Earth) and is released as the Sun heats the surface. After release, these atoms do not immediately escape from the Moon, as gravity keeps them within the orbit and they bounce off the warmer daytime surface, where they can be detected by the NMS. These data provide the basis for higher fidelity models of the interaction of argon and other gases with the lunar surface, and by extension to other bodies in the solar system that have very thin atmospheres. The Lunar Dust Experiment (LDEX) on the LADEE spacecraft recorded over 11,000 unambiguous dust impacts during its mission at the Moon that lasted from October 2013 until April 2014. These findings confirm that there is a dust cloud surrounding the Moon, which is sustained by the continual bombardment of interplanetary dust particles. Carbonaceous matter on the surfaces of black pyroclastic beads, collected from the Shorty crater during the Apollo 17 mission, represents the first identification of complex organic material associated with any lunar sample. It formed through the accretion of exogenous meteoritic kerogen from micrometeorite impacts into the lunar regolith (Thomas-Keprta et al., 2014). LRO temporal pairs are creating critical new determinations of the lunar impact rate and revealing exciting new details of ejecta distribution and the structure of the regolith

(Robinson et al., 2015; Speyerer et al., 2016). Diviner thermophysical property results, including global maps of the Diviner Rock Abundance (DRA), are excellent tools for regolith property investigations and landing site selection (Bandfield et al., 2011). CE3 provided ground-truth measurements on a relatively young, intermediate- to high-Ti basalt flow in the Imbrium basin. The LRO mission is providing data necessary to certify sites for safe landing, including high-resolution images and stereo Digital Terrain Models for many locations on the Moon for U.S. and international missions.

Current Implementation

The current lunar science program is driven by both sample studies on returned lunar samples and meteorites and by missions. There used to be a Lunar Quest (LQ) program for directed missions that sent LADEE. The Lunar Quest program included flight missions (LRO after the Human Exploration Office mission concluded, LADEE, International Lunar Network), instruments for lunar missions of opportunity, and research and analysis efforts for crosscutting lunar and exploration research (LASER and LMMP). The LQ program was cancelled in 2014, at the conclusion of the LADEE mission, and the LRO extended mission was transferred to Discovery and research objectives to SSERVI.

MARS

The most important new Mars results since publication of *Vision and Voyages* derive from the Mars Exploration Rover (MER) Opportunity, Mars Reconnaissance Orbiter (MRO), Mars Atmosphere and Volatile Evolution Mission (MAVEN), and Mars Science Laboratory (MSL) Curiosity measurements. Some expand on preliminary findings known at the time of *Vision and Voyages*; others reveal entirely new characteristics of Mars, and have implications for climate in the past few billion years and Mars's astrobiologic potential. The findings fall into four broad categories.

Ancient Wet and Habitable Environments

Mars Science Laboratory/Curiosity's in situ analysis of a ~3.7 Ga mudstone in Gale crater reveals that it definitely formed in a habitable environment. The mudstone's stratigraphy and lithology are consistent with deposition in a stream-fed lake. Depletion of the sediments in olivine and the presence of secondary gypsum veins and smectite indicate prolonged aqueous alteration and habitable pH and salinity conditions. Co-occurrence of minerals with Fe and S in mixed oxidation states would have provided a source of chemical energy (Grotzinger et al., 2014; Léveillé et al., 2014). By analogy with other similar lacustrine deposits identified by remote sensing, such habitable environments probably occurred in many locations on ~4 Ga Mars (Goudge et al., 2012, 2015).

Continued orbital reconnaissance has revealed outcrops that record at least a dozen distinct environments in which liquid water interacted with rock for a sufficiently long period to leave a mineral record, extending in age from the pre-4 Ga period to as recently as ~3 Ga. Of these, about half record surface water or hydrothermal environments whose mineral assemblages are consistent with pH, salinity, and water activity that could have been habitable.[1] The rest are not consistent with habitable conditions due to one or more factors (Carter et al., 2013; Ehlmann and Edwards, 2014; Wray et al., 2016). (See Figure 2.6.)

Hydration of the rock crust occurred mostly in the subsurface at ~4 Ga (Ehlmann et al., 2011b; Carter et al., 2013). This alteration is interpreted to have arisen by contact with saline hydrothermal fluids

[1] On Mars, "hydrothermal" can be much cooler than on Earth due to Mars's geophysical conditions.

(Arvidson et al., 2014). There is evidence for both endogenic and impact heating having driven alteration (Tornabene et al., 2013; Viviano-Beck et al., 2017).

A later period, perhaps around 3.7 Ga, had "peak" abundance of surface waters as recorded by valley networks, detrital and chemical sediments deposited in lake environments, and compositionally stratified clay deposits (Ehlmann et al., 2011a) containing 30 wt% or more clays possibly formed by pedogenesis—that is, chemical soil formation by chemical weathering (Le Deit et al., 2012; Poulet et al., 2014).

Surface water continued to be present sporadically at least until ~3 Ga in Arabia and Valles Marineris, forming fluvial valley, stream-fed paleoloakes, and locally secondary mineral deposits (Weitz et al., 2013; Wilson et al., 2016). Rock-water interactions probably due to subglacial volcanism and melting occurred at high southern latitudes (Ackiss et al., 2016).

Ancient Climate and Loss of the Atmosphere

Since *Vision and Voyages*, two distinct episodes of carbonate formation on Mars have been recognized. Newly discovered Fe/Ca-carbonates are greater than 4 Ga in age and have been exhumed by impacts (Wray et al., 2016). Their co-occurrence with smectite clays would be consistent with formation under several hundred millibars of CO_2, which is comparable to current Earth total surface pressure (Zolotov and Mironenko, 2016). Mg carbonates formed during the subsequent few hundred million years are restricted to an annulus around the Isidis impact basin, and sequester no more than 12 mb of CO_2, limiting crustal sequestration of carbon since ~4 Ga (Edwards and Ehlmann, 2015).

MAVEN measurements support stripping of enough martian atmosphere by solar wind to remove ~500 millibars of CO_2 in 4 byr, mostly during the 300-500 Ma after the magnetic field shut down (Jakosky et al., 2015, 2017a). These results are consistent with inferences above based on older carbonate-bearing deposits; with the finding from MSL Curiosity that D/H of water extracted from clays in ~4 Ga rocks was already increased by 3×, indicating early, substantial loss of water (Mahaffy et al., 2015); and with Ar isotopic measurements indicating loss of ≥2/3 of atmospheric neutrals (Jakosky et al., 2017b).

At the time of *Vision and Voyages*, later surface water was generally thought to have originated as rainfall. Newer modeling indicates that precipitation as highland snowfall (the "Icy Highlands" model) may better explain the distribution of morphologic and mineralogic indicators of these later wet environments (Fastook et al., 2015; Wordsworth et al., 2015).

More Recent (<3 Ga Age) Climate Change

Mars Reconnaissance Orbiter (MRO) radar sounding of the polar caps has revealed a massive amount of CO_2 ice buried in the south polar cap, which if released would double the present mass of atmosphere and greatly expand the temporal and spatial range at which surface temperature and pressure exceed the triple point of water (Phillips et al., 2011). It has also revealed nonuniform "packets" of reflectors, which may be related to obliquity changes. Modeling of the topmost layer suggests the last ice age was ~370,000 years ago (Smith et al., 2016).

Shallow, (≥95 wt%) subsurface water ice has been observed directly at widespread midlatitude locations where the ice is exposed in fresh impact craters (Dundas et al., 2014). Where exposed locally in scarps, the water ice forms continuous sheets tens of meters in thickness (Dundas et al., 2018). Its presence is inferred over wide areas even where not directly observed, based on radar (Putzig et al., 2014; Stuurman et al., 2016) and occurrence of expanded secondary craters (Viola et al., 2015) and terraced craters (Bramson et al., 2015). There is not wide agreement on the process that could concentrate water ice in excess of available pore space (~35 percent): late Amazonian snowfall (Head et al., 2003; Bramson et al., 2017) or concentration by intergranular flow of vapor or brines (Sizemore et al., 2015) have been proposed.

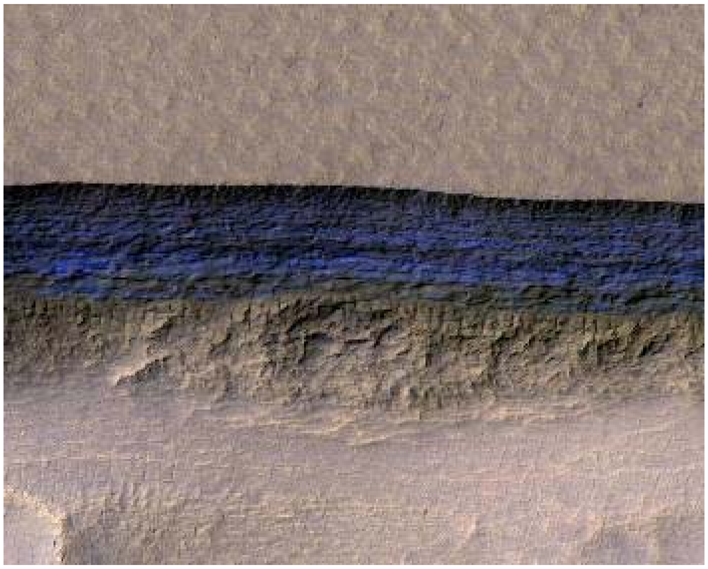

FIGURE 2.6 Color-enhanced HiRISE image showing a cross section of a thick sheet of shallow excess ice. The view covers an area about 500 meters wide. The upper third of the image shows level ground that is about 130 meters higher in elevation than the ground in the bottom third. In between, the scarp descends sharply, exposing about 80 vertical meters of water ice. The presence of exposed water ice at this site was confirmed by observation with CRISM. The site is located at 56.6°S, 114.0°E. SOURCE: NASA Jet Propulsion Laboratory, "Steep Slopes on Mars Reveal Structure of Buried Ice," January 11, 2018, courtesy of NASA/JPL-Caltech/University of Arizona/USGS.

Dynamic Modern Mars

At the time of *Vision and Voyages*, martian sand bedforms were thought to be inactive. From orbital and landed imaging, it is now known that modern Mars has active sand sedimentation, migrating dunes, and Earth-like transport rates of sand (Bridges et al., 2012, 2017). Sand originates from mineralogically diverse local sources (Chojnacki et al., 2014a, 2014b). Eolian sorting processes create further diversity in sand composition (LaPotre et al., 2017).

Intensive gully imaging by MRO has shown that gullies actively grow during late winter due to early springtime ablation of seasonal CO_2 frost, when temperature does not permit flow even of brines. Rather, dry granular flow initiated by CO_2 sublimation appears to be the dominant processes in forming gullies (Pilorget and Forget, 2016).

Recurring slope lineae (RSL) form in summertime on sunward-facing slopes where temperatures exceed 253K, grow and extend downslope over the summer, and fade during autumn (McEwen et al., 2011, 2014). At least locally, they form where perchlorates are present and could depress the freezing point of brines by up to 70° below that of pure water (Ojha et al., 2015). These properties suggest briny flow, deliquescence, or dry granular flow on warm slopes initiated by vapor evaporated from brine or deliquescence.

Occurrence of martian methane has been confirmed by MSL/SAM. Its abundance increases above a negligible background abruptly, and decreases more quickly than models of atmospheric chemistry predict (Webster et al., 2015). Although the origin could be biotic, alternatively it could form from serpentinization of olivine on modern Mars, or on ancient Mars but trapped, and released episodically (Etiope et al., 2013; Kite et al., 2017). (See Figure 2.7.)

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FIGURE 2.7 SAM methane measurements versus martian sol after MSL landing. Larger error bars are direct-ingest results, and the two with smaller error bars labeled “EN” are values from methane enrichment runs. All measurements were made from nighttime ingest, except the two marked “D” that were ingested during the day and analyzed at night. The shaded boxes show the occurrence and duration of the SAM-evolved gas analysis runs for rock and soil samples. SOURCE: C.R. Webster, P.R. Mahaffy, S.K. Atreya, G.J. Flesch, M.A. Mischna, P.-Y. Meslin, K.A. Farley, et al., the MSL Science Team, Mars methane detection and variability at Gale crater, *Science* 347(6220):415-417.

JUPITER

Juno arrived in Jupiter orbit on July 5, 2016, and results from the mission are already leading to a new understanding of the planet’s workings and interior. Among the new discoveries are a deeply penetrating ammonia-based weather system and a stronger and more irregular magnetic field than previously thought (Bolton et al., 2017).

The discovery by Juno that Jupiter’s gravity field (Folkner et al., 2017) is north-south asymmetric and the determination of its nonzero odd gravitational moments J3, J5, J7, and J9 demonstrates that the observed east-west winds persist to a depth of about 3000 km (Kaspi et al., 2018). The initial results from the gravity experiment suggest an enrichment of heavier elements toward the center of the planet, perhaps of order 10 or so Earth masses, but this core may extend out as far as half the planet, meaning that the heavier elements are partially dissolved in hydrogen. (It could be water ice, for example. Gravity indicates nothing about the composition, only that the material is more dense than a solar composition mix.)

Juno discovered clusters of cyclones encircling Jupiter’s poles. (See Figure 2.8.) This is very different than anticipated, and the structure differs greatly from that at Saturn’s poles, where the north pole’s cyclones are organized in a hexagonal pattern (Adriani et al., 2018). Furthermore, Juno’s microwave radiometer discovered an equatorial belt of ammonia that appears to extend at least to a pressure of 250 bars, but away from this belt there is considerable variability throughout the deep atmosphere (Bolton et al., 2017). This discovery demonstrates that Jupiter’s atmosphere, at least with respect to ammonia (and presumably water), is not well mixed below the 5-10 bar region as previously assumed. Jupiter’s atmosphere also appears to be depleted in ammonia to at least 100 bars (Li et al., 2017).

The Jovian magnetic field contains patches of low and high magnetic field flux that are not yet fully characterized because of their limited spatial extent. Jupiter’s dynamo extends out to as much as 90 percent of the radius (Bolton et al., 2017).

Juno found similarities but also strong differences between Jupiter’s and Earth’s auroras (Mauk et al., 2017; Connerney et al., 2017). Juno discovered strong magnetic field-aligned electric potentials over Jupiter’s main aurora. Electric potentials are indicated (up to 400 kilovolts) that are an order of magnitude larger than the very largest observed at Earth. Despite the magnitude of these potentials, they are not associated with the most intense auroras at Jupiter as they are at Earth.

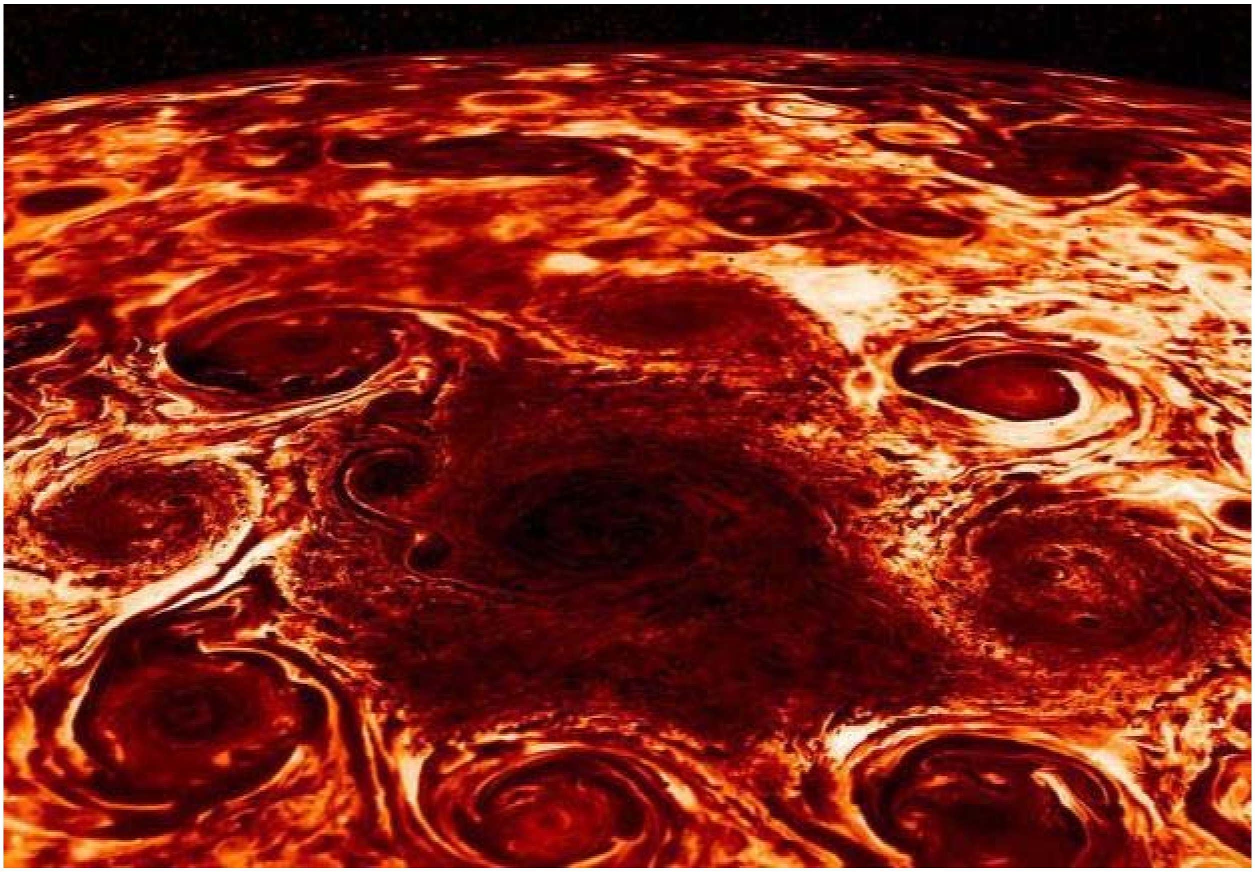

FIGURE 2.8 Cyclones at the north pole of Jupiter, as viewed in the infrared. SOURCE: NASA, "NASA Juno Findings—Jupiter's Jet-Streams Are Unearthly," March 7, 2018, https://www.nasa.gov/feature/jpl/nasa-juno-findings-jupiter-s-jet-streams-are-unearthly, courtesy of NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM.

SATURN SYSTEM

The spectacular Cassini mission ended its 13-year voyage in the Saturn system in September 2017, going out in a blaze of glory. Some of the highlights of Cassini since the publication of *Vision and Voyages* are described here.

Cassini found that Enceladus is jetting water vapor to great distances beneath its south pole (Dougherty et. al., 2006). (See Figure 2.9.) The source of the water vapor was found to lie beneath distinct dark-colored cracks on the surface, requiring a lake or an ocean beneath the ice (Porco et al., 2006). Images of Enceladus, acquired over seven years, were used to determine the satellite's precise rotation state and to thereby derive the physical libration of the body. The results were found to require a global subsurface ocean (Thomas et al., 2016), rather than a localized subsurface sea.

Data acquired by Cassini's Cosmic Dust Analyzer (CDA) instrument on flybys through the Enceladus plumes indicate that the plumes originated in a salt-water reservoir that is, or has been, in contact with rock. Hsu et al. (2015) found that the composition and nanometer size of silica particles in the plume imply high-temperature (>90ºC) hydrothermal reactions. Waite et al. (2017) used Ion and Neutral Mass Spectrometer (INMS) data to identify H_2 in the Enceladus plume (at levels of 0.4-1.4 percent by volume), also pointing to water-rock interactions. Together, these results suggest that hydrothermal activity is able to transport material from the ocean floor at least 40 km up to the surface through the Enceladus plumes.

The hydrothermal material may mix in the ocean, cool to ice temperature, and then later vent. This is the first evidence of ongoing hydrothermal activity beyond Earth.

Data from the Visual and Infrared Mapping Spectrometer (VIMS) revealed that the brightness of the plumes is several times greater when Enceladus is near the point in its orbit farthest from Saturn (apokrone) than when near the point of closest approach to the planet (perikrone). Hedman et al. (2014) interpreted this to mean that material escapes from beneath Enceladus's surface most readily at times when the fissures from which the plumes emanate are predicted to be in tension, implying a direct correlation between plume activity and tidal stresses.

Cassini established that Titan is one of the most Earth-like bodies yet encountered, with weather, climate, and geology that provide new insights into the evolution of planet Earth. Cassini's extended missions revealed seasonal variations at Titan, including evidence of spring methane rain showers (Turtle et al., 2011), changes in atmospheric circulation (Teanby et al., 2012), and appearance of low-latitude hydrocarbon lakes (Griffith et al., 2012). Precise radio science measurements (Iess et al., 2012) at different locations around Titan's eccentric orbit demonstrated deformations in Titan's interior on the time scale of its orbital period large enough to require a water-rich ocean under an ice shell. Further analysis of gravity data indicated that Titan's ice shell is variable in thickness, with an average thickness of ~70 km, and that the ocean contains a high concentration of dissolved salts (Mitri et al., 2014). Titan is a new type of ocean world with stable surface liquids other than water.

Puzzling variations at periods slightly longer than the planetary rotation period but varying over months to years are observed in radiofrequency emissions (Gurnett et al., 2010), auroral activity, and many other magnetospheric phenomena. The effects are thought to be driven by rotating asymmetric flows in the high-latitude ionosphere arising from asymmetries in the upper atmosphere (Jia et al., 2012).

Cassini revealed the complexity of Saturn's rings and the dramatic processes operating within them. Details of ring structure have provided clues to the locations of new moons and the presence of both internal oscillations and static mass anomalies in Saturn's interior (Hedman and Nicholson, 2013, 2014). The mission also illuminated the critical role of charged dust in magnetospheric dynamics (Blanc et al., 2014), and the diversity of plasma interactions with moons in a single system (Simon et al., 2015).

In the grand finale, Cassini obtained some remarkable results for the rings and interior (gravity and magnetic fields), most of which are not yet published. The rings were found to be at the low mass end of previous estimates, suggesting that they are young. The rotation of Saturn's interior is still undetermined because the internal part of the magnetic field exhibits no longitudinal structure. The gravity field shows clear evidence of strong differential rotation in the outer 10-15 percent of Saturn's radius.

Europa

At Europa, enhanced hydrogen and oxygen ultraviolet (UV) emissions were observed above the southern hemisphere using the Hubble Space Telescope (HST) (Roth et al., 2014). These were interpreted as the dissociation products of water, hence evidence of water vapor plumes. (See Figure 2.10.) Although such UV emissions have not been observed again at any location on Europa so far, subsequent HST observations of Europa in transit against the disk of Jupiter have found indications of UV absorption by possible plume material at the southern hemisphere once. They have also found them at a low-latitude trailing hemisphere location twice, strengthening evidence for modern-day venting activity at Europa (Sparks et al., 2016).

Analysis of Galileo images of Europa shows several lines of evidence for subduction, and hence plate tectonics, resolving a long-standing issue of how Europa's ice shell accommodates its ubiquitous extensional surface features. A tectonic reconstruction of a portion of Europa's surface reveals evidence of spreading, transform motions, and partial removal of a 99-km wide slab along a discrete tabular zone interpreted to be a subduction-like convergent boundary (Kattenhorn and Prockter, 2014). Such a system would make Europa the only body in the solar system other than Earth to exhibit a system of plate tectonics.

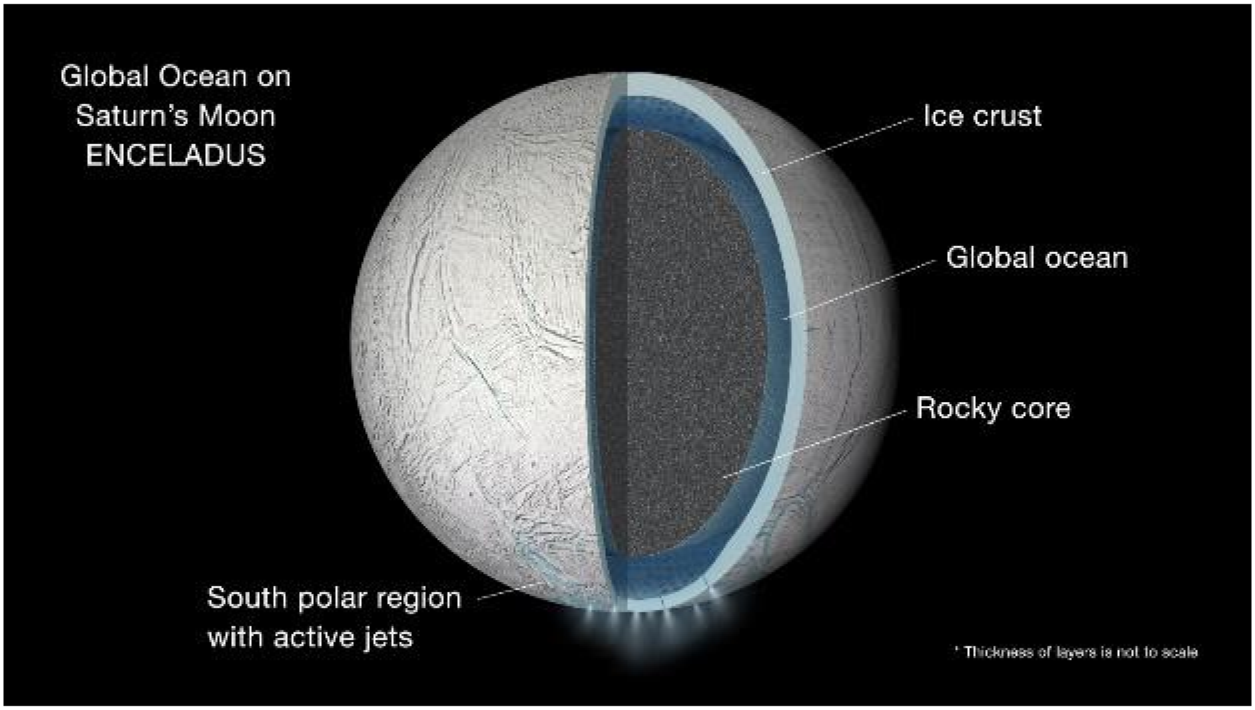

FIGURE 2.9 Cutaway view of the interior of Enceladus. SOURCE: NASA, “Cassini Finds Global Ocean in Saturn's Moon Enceladus,” September 15, 2015, https://www.nasa.gov/press-release/cassini-finds-global-ocean-in-saturns-moon-enceladus, courtesy of NASA/JPL-Caltech.

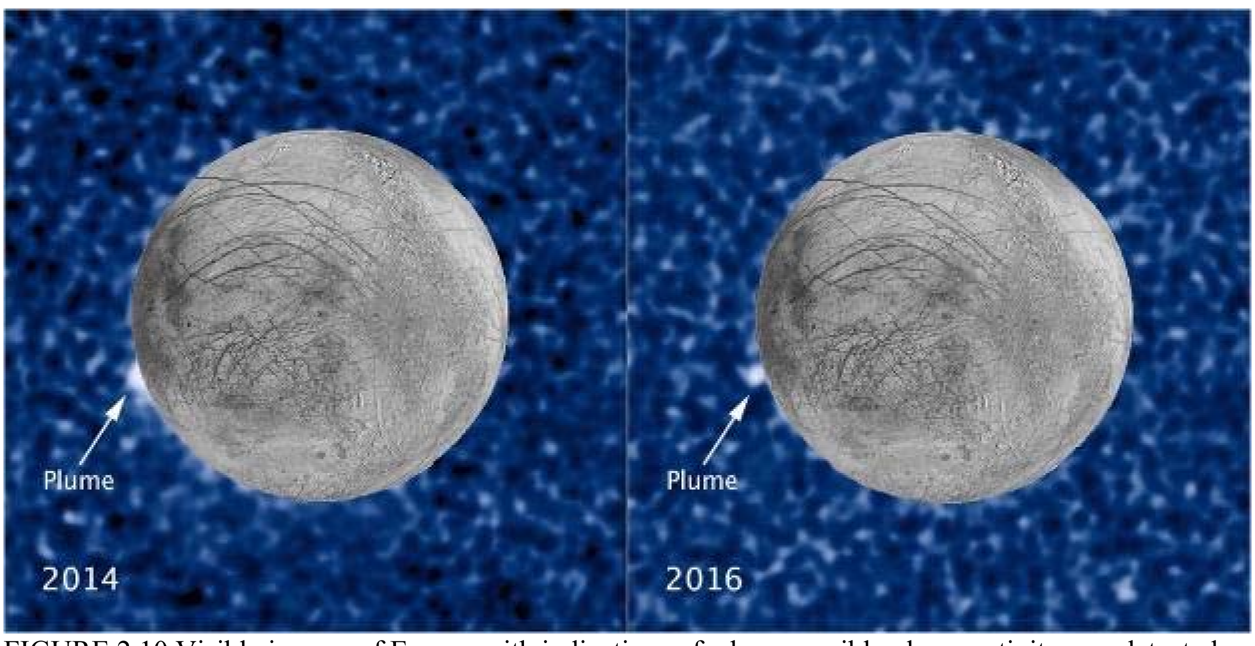

FIGURE 2.10 Visible images of Europa with indications of where possible plume activity was detected by HST on two occasions. SOURCE: NASA Jet Propulsion Laboratory, “Hubble Sees Recurring Plume Erupting From Europa,” April 13, 2017, https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA21443; courtesy of NASA/ESA/W. Sparks (STScI)/USGS Astrogeology Science Center.

Additional evidence of localized jets of vapor forming plumes just above Europa's surface (possibly intermittently) was found in archived data from the Galileo spacecraft two decades after the measurements were made (Jia et al., 2018). Galileo's closest pass by Europa on December 16, 1997, took it within 200 km of Europa's surface. Near closest approach, rapid changes of the magnetic field orientation and magnitude had been noted by the magnetometer team but had not been interpreted. Hubble images (e.g., Figure 2.10) suggesting the presence of plumes provided information on their height and width and the density of the vapor. Numerical simulations of the effect of a plume were used to determine how a plume would perturb the magnetic field along Galileo's orbit. The analysis was carried out both with and without a vapor plume (mainly water) located near Galileo's closest approach to Europa. The computation incorporated the effects of ionization of the neutral molecules by energetic electrons, revealing how such a structure would affect the magnetic field and the electron density near the plume. The results not only accounted for the previously puzzling changes of the measured magnetic field but also explained an extremely brief emission in the plasma wave spectrum that implied a significant increase of electron density coincident with the magnetic field anomaly. The highly localized increase of electron density was also consistent with the results of the numerical simulation. These results provide supporting evidence for strong hydrothermal activity at Europa and suggest the possibility of characterizing matter from Europa's ocean from a spacecraft passing near Europa such as the Europa Clipper mission.

Ceres and Vesta

The Dawn mission confirmed that Vesta, the second largest asteroid, is the parent body of the HED meteorites, based on data from three instruments: the gamma ray and neutron detector (GRaND), which gives elemental composition; the visible and infrared spectrometer (VIR), which provides mineralogy; and the framing camera (color bands). Dawn found that Vesta's gravity field is consistent with an iron core of the size predicated by HED-based differentiation models, and thus also confirmed that this body underwent differentiation early in the history of the solar system (Russell et al., 2012). The heavily cratered topography found by Dawn is transitional between planets and smaller asteroids. Dawn measurements provided ground-truth for HED meteorites and geological context for the Vesta asteroid family, as well as revealing significant surface contamination by carbonaceous material (McCord et al., 2012). (See Figure 2.11.)

At Ceres, the largest asteroid, the Dawn spacecraft has demonstrated that a global ocean existed in its early history. Dawn measured sodium carbonate and ammonium salts on the bright deposits in Ceres's Occator crater; these salts were dissolved in water and crystallized from subsurface brines, the chemistry of which has implications for models of Ceres's formation and evolution and likely requires an early subsurface reservoir rich in ammonium or chloride (Nathues et al., 2017). Surprisingly, some of this activity may have occurred only tens of millions of years ago. Gravity and topography data support a partially differentiated structure with the outer region being a mixture of ice and silicates (Park et al., 2016). Morphological evidence (pits and furrows) suggests small amounts of water ice in the subsurface (Schmidt et al., 2017) and spectroscopic evidence shows small amounts of water ice on the surface (Combe et al., 2016). Cryovolcanism has been suggested for Ceres based on landforms suggestive of viscous dome formation (Ruesch et al., 2016). (See Figure 2.12.) Together, the discoveries at Ceres indicate a remarkably active, volatile-rich dwarf planet.

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FIGURE 2.11 Topography on Vesta. SOURCE: Jaumann et al. (2012).

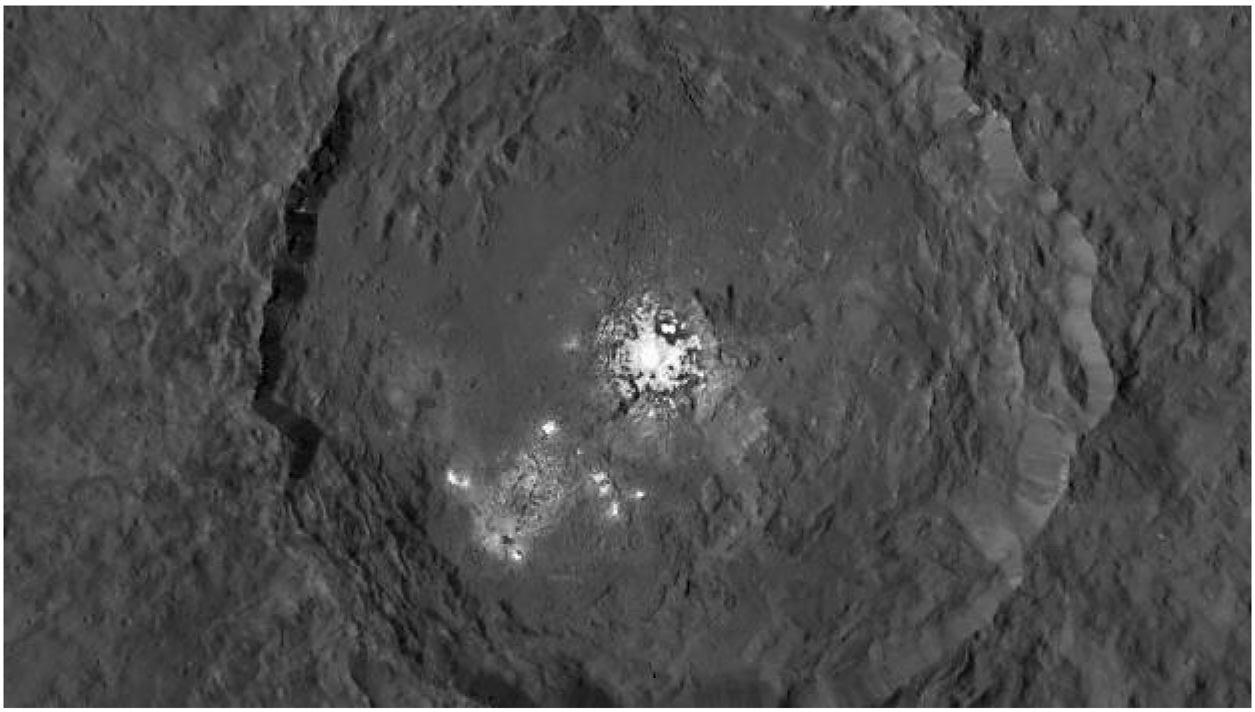

FIGURE 2.12 Occator crater on Ceres. The bright spots on the crater floor provide evidence of past subsurface brines. SOURCE: NASA, "Occator Crater and Ceres' Brightest Spots," March 22, 2016, https://www.nasa.gov/image-feature/jpl/occator-crater-and-ceres-brightest-spots, courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/PSI.

COMETS AND 'OUMUAMUA

The Rosetta mission at comet 67P/Churyumov-Gerasimenko ended in September 2016, after releasing the first-ever lander onto a comet surface in November 2014. The comet's D/H ratio was measured to be three times that of water on Earth, placing constraints on the type of object expected to have brought water to Earth early in its history (Altwegg et al., 2015). Although it is unlikely that comets delivered most of Earth's water, xenon isotope measurements from Rosetta show that comets did contribute to Earth's atmosphere (Marty et al., 2017) and comets have a full range of D/H values including several (e.g., Hartley 2) that are terrestrial. Rosetta measured the composition of volatiles escaping from comet 67P/C-G and offered new insight into the interior structure of a comet; molecular oxygen was observed for the first time at the comet (Bieler et al., 2015), with implications for the comet's formation. Rosetta included two U.S.-supplied instruments. Remarkably detailed morphological and mechanical details of the cometary surface were obtained, useful for both future cometary missions and for constraining ideas for how comets form and evolve. (See Figure 2.13.)

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FIGURE 2.13 A small part of the surface of comet 67P/Churyumov-Gerasimenko, showing the resting place of the lander Philae. SOURCE: European Space Agency, "Philae Found!," September 5, 2016, http://www.esa.int/Our_Activities/Space_Science/Rosetta/Philae_found; main image and lander inset credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; context: ESA/Rosetta/NavCam—CC BY-SA IGO 3.0

An interstellar interloper was discovered on October 19, 2017, with the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) 1 telescope at the University of Hawaii (Meech et al., 2017). This is a morphologically unusually prolate body. The interstellar nature of this object, known as A/2017 U1 ('Oumuamua), was confirmed by the Jet Propulsion Laboratory (JPL) Center for Near-Earth Object Studies (CNEOS). The substantially hyperbolic orbit, with heliocentric encounter velocity of ~26 km/sec, far greater than could have arisen from solar planetary perturbations, requires that it originated outside the solar system (collision cannot lead to the observed eccentricity of the object). Although it passed perihelion only 0.25 AU from the Sun, no sign of coma or volatile activity was observed at any time, so this was not labeled as a comet, although it is possibly a body that once had cometary volatiles or has encased these volatiles beneath an involatile surface crust (Fitzsimmons et al., 2018). The existence of small bodies floating around between the stars is no surprise; the Oort Cloud of our own solar system provides ample evidence that planet formation is a messy process that results in many small bodies escaping into interstellar space.

PLUTO AND CHARON

The New Horizons spacecraft made its closest approach to Pluto in July 2015. (See Figure 2.14.) The mission spectacularly demonstrated that Pluto is a far more dynamic world than anticipated. The Pluto system is complex in the variety of its landscapes, including 3.5 km high mountains, the diversity of its manifestation of activity, and its range of surface ages (Stern et al., 2015; Weaver et al., 2016; Moore et al., 2016; Grundy et al., 2016; Gladstone et al., 2016; McKinnon et al., 2016). The orientation of the region named Sputnik Planitia, a nitrogen ice sheet on the anti-Charon point of Pluto, may indicate reorientation and tidal wander of the shell facilitated by a subsurface ocean (Nimmo et al., 2016). Polygonal patterns on the nitrogen surface are thought to arise from convection in a layer of solid nitrogen (Trowbridge et al., 2016). The "bedrock" of Pluto is thought to be water ice, which has been detected on the surface (Protopapa et al., 2017). Charon's dark red polar cap may be the result of atmospheric gases that escaped Pluto and settled on Charon's surface (Grundy et al., 2016). Pluto's atmosphere behaves differently than believed, pre-New Horizons; for instance, the atmospheric nitrogen was shown to escape at a much lower-than-predicted rate and it is now thought that the atmosphere does not freeze out when Pluto is near aphelion (Olkin et al., 2017). (See Figures 2.15, 2.16, 2.17, and 2.18)

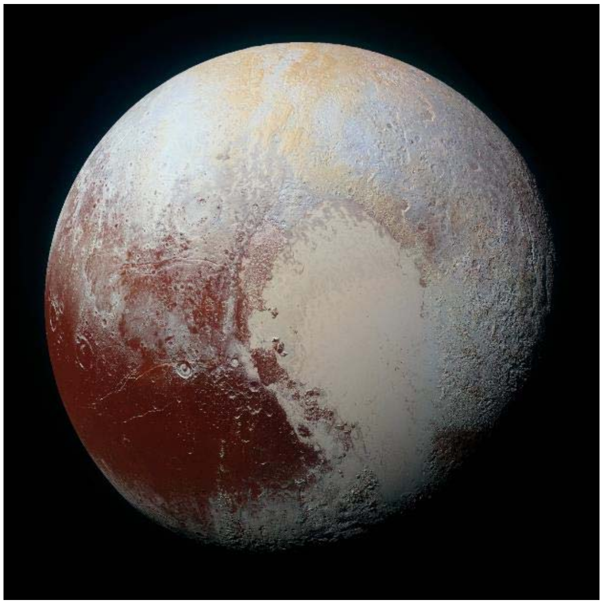

FIGURE 2.14 Global view of Pluto provided by the New Horizons spacecraft. SOURCE: NASA, "The Rich Color Variations of Pluto," September 24, 2015, https://www.nasa.gov/image-feature/the-rich-color-variations-of-pluto; courtesy of NASA/JHUAPL/SwRI.

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FIGURE 2.15 Perspective view of Pluto's highest mountains, Tenzing Montes, along the western margins of Sputnik Planitia, which rise 3-6 km above the smooth nitrogen-ice plains in the foreground. The mounded area behind the mountains at upper left is the Wright Mons edifice interpreted to a volcanic feature composed of ices. Area shown is approximately 500 kilometers across. SOURCE: Lunar and Planetary Institute, "Tenzig Montes," released July 10, 2018, https://www.lpi.usra.edu/features/070918/pluto/; courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Lunar and Planetary Institute/Paul Schenk.

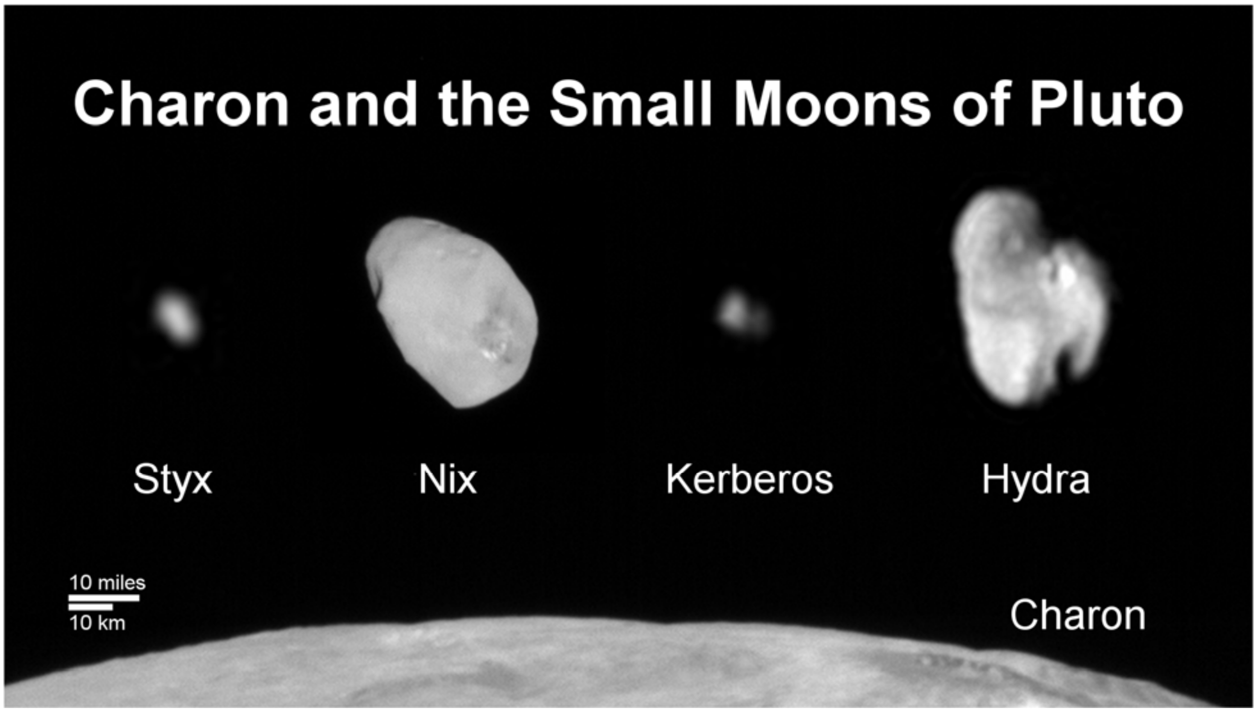

FIGURE 2.16 All the moons of Pluto. SOURCE: NASA, "Charon and the Small Moons of Pluto," October 22, 2015, https://www.nasa.gov/image-feature/charon-and-the-small-moons-of-pluto; courtesy of NASA/JHUAPL/SwRI.

FIGURE 2.17 Pluto's largest moon, Charon. SOURCE: NASA, "Pluto's Big Moon Charon Reveals a Colorful and Violent History," October 1, 2015, https://www.nasa.gov/feature/pluto-s-big-moon-charon-reveals-a-colorful-and-violent-history; courtesy of NASA/JHUAPL/SwRI.

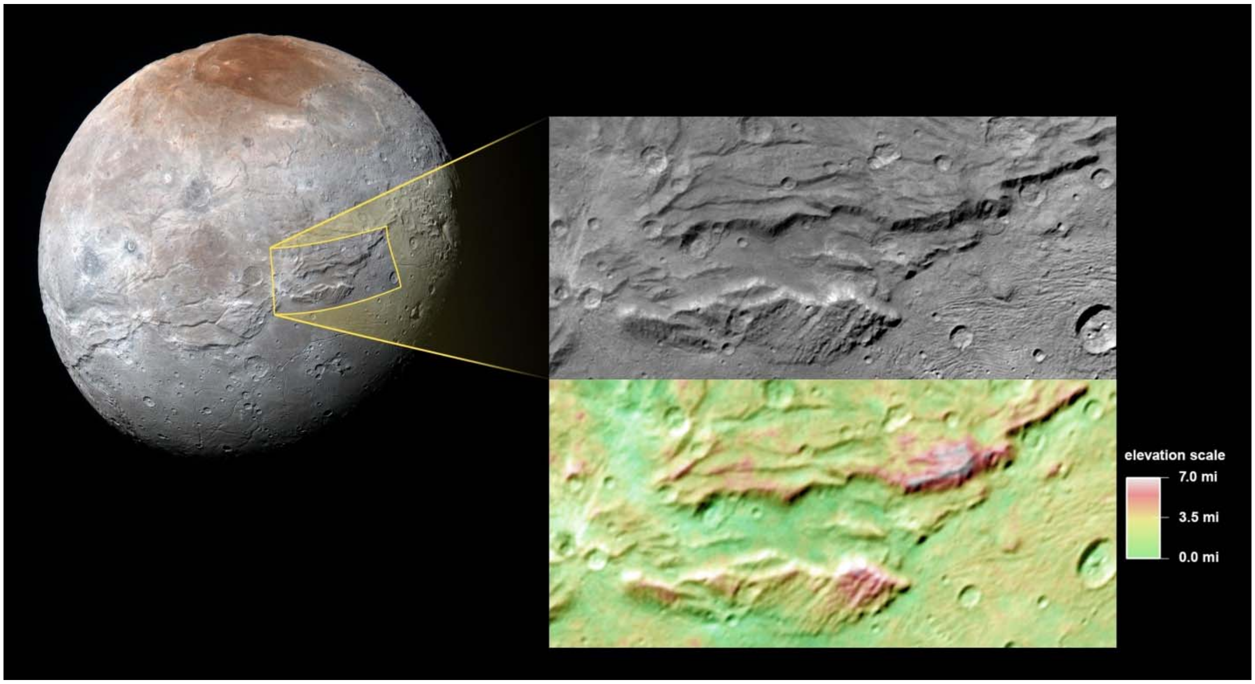

FIGURE 2.18 Images of crust fracturing on Charon, suggesting that it might of once had a subsurface ocean which froze and expanded, stretching the surface. SOURCE: NASA, "Pluto's 'Hulk-like' Moon Charon: A Possible Ancient Ocean?," PIA20467, https://photojournal.jpl.nasa.gov; courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute.

EXOPLANETS

No summary of recent developments in planetary science would be complete without a mention of the remarkable explosion in discoveries of exoplanets since the last decadal survey. It is of particular significance that many of these bodies are intermediate in nature between Earth-like bodies and Uranus or Neptune-like bodies. They are variously described as super-Earths and sub-Neptunes, different from anything in our solar system, yet they can tell us much about how planets form and evolve (Fulton et al., 2017). Exoplanets form planetary systems that differ markedly from our own, with many planets, even ones far larger than Jupiter, at close distance from the central star. This discovery has given impetus to new concepts of planetary system formation, and has given new incentives to improve our understanding of how our own solar system formed.

CONCLUSION

This chapter has provided only a brief overview of the tremendous scientific discoveries made since the *Vision and Voyages* report was released in March 2011. New discoveries have been made from the core to the magnetospheres of all classes of objects in our solar system. A rich collection of missions is continuing to deliver profound advances in the understanding of solar system formation and evolution, which will inform science priorities for the remaining years of the *Vision and Voyages* decade and beyond.

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3

Assessment of Current Progress vis-à-vis *Vision and Voyages*, and Guidance for the Rest of the Decade

This chapter assesses the degree to which NASA's current planetary science program addresses the strategies, goals, and priorities outlined in *Vision and Voyages* and other relevant National Research Council (NRC) and National Academies of Sciences, Engineering, and Medicine reports, and assesses NASA progress toward realizing these strategies, goals, and priorities and effectiveness in maintaining programmatic balance.

This chapter recommends actions that could be taken to optimize the science value of the planetary science program, and provides guidance about implementation of the decadal survey's recommended mission portfolio and decision rules for the remaining years of the current decadal survey.

In this assessment, the committee was instructed not to revisit or redefine the scientific priorities or mission recommendations from the decadal survey. However, the committee includes guidance on how to take into account emergent discoveries since the decadal survey in the context of current and forecasted resources available to it.

CADENCE AND BUDGET CONSIDERATIONS

The NASA Planetary Science Division (PSD) manages a portfolio consisting of missions, research and analysis (R&A), technology investments for future missions and analysis, infrastructure to support technology, laboratory work, fieldwork (part of R&A), ground-based telescopes, and management efforts. *Vision and Voyages* made specific recommendations on how best to balance that portfolio to maintain a vibrant research and development community, which in turn serves NASA. These recommendations were based on the budget given at the time, but also made clear how to respond to budget decreases as well as increases. Specifically, "If cuts to the program are necessary, the first approach should be de-scoping or delaying flagship missions. Changes to the New Frontiers or Discovery programs should be considered only if adjustments to flagship missions cannot solve the problem. And high priority should be placed on preserving funding for research and analysis programs and for technology development." Although *Vision and Voyages* did not explicitly state this, delaying flagship missions may be counter to the purpose and detrimental unless it is applied before the mission enters formulation, because money expenditures increase dramatically once formulation starts. The impact of budget changes can actually in the aggregate not only affect the flagship severely but also disrupt the whole portfolio in a major way. Flagships can have enormous impacts on the overall program, and must be initiated and managed with extreme prudence.

Decadal Findings: Figure 3.1 shows the PSD budget as assumed by the decadal survey in 2011 (this figure was generated by the committee). Technology and R&A wedges are shown at the bottom as foundational activities. MAX-C (Mars Astrobiology Exploration-Cacher) was the highest priority flagship mission and the Jupiter Europa Orbiter (JEO) was included if the cost could be reduced and PSD budgets increased. Solid areas represent survey recommendations with cost and technical evaluation (CATE) estimates, and the vertical stripe areas represent the commitments—existing programs and overhead—given to the survey committee by NASA. This plot has been organized to allow direct comparison with NASA budget projections.

Assessment: The current view of the budget is shown in Figure 3.2, generated by the committee. The budget projection from 2013 to 2022 is roughly in line with what *Vision and Voyages* projected in 2011. This equates to $17.1 billion currently as projected versus $17.6 billion assumed during the decadal survey. While there is a *slightly* reduced budget relative to what the decadal survey assumed occurred during the first half of the decade, NASA initiated both Mars 2020 (reduced scope MAX-C) and Europa Clipper (reduced scope JEO). Although Mars 2020 is behind schedule relative to a de-scoped MAX-C as envisioned in *Visions and Voyages*, implementation of the "lean and rapid" architecture could result in Earth return of the samples on or ahead of the envisioned schedule when *Vision and Voyages* was written.

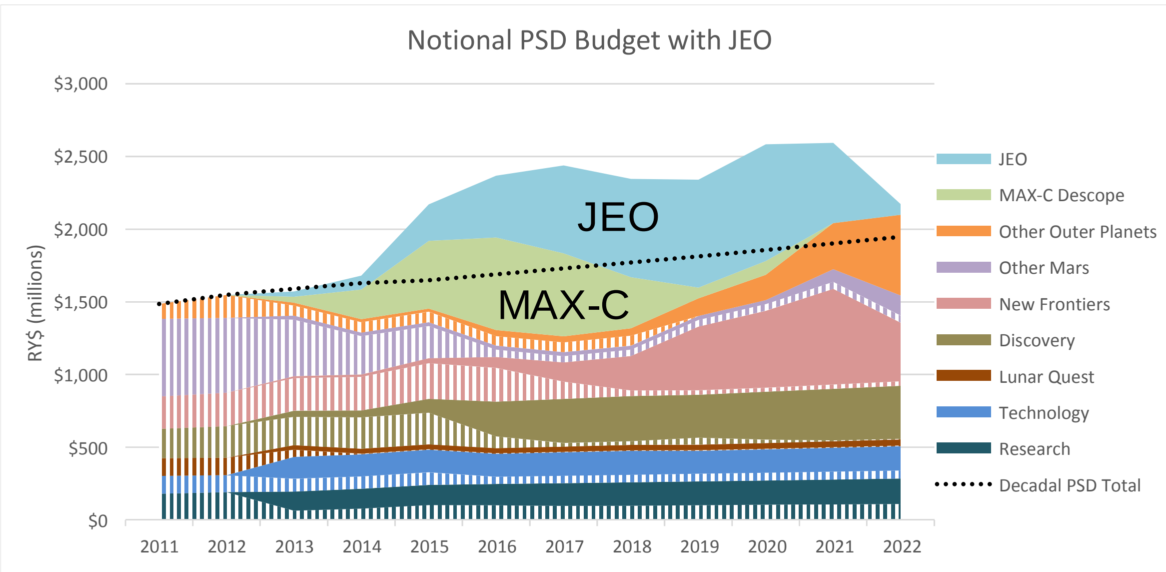

FIGURE 3.1 Budget outlook and assumptions from *Vision and Voyages* (NRC, 2011).

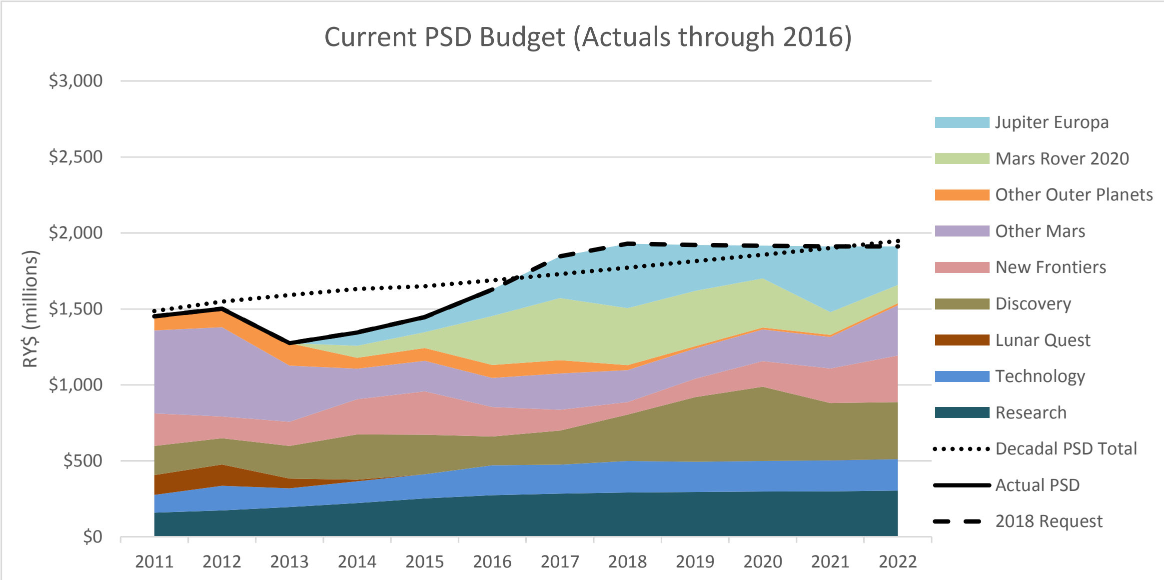

FIGURE 3.2 Budget outlook and assumptions from FY 2018 Budget Request (2017). This indicates real-year dollars.

R&A PROGRAMS AND TECHNOLOGY INVESTMENT

Vision and Voyages recommended an increase to the R&A budget "as multiple small grants" to "increase the number of ideas funded for planetary research and analysis." In particular, *Vision and Voyages* recommended that NASA increase the research and analysis budget for planetary science by 5 percent above the total finally approved FY 2011 expenditures in the first year of the coming decade, and increase the budget by 1.5 percent above the inflation level for each successive year of the decade.[1]

In 2017 the National Academies produced the report *Review of the Restructured Research and Analysis Programs of NASA's Planetary Science Division*. That report did not address funding levels, only whether the new structure mapped all the research.

So that the committee could assess NASA's response to the survey's recommendations, Planetary Science Division director Jim Green on two occasions presented to the committee on the levels of spending by PSD on research and analysis (R&A), technology, and infrastructure. These presentations were not granular enough to assess the *Vision and Voyages* recommendations, so the committee worked with analysts within PSD to develop a more rigorous analysis. This analysis was conducted using keyword searches within funded contracts and grants.

The most detailed analysis year is for FY 2016, where PSD has complete keyword assignment and program knowledge. The methodology and keyword definition was based on this year to fully illustrate the results of the keyword search and breakout process. Analysts chose multiple keywords for infrastructure and technology, both from a database and from talking with program managers, who may choose their own keywords. For any grant that has multiple keywords assigned, the amount awarded was apportioned equally among the keywords, so this analysis represents an overall aggregate rather than an accurate accounting within each grant. The funding by R&A, technology, and technology support and infrastructure, FY 2011-2016, is broken out in Table 3.1 based on data from NASA. Because programs have come and gone over the decade, some programs (such as Lunar Quest) that were phased out before FY 2016 contain only the bottom-line number rather than a fuller breakout, although even in these cases

[1] In 2017 the Space Studies Board produced the report *Review of the Restructured Research and Analysis Programs of NASA's Planetary Science Division*.

the split between technology, infrastructure, and R&A was done by keyword.[2]

A similar keyword analysis was then used to reach the overall research spending across the R&A portfolios. (See Table 3.2.) The majority of activities in this category are competed grant activities, or "small" grants to the research community through calls like NASA ROSES. This category also includes the NASA Astrobiology Institute (NAI) (but not the Solar System Exploration Research Virtual Institute [SSERVI]). NASA PSD facilities such as the Ames Vertical Gun Range (AVGR), Reflectance Lab (RELAB), GEER at Glenn Research Center, the Aeolian Facility at Ames, and support to the Lunar and Planetary Institute (LPI) are considered infrastructure and their funding is not counted in R&A in this report.[3] Similarly, other infrastructure investments like the Deep Space Network (DSN) and Planetary Data System (PDS) are not counted under R&A spending.

Because R&A and technology efforts are spread across PSD portfolios and funding lines, accurate spending numbers do not come from single program lines or Work Breakdown Structure (WBS) codes. The keyword search does a more accurate (although still not perfect) accounting. For example, some awards made through the PICASSO and MatISSE programs actually drew funding from the Icy Satellites Surface Technology portfolio. These awards were still considered competed R&A, but were paid out of a different Work Breakdown Structure. Another consideration is that research that is conducted as part of a competed mission—that is, by funded co-investigators on a mission team—is not included in this analysis; however, competed participating scientist programs are counted under R&A. Similarly, technology developed by individual missions is not counted in the technology total, but technology development funded by program offices in service of directed missions is counted (for example, the Mars Helicopter development).

The actual spending for R&A and technology as compared to the *Vision and Voyages* recommendations is shown in Table 3.3 and Figure 3.3.

R&A spending levels have risen 32 percent relative to FY 2011 spending levels, the year *Vision and Voyages* had budget information. This well exceeds the *Vision and Voyages* recommendation.

Finding: This analysis was challenging, since PSD does not track spending on R&A and technology in the way the decadal survey defined them. This can create misunderstandings within the science community.

Recommendation: NASA is largely following or exceeding the *Vision and Voyages*-recommended levels of R&A and technology spending. It should continue to make these critical investments.

Recommendation: The next decadal survey committee should work with NASA to better understand the categorization and tracking of the budget for each of the R&A program elements, specifically providing insight into the budget for (1) principal investigator (PI)-led, competed, basic research and data analysis; (2) ground-based observations; (3) infrastructure and management; and (4) institutional or field center support. Also, the next decadal survey should be unambiguous when stipulating programs and recommended levels of spending.

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[2] Neither the committee nor the reader has access to the NASA accounting system or the keywords they use. The committee asked NASA to do a breakout, and the method they chose was keyword analysis. Table 3.2 gives programs, not keywords. The committee does not have the list of keywords.

[3] In 2016 NASA's PSD performed a review of large facilities, how they are working, and the extent to which they serve the science needs of the broader planetary community; see https://www.lpi.usra.edu/psd-facilities/documentations-presentations/2015-16-Planetary-Facilities-Review-Web-Release.pdf.

TABLE 3.1 PSD Spending on R&A, Technology, and Technology Support and Infrastructure, FY 2011-2016

	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016
PSD Research and Analysis						
Research and Analysis	141.4	177.7	156.5	174.8	176.7	204.4
Technology Programs	21.1	18.0	19.6	18.4	21.4	18.2
R&A Subtotal	162.5	195.7	176.1	193.2	198.1	222.6
PSD Technology (see breakout below)						
Research and Analysis	21.1	18.0	19.6	18.4	21.4	18.2
Advanced Technology	73.5	97.0	63.2	40.6	20.1	53.1
Mars Exploration Program	2.5	5.0	4.0	4.0	7.0	23.1
Near Earth Object Observations				0.5	0.9	1.0
Europa / Outer Planets	0.0		16.2		17.4	7.4
Discovery Futures	2.3	19.2	1.5	29.3	8.1	9.8
New Frontiers					9.4	7.2
Lunar Quest	4.0	2.8	2.8			
Icy Satellite Technology						25.0
Technology Subtotal	**103.4**	**142.0**	**107.2**	**92.8**	**84.4**	**144.8**
PSD Technology Support and Infrastructure						
Planetary Science Program Support (for technology)	0.9	0.9	1.0	0.9	0.9	0.9
Radioisotope Power Systems Studies and Management (includes Launch Approval engineering)	8.0	15.8	15.2	11.8	8.2	6.6
Advanced Technology:						
Department of Energy—Infrastructure				51.5	57.4	55.8
Department of Energy Plutonium Supply Project*				13.8	16.2	16.2
Advanced Multi-Mission Operations System	31.7	35.2	35.1	33.7	35.4	35.8
Support and Infrastructure Subtotal	**40.6**	**51.9**	**51.4**	**111.7**	**118.1**	**115.3**
Metrics						
PSD Budget	1446.2	1435.4	1223.7	1345.7	1446.7	1619.7
R&A (%)	11.2%	13.6%	14.4%	14.4%	13.7%	13.7%
R&A change year over year		20.4%	–10.0%	9.7%	2.6%	12.4%
Technology (%)	7.2%	9.9%	8.8%	6.9%	5.8%	8.9%
Tech Support and Infrastructure (%)	2.8%	3.6%	4.2%	8.3%	8.2%	7.1%

*95% of this budget line item is being counted as infrastructure, while the remaining 5% is counted as technology (innovative process improvements),

TABLE 3.2 Technology Spending Broken Out by Funding Source (and Program for FY 2016)

	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016
Technology within the Research and Analysis Program						
PIDDP						0.3
MatISSE						3.2
PICASSO						8.6
PSTAR						2.4
MMAMA						0.2
ASTID						0.3
ASTEP						0.0
Planetary SERA						2.0
LARS						0.6
PDART						0.2
NAI						0.4
Subtotal	**21.1**	**18.0**	**19.6**	**18.4**	**21.4**	**18.2**
Technology within the Advanced Technology Program						
In-Space Propulsion						
Radioisotope Power Systems						18.6
DOE Plutonium Processing						0.9
Advanced Multi-Mission Operations System						1.2
Advanced Technology:						
Hot Operating Temperature Technology (HOTTech)						5.2
Simplex Technology:						0.3
Phenolic-Impregnated Carbon Ablator heat shield (PICA)						0.1
Gondola for High-Altitude Planetary Science (GHAPS)						0.5
Advanced Energy Conversion (AEC)						7.0
Near Earth Object Detectors						6.0
Mars Helicopter						6.5
Planetary Protection						0.3
Tech Planning/Studies						0.5
STMD Co-Funded:						
High-Performance Spaceflight Computing (HPSC)						1.3
Supersonic Parachute (SPEAR)						3.0
Heat-shield for Extreme Entry Environment Technology (HEEET)						1.0
Entry Systems Instrumentation (ESI)						0.2
In-Space Engine 100 lbf (ISE100)						0.3
Extreme Environment Solar Power (ESSP)						0.4
Subtotal	**73.5**	**97.0**	**63.2**	**40.6**	**20.1**	**53.1 0**
Technology within the Mars Program						
Helicopter						3.0
Mars Program Office Transfer for Break-the-Chain						0.5
Mars Ascent Vehicle (MAV)						12.0
Parachute						2.6
Base Research (Base)						5.0
Subtotal	**2.5**	**5.0**	**4.0**	**4.0**	**7.0**	**23.1**
Technology within Europa / Ocean Worlds Programs						
Surface Sampling Systems						3.2
Power Storage						0.5
Intelligent Landing Systems						3.6
Planetary Protection Study						0.1
Subtotal	**0.0**	**0.0**	**16.2**	**0.0**	**17.4**	**7.4**

	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016
Technology within the Discovery Program						
NASA's Evolutionary Xenon Thruster Commercial (NEXT-C)						2.9
Heat-shield for Extreme Entry Environment Technology (HEEET)						0.0
Deep Space Optical Communications						0.6
Hall Thruster and Power Processing Unit						0.4
Gondola for High-Altitude Planetary Science (GHAPS)						3.9
CubeSats (LunaH-Map, MarCO)						2.0
Subtotal	**2.3**	**19.2**	**1.5**	**29.3**	**8.1**	**9.8**
Technology within the New Frontiers Program						
Sample Tech for Comet Surface Sample Return						0.9
Sample Tech for Advanced Pointing Imaging Camera						1.2
Navigation Doppler Lidar Sensor						0.8
Atmospheric Constant Exploration Systems for Planetary Probes						1.0
Tunable Laser Spectrometer for Saturn Probe and Venus In Situ Explorer Concepts						0.9
Planetary Object Geophysical Observer for Asteroid Exploration						0.8
Micro-electrical Mechanical Systems Micro-concentrator for Low-Intensity Low-Temperature Photovoltaics						1.0
Venus Entry Probe Prototype						0.5
Subtotal	**0.0**	**0.0**	**0.0**	**0.0**	**9.4**	**7.2**
Technology within the Icy Satellite Program						
Concepts for Ocean Worlds Life Detection Technology (COLDTech)						20.9
Planetary Science and Technology from Analog Research (PSTAR)						4.1
Subtotal	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**25.0**

TABLE 3.3 Spending for R&A and Technology as Compared to *Vision and Voyages*

	FY 2011	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	FY 2018
PSD budget ($ millions)	1446.2	1435.4	1223.7	1345.7	1446.7	1619.7	1846.0	2228.0
U.S. inflation rate*	—	2.1%	1.5%	1.6%	0.1%	1.3%	2.1%	1.5%
R&A—5% over 2011 for FY 2012 and 1.5% over inflation after that								
Decadal recommended ($ millions)	—	170.6	175.8	181.3	184.2	189.4	196.2	202.2
Actual spending ($ millions)	162.5	195.7	176.1	193.2	198.1	222.6	—	—
Spending as a % of PSD budget	11.2%	13.6%	14.4%	14.4%	13.7%	13.7%		
Technology—6% to 8% of PSD budget								
Decadal recommended ($ millions)	—	86.1-114.8	73.4-97.9	80.7-107.7	86.8-115.7	97.2-129.6	110.8-147.7	133.7-178.2
Actual spending ($ millions)	103.4	142.0	107.2	92.8	84.4	144.8	—	—
Spending as a % of PSD budget	7.2%	9.9%	8.8%	6.9%	5.8%	8.9%		

*From the Bureau of Labor Statistics.

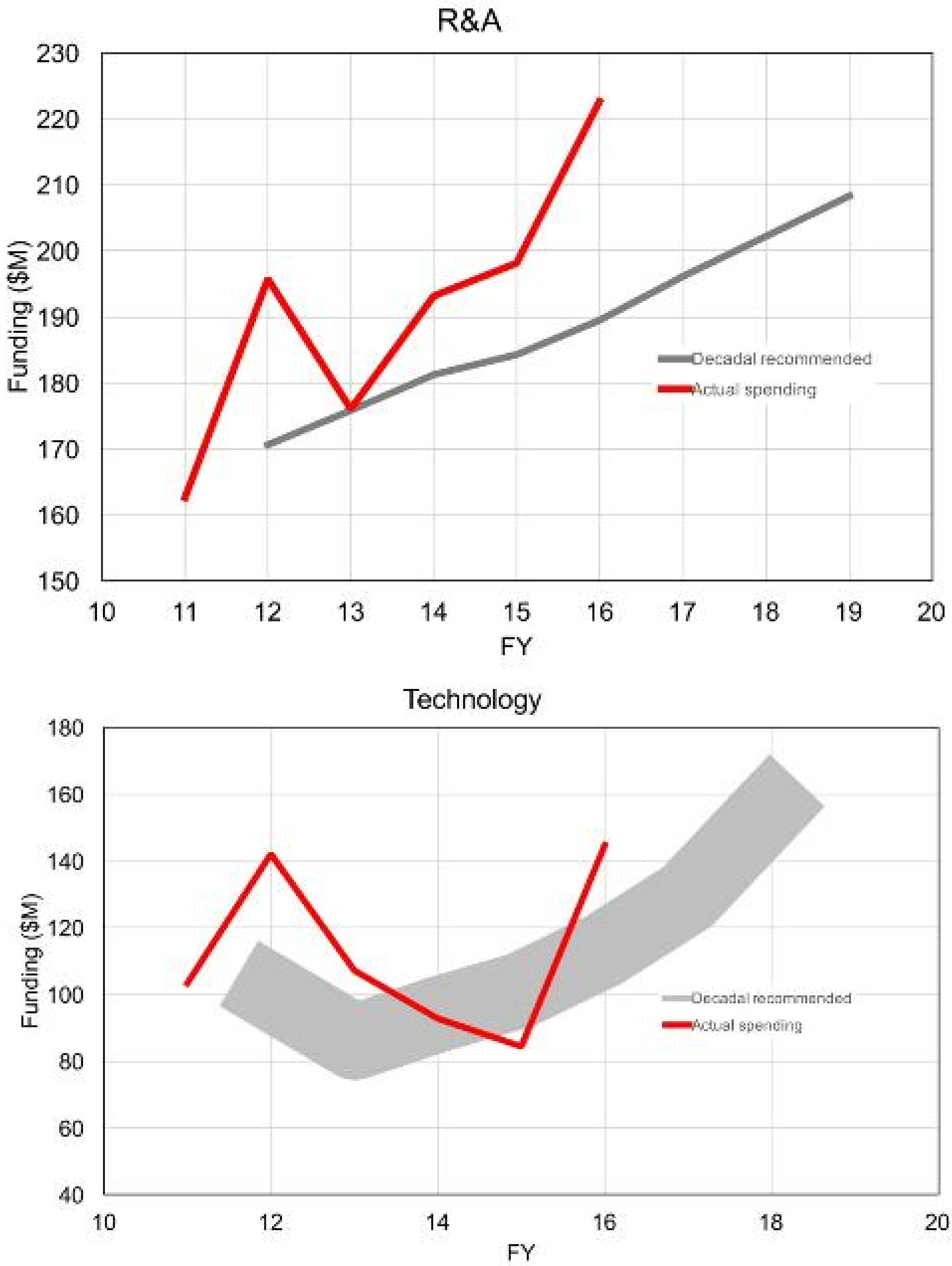

FIGURE 3.3 Actual spending levels for R&A and technology compared with the recommended levels from *Vision and Voyages* (NRC, 2011).

PROGRAMMATIC BALANCE (AMONG MISSION CLASSES)

Decadal Findings: *Vision and Voyages* identified key themes in planetary science to guide the selection of missions in the planetary program:

- Building new worlds—understanding solar system beginnings;
- Planetary habitats—searching for the requirements for life; and

- Workings of solar systems—revealing planetary processes through time.

Advances in meeting these objectives were shown to require a mix of missions varying in scale, cost, and complexity. *Vision and Voyages* emphasized the importance of balancing the program not only in the area of mission size and cost, but also in terms of the selection of target bodies and scientific questions addressed. It stated: "NASA's suite of planetary missions for the decade 2013-2022 should consist of a balanced mix of Discovery, New Frontiers, and flagship missions, enabling both a steady stream of new discoveries and the capability to address larger challenges like sample return missions and outer planet exploration." The recommended program was designed to achieve such a balance. Specific medium and large missions were identified and prioritized. Targets of special interest for small missions were identified in the report, but *Vision and Voyages* stated that NASA should continue the competitive Discovery program.

The *Vision and Voyages* committee was required to conduct an independent cost estimate of all large missions (both flagships and New Frontiers) in the report. The cost and technical evaluation (CATE) process was specifically designed to address this issue by taking a realistic approach to cost estimation and the technical maturity of the proposed missions. *Vision and Voyages* also emphasized the importance of an appropriate balance among the many potential targets in the solar system. Achieving this balance was one of the key factors that went into the recommendations for medium and large missions. The decadal committee noted that there should be no entitlement in a publicly funded program of scientific exploration. It further noted that achieving balance must not be used as an excuse for avoiding difficult but necessary choices. The decadal committee's recommendation implicitly assumed that Discovery missions would address important questions that do not require medium or large missions.

Four criteria were recommended in *Vision and Voyages* to evaluate the missions to be flown. The first and most important was science return per dollar. Science return was judged with respect to the key scientific questions, and costs were estimated using a CATE study. The second criterion was programmatic balance, striving to achieve an appropriate balance among mission targets across the solar system and an appropriate mix of small, medium, and large missions. The other two criteria were technological readiness and availability of trajectory opportunities within the 2013-2022 time period.

For the large mission (flagship) category, all of the options under consideration proved to be of a higher cost than originally anticipated. The highest priority was a Mars rover mission (then called MAX-C, now called Mars 2020); a first step in the return of samples from Mars, but with a mission architecture that was derived from the Mars Science Laboratory (MSL)/Curiosity mission. This recommendation was contingent on reducing the cost to $2.5 billion FY 2015 (the original CATE estimate was $3.5 billion)—the current Mars 2020 budget is ~$2.5 billion. This mission was conceived to have significant scientific return in addition to being the first step in a campaign to return samples, but it also meant an implicit commitment beyond the time frame of the decadal survey.

The second priority flagship was a Europa orbiter mission (then called the Jupiter Europa Orbiter), but here too, the choice was contingent on the development of a mission design that was much reduced in cost from the original concept, which the CATE estimated at $4.7 billion, and new money had to be found. This mission, no longer an orbiter but a multiple-flyby mission, has now become the Europa Clipper, which achieves many but not all of the science goals identified for the Jupiter Europa Orbiter mission.

Vision and Voyages emphasizes that the gas giants, Uranus and Neptune, are of great scientific interest but have received little attention in the NASA planetary program. The scientific importance of these bodies calls for additional investigation such as could be achieved by a third flagship class mission, a Uranus Orbiter and Probe. Thus a mission to an ice giant would be central to revealing planetary processes through time and understanding solar system beginnings.

Two further targets for flagship class missions are discussed in *Vision and Voyages*: an Enceladus Orbiter and a Venus Climate mission, even though *Vision and Voyages* did not envision commencement of additional flagship missions in this decade. The Planetary Science Division responded to the suggestions in *Vision and Voyages* concerning a Venus mission by creating a science definition team jointly with the Russian Space Agency. This type of preliminary study is most appropriate in planning for the large missions of the next decade and encourages continued study of possible mission architectures.

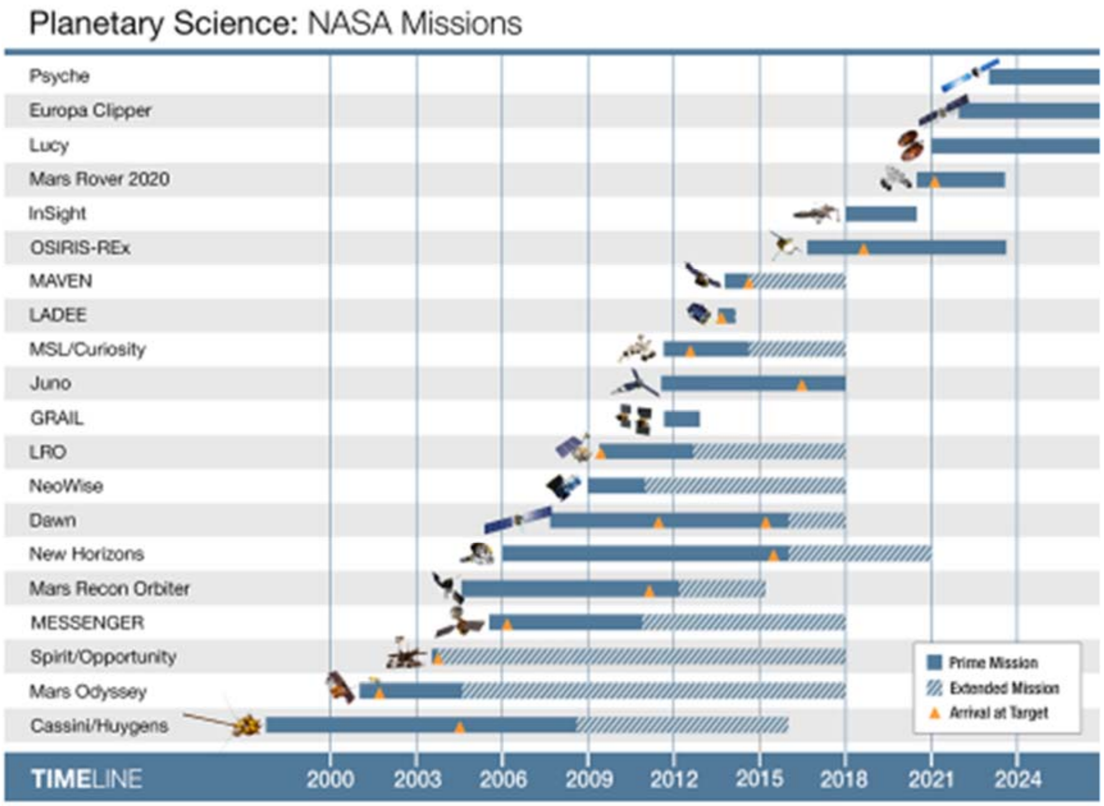

FIGURE 3.4 Planetary missions active, in development, or recently completed. MESSENGER, Dawn, Kepler, and GRAIL are Discovery-class missions (neither MESSENGER nor GRAIL are still active). New Horizons and Juno are New Frontiers missions; Cassini is a flagship mission. SOURCE: NASA.

Assessment: NASA's current portfolio of missions is shown in Figure 3.4. Considerable progress has been made toward meeting the large mission goals of the *Vision and Voyages*. The Mars 2020 rover represents the first step in the goal of Mars sample return, as described in Chapter 5. The Europa Clipper mission has been de-scoped from the mission concept envisaged at the time of *Vision and Voyages*, and funding has been allocated for this mission. A Uranus Orbiter and Probe mission has yet to be initiated; however, NASA has carried out a study on a mission to the ice giants, as described later in this chapter.

NASA announced two Discovery calls (June 2010 and November 2014; another is expected in ~February 2019) and one New Frontiers call (December 2016). Over that time period, NASA initiated one New Frontiers mission (OSIRIS-REx), and three Discovery missions (InSight, Lucy, and Psyche, although InSight was part of the previous decadal survey period), as well as selecting Comet Astrobiology Exploration Sample Return (CAESAR) and Dragonfly as New Frontiers finalists. (See Figures 3.5 and 3.6.)

Finding: NASA has initiated several missions in the last 5 years that respond to the *Vision and Voyages* priorities (Europa Clipper, Mars 2020, OSIRIS-REx, Lucy, Psyche, and InSight). However, the recommended balance across the solar system and among mission classes has not been fully achieved. This lack of balance undermines the compelling comparative planetology investigations recommended by the decadal survey, particularly for the terrestrial planets. The discovery of numerous Earth-size and

Neptune-size exoplanets provides even greater urgency to initiate new missions to Venus and the ice giants.

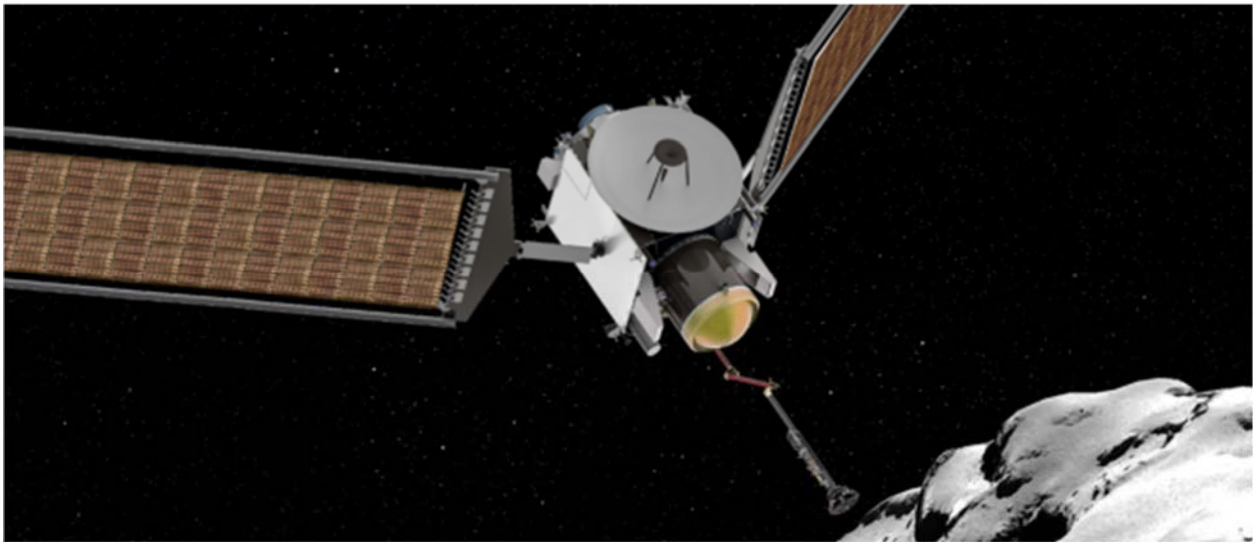

FIGURE 3.5 Artist concept of CAESAR spacecraft. SOURCE: NASA.

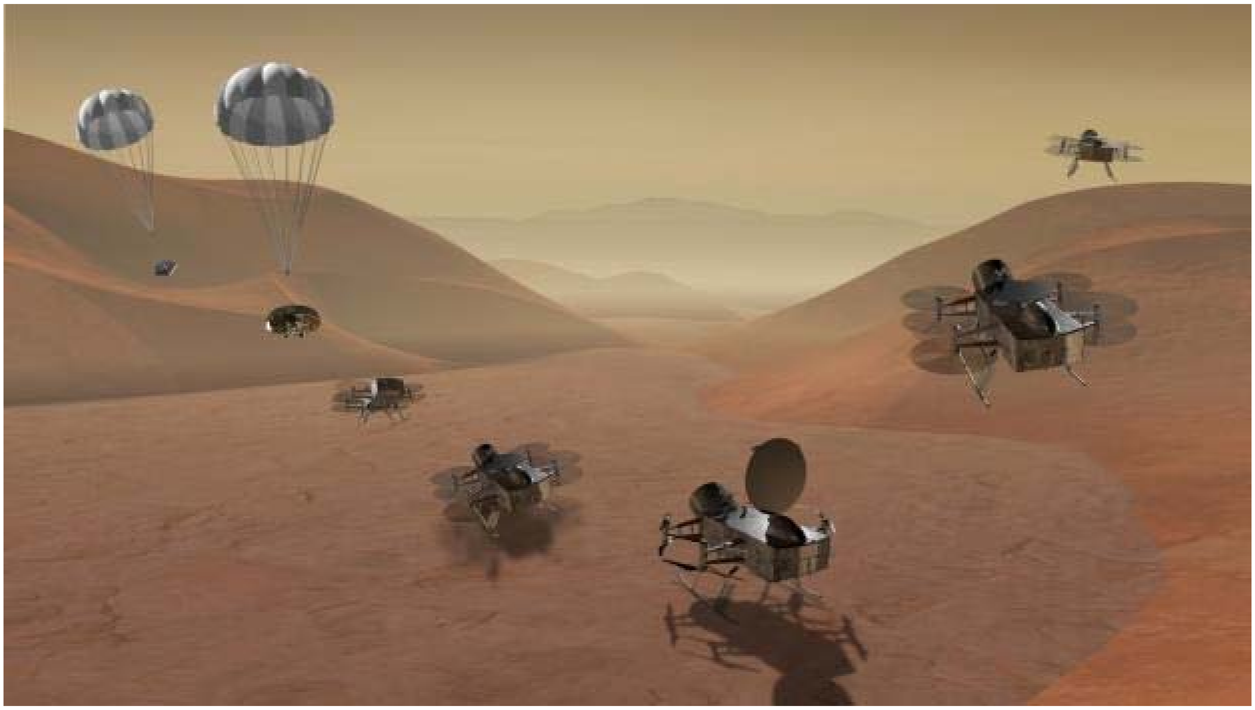

FIGURE 3.6 Concept image of Dragonfly. SOURCE: NASA, "NASA Invests in Concept Development for Missions to Comet, Saturn Moon Titan," December 20, 2017; courtesy of NASA.

DISCOVERY MISSIONS

Decadal Findings: *Vision and Voyages* concluded that there is much compelling science that can be addressed by small (Discovery class) missions, and recommended continuation of the Discovery program at its then-current level, adjusted for inflation, with a cost cap per mission that is also adjusted for inflation from the current value (i.e., to about $500 million in fiscal year [FY] 2015). The survey recommended a regular, predictable, and preferably rapid (≤24 month) cadence for release of Discovery announcements of opportunity (AOs) and for selection of missions. *Vision and Voyages* also recommended that NASA continue to allow proposals for Discovery missions to all planetary bodies including Mars. It further recommended that future Discovery AOs allow proposals for space-based telescopes, and that planetary science from space-based telescopes be listed as one of the goals of the Discovery program. Finally, the decadal survey noted that Missions of Opportunity provide a chance for new entrants to join the field, for technologies to be validated, and for future PIs to gain experience, and welcomed the introduction of the highly flexible SALMON approach. It recommended that this be used wherever possible to facilitate Mission of Opportunity collaborations.

Assessment: Around the time of the *Vision and Voyages* report, an AO was released in June 2010 that resulted in the InSight selection in August 2012. The InSight launch was originally planned for March 2016, but delayed to May 2018. In late 2016 NASA indicated that this delay cost NASA ~$153 million, an overrun that impacted the overall program. The Planetary Science Division released the next Discovery announcement of opportunity on November 5, 2014, four years after the last AO (2010) release. (See Figure 3.7.)

FIGURE 3.7 InSight with wings out for solar array test. SOURCE: NASA, "InSight Lander Solar Array Test," January 23, 2018, https://mars.nasa.gov/insight/multimedia/images/2018/insight-lander-solar-array-test; courtesy of Lockheed Martin Space.

As recommended by the decadal survey, this AO allowed all solar system bodies, except Earth and the Sun, and did not restrict the type of complete mission to be proposed, although it did not list space-based telescopes as one of the goals of the Discovery program as recommended in *Vision and Voyages*. The AO cost cap was $450 million in FY 2015 dollars for phases A though D, not including the cost of the Expendable Launch Vehicle (ELV) or the value of any contributions. Phase E and F costs are no longer under the AO cost cap. This AO approach meets the recommendations of the decadal survey for the cost of future Discovery missions.

Two missions were selected from this 2014 AO for flight, Lucy and Psyche. Lucy will explore six Jupiter Trojan asteroids trapped by Jupiter's gravity in two swarms that share the planet's orbit, one leading and one trailing Jupiter. Lucy is scheduled to launch in October 2021, arrive at its first destination, a main belt asteroid, in 2025, and continue science investigations until 2033. The Psyche mission will explore a large metal asteroid, known as 16 Psyche. This asteroid is thought to be composed mostly of metallic iron and nickel, and could be an exposed core of an early planet that could have been as large as Mars, but that lost its rocky outer layers due to violent collisions billions of years ago. Psyche is targeted to launch in October 2023, arriving at its target in 2030. (See Figures 3.8 and 3.9.)

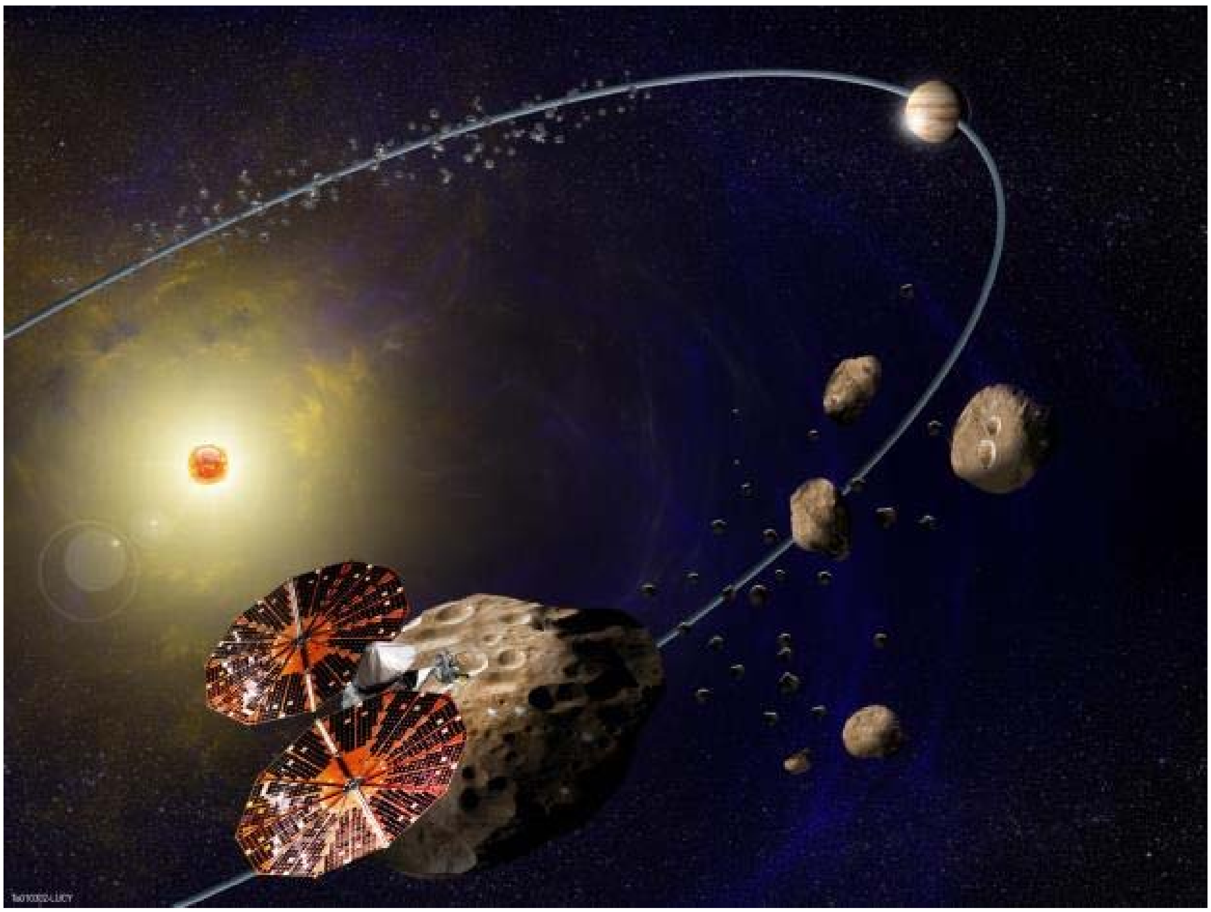

FIGURE 3.8 Concept image of Lucy visiting asteroids. SOURCE: NASA, "NASA Selects Mission to Study Jupiter's Trojan Asteroids," January 4, 2017, https://www.nasa.gov/feature/goddard/2017/nasa-selects-mission-to-study-jupiter-s-trojan-asteroids; courtesy of Southwest Research Institute.

FIGURE 3.9. Concept image of the Psyche mission. SOURCE: NASA Jet Propulsion Laboratory, "Artist's Concept of Psyche Spacecraft with Five-Panel Array," PIA21499, https://photojournal.jpl.nasa.gov; courtesy of NASA/JPL-Caltech/Arizona State University/Space Systems Loral/Peter Rubin.

In addition to selecting the Lucy and Psyche missions for formulation, the agency will extend funding for the Near Earth Object Camera (NEOCam) project for an additional year. The NEOCam space telescope is designed to survey regions of space closest to Earth's orbit, where potentially hazardous asteroids may be found.

Discovery AOs were released in 1994, 1996, 1998, 2000, 2004, 2006, 2010, and 2014, with the next AO planned for 2019. Twelve missions have been selected from these AOs to date. Since the first two missions were directed, 14 Discovery missions have been approved for an overall program average of 1 mission every 24 months—the recommended average in *Vision and Voyages*. While this is overall a good record, the recommendation in *Vision and Voyages* was created because the AO releases in the previous decade did not meet the targeted 24-month cadence, and in the present decade the rate will also not meet that recommended by the decadal survey. Because of the high investment required to prepare and review Discovery proposals, the rate of mission selection and launch may be considered as a proxy for the Discovery AO release, particularly in the 2014 round, where two missions (Lucy and Psyche) were selected, to enable a healthier Discovery portfolio. However, there will only be two selection rounds and three launches in this decade, including Psyche's launch in 2023. The reduced pace of Discovery AOs in this decade was driven by the reductions to the Planetary Science Division's budget in the early part of this decade, coupled with the focus on initiating two flagship-class missions. Additional funding was added to the PSD budget in more recent years. Since the funding situation has improved, the planned release of the next AO in 2019 works toward restoring the Discovery rate of announcements and flight.

Finding: NASA's decision to eliminate phase E funding and launch vehicle cost from the Discovery AO has been enabling for missions to the outer solar system.

Finding: Although two Discovery missions were selected from the 2014 AO, the next AO will not be issued until 2019. NASA will not have met the *Vision and Voyages* goal of a Discovery AO release every 24 months unless three missions are selected from the two potential future AOs.

Recommendation: NASA should issue Discovery announcements of opportunity (AOs) at the *Vision and Voyages* recommended cadence of ≤24 months, recognizing that an AO that selects two missions would count as two AOs for the purpose of meeting the *Vision and Voyages* recommendation. To approach meeting the *Vision and Voyages* recommendation, NASA should select three missions from AOs issued in 2019 and 2021.

In order to minimize the stress on the community, NASA could stagger New Frontiers and Discovery AOs.

MEDIUM (NEW FRONTIERS) MISSIONS

Decadal Findings: At the time of the survey, two medium (New Frontiers) missions were under way (New Horizons to Pluto and beyond, and Juno to Jupiter) and a third had not yet been announced; OSIRIS-REx, an asteroid sample return mission, was subsequently chosen.

Vision and Voyages recommended medium-class mission decision rules to achieve an appropriate balance among small, medium, and large missions, and that NASA should select two New Frontiers missions in the decade 2013-2022. The decadal survey committee's statement of task called for a list of specific mission objectives for these New Frontiers missions. On the basis of their science value and projected costs, the committee identified seven candidate New Frontiers missions for the decade 2013-2022, with no priority among them: Comet Surface Sample Return; Io Observer; Lunar Geophysical Network; Lunar South Pole-Aitken Basin Sample Return; Saturn Probe; Trojan Tour and Rendezvous; and Venus In Situ Explorer.

The decadal survey chose five candidates for the New Frontiers 4 opportunity with no relative priority: Comet Surface Sample Return; Lunar South Pole-Aitken Basin Sample Return; Saturn Probe; Trojan Tour and Rendezvous; and Venus In Situ Explorer. The decadal survey also recommended that the list for the New Frontiers 5 selection be augmented by adding two more missions, Io Observer and Lunar Geophysical Network.

In addition, the survey proposed a modest but significant change to the cost cap for this class of mission by adjusting the cost cap to $1.0 billion FY 2015, excluding launch vehicle costs.

Assessment: The Planetary Science Division released the New Frontiers 4 (NF4) announcement of opportunity on December 9, 2016. This AO called for proposals that address at least one out of any of the six mission themes listed here

- Comet Surface Sample Return,
- Lunar South Pole-Aitken Basin Sample Return,
- Ocean Worlds (Titan and/or Enceladus),
- Saturn Probe,
- Trojan Tour and Rendezvous, and

- Venus In Situ Explorer.

This list differed from the survey by adding a new category, Ocean Worlds (Titan and/or Enceladus), that was not included in the survey's original list. Prior to including the new category in the NF4 solicitation, the director of PSD sought the advice of the National Academies Committee on Astrobiology and Planetary Science (CAPS). CAPS cannot make recommendations to NASA and did not endorse this addition to New Frontiers 4.[4] No changes to the New Frontiers 4 solicitation were made as a result of prior National Academies reports.[5]

Proposals from this solicitation were reviewed by NASA, and in December 2017 NASA selected two missions to go into the step 2 of the New Frontiers 4 competition. One selection, Comet Astrobiology Exploration Sample Return (CAESAR), is designed to return a sample from the comet visited by Rosetta, 67P/Churyumov-Gerasimenko. The second selection, Dragonfly, proposes to explore Titan's prebiotic chemistry and habitability with a drone-like rotorcraft. The down selection to one mission will occur in 2019. NASA also provided technology development funds for spacecraft contamination techniques for the Enceladus Life Signatures and Habitability (ELSAH) mission, as well as for the Venus Element and Mineralogy Camera from the Venus In situ Composition Investigations (VICI) mission proposal for further study.

The 2016 AO increased the cost cap to $850 million, not including the launch vehicle, contributions, and phases E and F—similar to the approach used for the 2014 Discovery mission AO. Comparing the survey's recommended $1 billion versus this $850 million is difficult because the operations costs in phase E can vary widely depending on the length of the mission operations.

The survey recommended that two missions be selected in this decade. The next New Frontiers announcement of opportunity is now planned for 2023, so the Planetary Science Division will not achieve the recommended rate proposed by the survey. As with the Discovery program, this was partially attributable to the budget cuts that were imposed on PSD during the early part of the decade. PSD has stated that its objective is to have two New Frontiers missions each decade, and the current budget forecast looks like this is achievable. Final selection for New Frontiers 4 is planned for July 2019.

The *Vision and Voyages* New Frontiers mission list included a Trojan tour and rendezvous mission as one of the options for New Frontiers mission proposals. In 2017 NASA selected a Discovery class mission, Lucy, to conduct a tour of the Trojan asteroids. Lucy will address some but not all of the objectives of the Trojan Tour and Rendezvous mission as described in *Vision and Voyages*. Its visible imaging, shortwave infrared (SWIR) spectroscopy, and thermal infrared imaging investigations address the geologic, spectral reflectance, and surface textural investigations for Trojan Tour and Rendezvous. The radio science and imaging experiments together will constrain density. Trojan Tour and Rendezvous would have used measurements of elemental abundances, of key major and minor elements including hydrogen, as a primary constraint on Trojan asteroid origins. The absence of such measurements from Lucy may leave key Trojan science questions—origin and volatile content—open to future investigation.

Finding: New Ocean Worlds targets were introduced into the New Frontiers 4 call. This addition to the list of allowed New Frontiers missions was made outside the decadal survey process. While the Outer Planets Assessment Group (OPAG) supported the addition, the Lunar Exploration Analysis Group

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[4] However, the CAPS co-chair reported the principal messages he received from the CAPS membership to the Space Studies Board and stated that "Enceladus and Titan are significant elements of the decadal survey, and their inclusion is consistent with the overall scientific priorities discussed in the survey report."

[5] In 2007 the National Academies produced the report *New Opportunities in Solar System Exploration: An Evaluation of the New Frontiers Announcement of Opportunity*, which evaluated options prior to the release of NASA's New Frontiers 3 announcement of opportunity. The decadal survey committee was aware of the National Academies report while writing *Vision and Voyages*. However, the recommendations of the 2007 report were not intended to apply to future New Frontiers opportunities. The only National Academies-recommended missions for New Frontiers 4 and 5 are the ones in the *Vision and Voyages* report. No changes to the New Frontiers 4 solicitation were made in response to Academies reports.

(LEAG), Small Bodies Assessment Group (SBAG), Venus Exploration Analysis Group (VEXAG), and Mars Exploration Analysis Group (MEPAG) did not support this change (as per presentations to this committee). Such a process could undermine the scientific priorities of the decadal survey and community support for them.

Finding: The pace of New Frontiers class missions is behind the recommended cadence of 2 per decade, with only 1 mission likely this decade.

Finding: Given the current cadence for New Frontiers, the New Frontiers 5 call may occur while the next decadal survey is under way, but both Lunar Geophysical Network and Io Volcanic Observer were recommended by *Vision and Voyages* for New Frontiers 5 and the committee believes they still remain valid missions for New Frontiers 5.

Recommendation: NASA should issue the New Frontiers 5 announcement of opportunity as soon as possible, but at a minimum release the announcement of opportunity no later than five years after the issuance of the New Frontiers 4 announcement of opportunity (i.e., December 2021).

Recommendation: If scientific discoveries or external factors compel NASA to reassess decadal survey priorities, such as the list of New Frontiers missions, NASA should vet these changes via CAPS, and allow for input from the community via assessment and analysis groups as time permits.

LARGE (FLAGSHIP) MISSIONS

Europa Clipper

Decadal Findings: *Vision and Voyages* named a Europa orbiter mission as its second priority flagship but deemed the $4.7 billion cost of the Jupiter Europa Orbiter (JEO) mission concept that NASA had developed to be unaffordable given the expected budget profile. JEO was conceived as one component of the Europa Jupiter System Mission (EJSM). The other component was ESA's Jupiter Ganymede Orbiter (JGO); this spacecraft subsequently morphed into the Jupiter Icy Moons Explorer (JUICE) mission. The original JEO mission profile would have taken the spacecraft into the Jovian system for 30 months of measurements of the Jupiter atmosphere, rings, and environment, as well as the larger Galilean satellites, Io, Ganymede, and Callisto, before entering Europa orbit for approximately nine months. Once in orbit the spacecraft would have carried out a number of detailed geophysical, geological, and particles and fields measurements. JEO would also have carried out synergistic measurements with the JGO spacecraft, expected to be carrying out its mission in the Jupiter system at the same time. The survey directed NASA to develop a mission design that was much reduced in cost from the original concept, and to find new money to fund the mission.

Assessment: In order to meet the first challenge of bringing the cost down, a new mission was developed in which the science return was scaled back such that the Jupiter system science was entirely eliminated, and the mission trajectory modified such that the spacecraft no longer enters orbit about Europa. Instead it orbits Jupiter, and encounters Europa multiple times over a ~3-year period, making over 40 close flybys of the surface. The new trajectory enables global coverage of Europa to be built up over the course of the mission, and has the benefit of enabling the spacecraft to dip in and out of the Jovian magnetosphere, which slows the effects of radiation damage, thereby prolonging the lifetime of the spacecraft. This approach preserves much of the JEO Europa science proposed to the decadal—estimates from the project science office are 73 percent—but the major loss is to the geophysical science objectives; without being in orbit it is challenging to establish the interior structure of Europa. In addition, all the Jupiter system and other Galilean satellite science has been completely deleted from the mission concept (but Europa, Ganymede, and Callisto will be studied by JUICE, which has some U.S. participation). The proposed cost of this mission is ~$3.1 to $4 billion, including launch vehicle.[6]

The second challenge given to the Europa mission by *Vision and Voyages* was that new funding had to be secured, since the worst-case funding scenario analyzed could not accommodate a Mars sample return mission as well as a Europa flagship mission. This has also been accomplished; the Europa Clipper mission has received strong congressional support and moved into Phase A in June 2016. Preliminary Design Review (PDR) is planned for August 2018 and Confirmation Review is scheduled for October 2018, after which more firm cost estimates for the project will become available.[7]

Finding: Europa was called out as a very high priority target in the last two planetary decadal surveys because of its high astrobiological potential. The Europa Clipper concept currently in phase B is reduced in cost from the Jupiter Europa Orbiter mission that was proposed to *Vision and Voyages*. New funding has been allocated by Congress for this mission. This committee finds that the Europa Clipper mission addresses most of the recommendations laid out by *Vision and Voyages*. (See Figure 3.10.)

Recommendation: NASA should continue to closely monitor the cost and schedule associated with the Europa Clipper to ensure that it remains executable within the approved life cycle cost (LCC) range approved at Key Decision Point-B (KDP-B) without impacting other missions and priorities as defined by the decision rules in *Vision and Voyages* (p. 36). If the LCC exceeds this range, NASA should de-scope the mission in order to remain consistent with the *Vision and Voyages* decision rules.

[6] GAO (2018, p. 49) also notes the following: "This estimate is preliminary, as the project is in formulation and there is uncertainty regarding the costs associated with the design options being explored. NASA uses these estimates for planning purposes."

[7] GAO (2018, p. 24) also notes the following: "The Europa Clipper project implemented a process whereby cost growth threats would be offset by de-scoping instruments in whole or in part. For example, if an instrument exceeds its development cost by 20 percent, the project would propose a de-scope option to NASA that brings instrument cost below that threshold. NASA has not de-scoped any instruments to date."

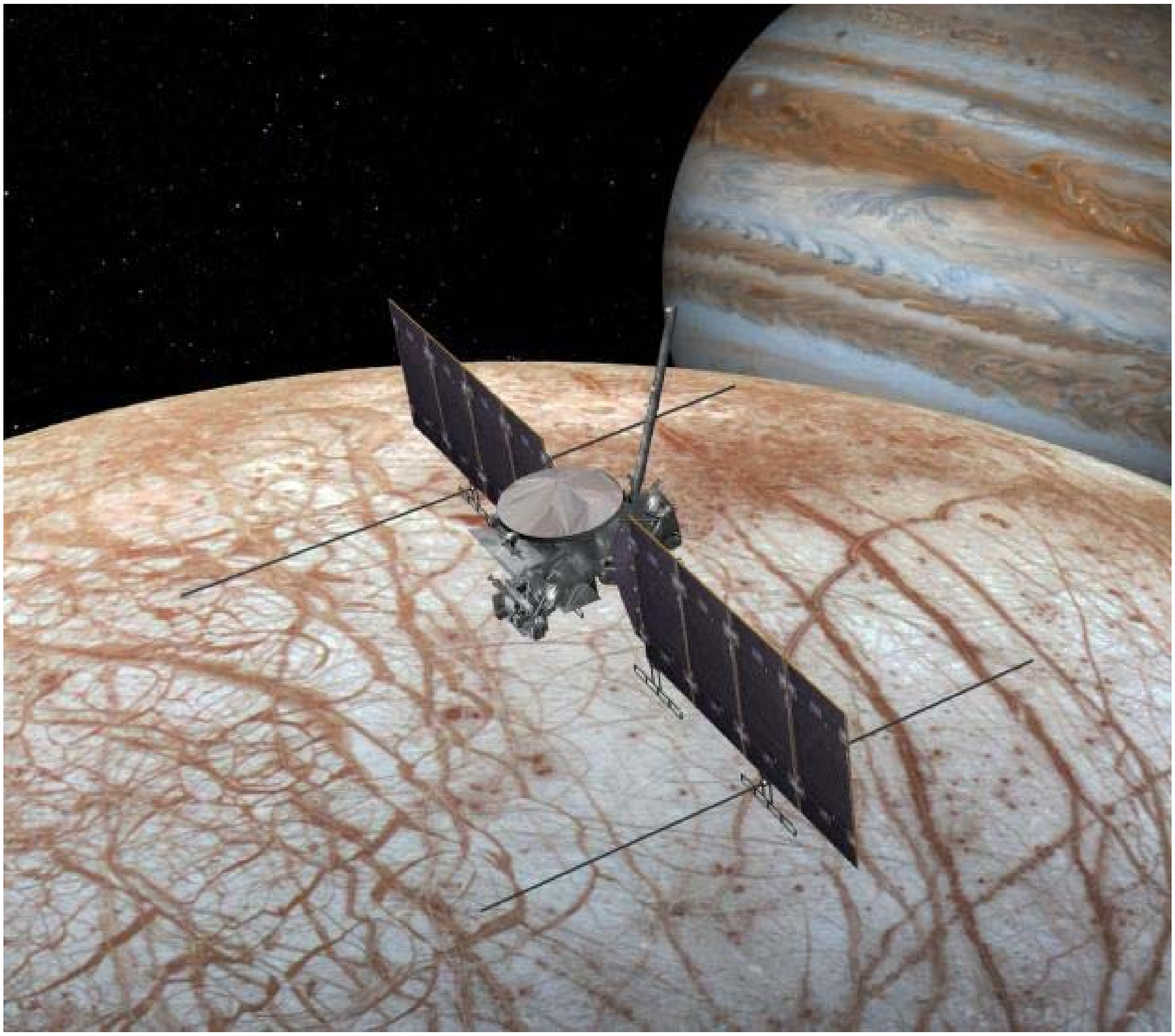

FIGURE 3.10 Artist concept of Europa clipper in action. SOURCE: NASA, "Europa Clipper Spacecraft (Artist's Concept)," PIA20025, April 20, 2016, https://photojournal.jpl.nasa.gov; courtesy of NASA/JPL-Caltech.

Europa Lander

NASA is currently studying a Europa Lander, the primary goal of which would be to search for evidence of habitability and potential biosignatures, for which in situ surface measurements will be required. The lander would launch after the Europa Clipper, which is designed to determine whether Europa is a habitable world and should be helpful in identifying landing sites.

Decadal Findings: *Vision and Voyages* notes the importance of searching for contemporary habitats elsewhere in the solar system with the necessary conditions conducive to life, and noted that a lander would probably be required to fully characterize organics on the surface of Europa. *Vision and Voyages* states that in situ measurements could help determine whether the isotope ratios of carbon, hydrogen, oxygen, and nitrogen in volatiles on Europa's surface are indicative of internal processing or resurfacing. Regarding the question of life, *Vision and Voyages* notes that: "A key future investigation of the possibility of life on the outer planet satellites is to analyze organics from the interior of Europa. Such analysis requires either a lander in the far term or the discovery of active Enceladus-style venting, which would allow analysis from orbit with a mission started in the next decade."

In 2016 JPL produced the "Europa Lander Study 2016" report, which underwent a Mission Concept Review in June 2017. Dr. Thomas Zurbuchen, NASA associate administrator for the Science Mission Directorate (SMD), then directed JPL to convene a team to explore additional architecture options for a potential Europa Lander. That team re-scoped the science and mission design. The planetary midterm committee heard briefings about the lander during its study, and in June 2018 the committee contacted the head of NASA's Planetary Science Division and asked for the latest releasable information on the Europa lander study and any releasable cost estimate. In response, NASA provided a 5-page summary of the Europa lander architecture representing the latest information, and indicated that there is no releasable cost estimate for the mission concept.[8] The midterm committee, although it lacks an official cost estimate, believes the mission cost to be in the multiple billions of dollars range.

Finding: NASA is currently working to define the scientific goals and assess the feasibility of implementation, the mission concept, and the estimated cost of a Europa lander.

Finding: A lander was not prioritized within the previous decadal survey (*Vision and Voyages*).

Recommendation: As a prospective flagship mission, the results of the NASA Europa lander studies should be evaluated and prioritized within the overall PSD program balance in the next decadal survey.

Ice Giants

Decadal Findings: *Vision and Voyages* outlined nine prioritized science objectives for an ice giant mission including an orbiter and atmospheric probe. In a mission concept study performed in support of the decadal survey, all of these objectives were addressed to some extent using a scientifically broadly based complement of small, high-heritage instruments based on successful, previously flown instrumentation.

Assessment: In 2015 NASA commissioned an *Ice Giants Predecadal Study Report* (delivered in 2017), to take a fresh look at science priorities and concepts for missions to the Uranus or Neptune system. The study team developed 12 science objectives, of which 2 were identified as higher priority. Compared to *Vision and Voyages*,

- Internal convection was identified as a new, high-priority objective;
- Study of the large and small moons was subdivided into several objectives, placing greater emphasis on characterization of the structure, origin, and composition of smaller moons, mass transport between moons, and the origin and evolution of organic compounds on the moons; and
- Investigation of clouds as a function of depth was dropped.

The core recommended payload complement meeting a $2 billion cost cap was nearly the same mass as with the *Vision and Voyages* ice giants mission study (50 vs. 55 kg), but was reduced to only two remote instruments (a Doppler imager for seismological measurements of interior structure and a camera), and a magnetometer, plus a probe with a mass spectrometer and an atmospheric structure instrument. The 2017 recommended payload did not include a nephelometer that was part of the *Vision and Voyages* strawman. A Doppler imager for investigation of giant planet structure, which accounts for half the

[8] "2018 Europa Lander Architecture Update," May 17, 2018 (provided to the committee in early June 2018).

payload mass, has not been flown previously on any spacecraft. The notional instruments were significantly more massive than assumed in the previous study, possibly due to assumed additional radiation shielding appropriate to a Jovian environment.

The mission concept described in the 2017 *Ice Giants Predecadal Study* report is ambitious in investigating the interior structure of an ice giant using a Doppler imager, analogous to undertaking helioseismological investigations of the Sun. This approach at any giant planet, including ice giants, is currently unproven theoretically or experimentally. Indeed, the study itself states: “There are several significant risks associated with a Doppler imager-type instrument, however, which must be assessed before selecting it for any actual ice-giant flight opportunity. The one easily addressed is the TRL level (currently 6), which—while a common level for a proposal—is the lowest for any instrument considered for the main spacecraft. More problematic is that while oscillations have likely been detected on Jupiter (Gaulme et al., 2011) and Saturn (Hedman and Nicholson, 2013), we do not know if the oscillation amplitudes on Uranus or Neptune will be detectable, and their excitation mechanism is not well-enough understood to even make an accurate prediction from what we see on the gas giants.”

In order to accommodate this large instrument, the proposed payload is reduced in scientific scope. Loss of several instruments from the *Vision and Voyages* strawman payload compromises some of the principal objectives for an Ice Giant mission. Without data from plasma spectrometers, studies of the structure and dynamics of the magnetosphere and effects of solar wind on the magnetosphere will be incomplete, and characterization of the internal field may be degraded. Without a UV imaging spectrograph, a visible/near-IR imaging spectrometer, and a thermal IR radiometer, important investigations of the composition and regolith structure at both large and small satellites will be incomplete, and compositional information on the ice giant atmosphere away from the probe site will not be obtained. In the event that the Doppler imager does not perform successfully, a large part of the *Vision and Voyages* science objectives would be degraded or lost. The reduction of the magnetospheric objectives of an ice giant flagship mission appears premature. The magnetospheres of these planets represent numerous unique physical situations that will enable a broader and more general understanding of planetary magnetospheric physics. The magnetic field of both Uranus and Neptune may be crucially important in understanding their internal structure.

Finding: Exoplanet discoveries further enhance the importance of an ice giants mission, already recognized as a high priority in *Vision and Voyages*. (See Chapter 2 for further explanation.)

Finding: The notional ice giants mission described in *Vision and Voyages* would address a broad range of ice giant science objectives using mature instrumentation.

Finding: The objectives of the mission concept described in the 2017 ice giants predecadal study have been changed significantly from the original *Vision and Voyages* science objectives. The scientific payload carries significant risk of failing to make the measurements proposed in *Vision and Voyages*. Furthermore, if the Doppler imager were not successful scientifically, a large part of the revised science objectives would be degraded or lost.

Recommendation: NASA should perform a new mission study based on the original ice giants science objectives identified in *Vision and Voyages* to determine if a more broad-based set of science objectives can be met within a $2 billion cost cap.

CONTINUING MISSIONS

Decadal Findings: Before suggesting new missions, *Vision and Voyages* encouraged NASA to “Continue missions currently in flight, subject to … senior review,” and to “ensure a level of funding that is adequate for successful operation, analysis of data, and publication of the results of these missions, and for extended missions that afford rich new science return." Figure 3.4 indicates that NASA's planetary program is supporting a large portfolio of missions of varying scales and at different stages of operation, and is exploring a diverse set of target bodies, as proposed in *Vision and Voyages*. Collectively, the operating missions are well distributed among size and scale of mission cost.

Assessment: The Planetary Science Division has held senior reviews to ensure that mission extensions are justified by important science objectives and that the costs are appropriate. For example, funding of Cassini's extended mission enabled investigators to acquire extensive information on Enceladus and Titan and their oceans, providing new insight into planetary evolution, dynamics, and habitat. The extended mission characterized seasonal effects in Saturn's atmosphere and magnetosphere and established more fully the internal mass distribution and the high-order internal magnetic field components, both central to understanding the deep interior of the planet.

The 2017 National Academies study *Extending Science: NASA's Space Science Mission Extensions and the Senior Review Process* pointed out the importance of continuing extended missions. It also recommended transitioning from a two-year cadence to a three-year cadence for senior reviews, which NASA is now adopting. The committee agrees with the recommendations in that report and with NASA's continuance of extended missions and adoption of a three-year cadence for senior reviews. (See Figure 3.11.)

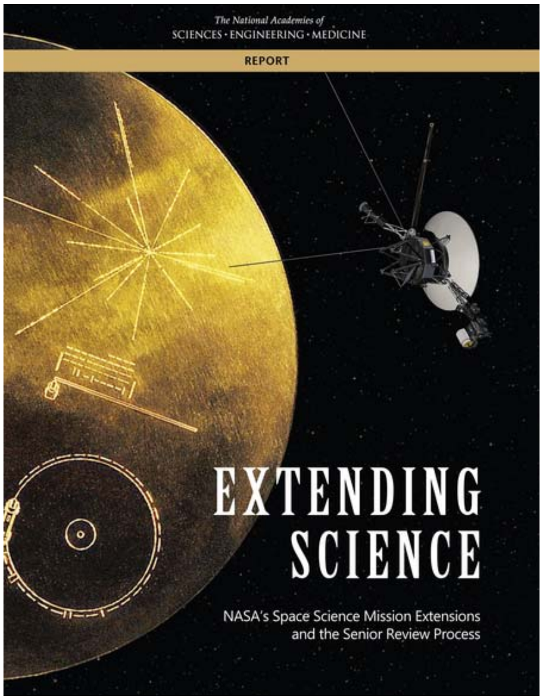

FIGURE 3.11 *Extending Science: NASA's Space Science Mission Extensions and the Senior Review Process* recommended that all four NASA Science Mission Directorate divisions transition to a 3-year cadence for senior reviews of missions in their extended phases. Planetary Science Division has now undertaken this new cadence. SOURCE: NASEM (2016).

Need for Flagship Program Cost/Risk Review Process

In the 2008 Space Act, Congress mandated a "lifecycle cost and technical readiness" review of proposed NASA projects. Such reviews have become an important part of the decadal survey process. The cost and technical evaluation (CATE) process is used by decadal surveys to provide an independent, standardized process to produce a figure-of-merit for technical and cost risk that aids in science prioritization. CATE is used to forecast the potential cost of the final system as built, which may undergo multiple iterations and may be very different than what was initially conceived.

Concepts conceived during decadal surveys are typically in preliminary stages of development—pre-phase A (in NASA project-lifecycle terms)—and are estimated to be of a certain complexity and associated cost. Downstream of the decadal survey, as the project is formulated, complexity grows as the development team understands more about the undertaking, new requirements may be introduced, and new instrumentation may be added. The rate at which a needed technology matures may be slower than had been expected. Cost and schedule growth follow such developments. When a project moves into implementation (phases C and D), it typically encounters new technical challenges—for example, during integration and testing—that the project team must work to overcome.

The Preliminary Design Review is the major milestone in development where NASA's independent cost estimation process engages. Key Decision Point-C (after PDR) is when NASA conducts an independent cost estimate of the mission. This is usually the point at which the agency commits to further development of the mission, or reevaluates the mission. A major cost increase for a single large strategic (flagship) mission can have a dramatic effect upon the overall program.

The committee was aware of the experience of the NASA astrophysics program, where cost overruns of large strategic missions have threatened the balance of that program. The astrophysics decadal survey midterm review report *New Worlds, New Horizons—Midterm Assessment*, published in 2016, included a recommendation for an independent review of the Wide Field Infrared Survey Telescope (WFIRST) program prior to KDP-B, a review that NASA subsequently performed. The planetary community can learn from this experience.

An independent review consists of an independent group of experts that looks at the scope and resources from a different perspective than a standard review board would in the context of the 7120.5/7123.1 criteria. To be of value, this review should be conducted ahead of SRR/MDR, and after instruments are selected, to properly assess the system-level impacts induced by selection of instruments and system level complexity, among other things.

Because large strategic (flagship) missions have the potential to disrupt the rest of the planetary science program if they overrun, the committee believes that they deserve extra attention regarding cost and schedule. An important point for this to happen in mission development is before Key Decision Point-C.

Recommendation: NASA's Planetary Science Division should implement an Independent Cost and Risk Review Process at Mission Definition/System Definition Review (Key Decision Point-B, or KDP-B) specifically for large planetary flagship missions to ensure that potential mission costs and cost risks are understood.

PSD INFRASTRUCTURE

Vision and Voyages called out multiple kinds of supporting investments, including laboratories and facilities, Earth-based telescopes, balloons and sounding rockets, the Deep Space Network, high-performance computing, sample curation, and data archiving. The committee assessed NASA performance in several, but not all, of these areas. In particular, data archiving and interoperability has come to the fore given the federal government's initiative to make federally funded research results available to the public. Because NASA policy is evolving rapidly to meet the new guidelines, this committee was not able to assess current performance.

Space and Earth-Based Telescopes

Decadal Findings: *Vision and Voyages* pointed out the importance of Earth-based telescopic facilities, particularly in chapters covering giant planets and primitive bodies, but also in other areas, highlighting the cross-cutting importance of these facilities. These assets include ground-based optical and radar telescopes (including the Infrared Telescope Facility, the Keck Observatory, Goldstone, Arecibo, and the Very Long Baseline Array), balloon- and rocket-borne telescopes, and space-based telescopes (Hubble Space Telescope, the Chandra X-ray Observatory, the Stratospheric Observatory for Infrared Astronomy, WISE, and others), all of which make important and often unique contributions to planetary science. Hubble observations remain a high priority for planetary research through the mission's remaining lifetime, particularly because there is no ultraviolet-optical high-resolution alternative from the ground. *Vision and Voyages* stated: "The committee's overall assessment is that NSF grants and support for field activities are an important source of support for planetary science in the United States and should continue."

Assessment: Since *Vision and Voyages* was released, significant discoveries have been made using ground-based facilities, representing progress toward *Vision and Voyages* goals, including the possible discovery of and continued study of/search for Europa plume activity; the study of auroral activity on Saturn (in coordination with Cassini) using the unique UV capabilities of the Hubble Space Telescope (HST); use of HST to successfully find target choices for New Horizons following the Pluto encounter; HST observations of 2014 MU69 occultations to characterize the New Horizons target; and unique HST observations of Ceres in the UV in support of the Dawn mission. With the heightened emphasis on planetary defense, radar observations have been crucial for refining orbits of near-Earth asteroids in order to assess future impact probabilities and to plan and execute missions to these bodies. Arecibo, with its higher sensitivity but limited sky pointing range, and Goldstone, with fully steerable capability, are complimentary and essential components of radar observations of near-Earth asteroids.

Finding: The Arecibo observatory is uniquely important for radar studies of asteroids, including characterization of potentially hazardous asteroids.

Finding: The loss of the unique capabilities of the Hubble Space Telescope (HST) will leave fewer opportunities for space-based telescope time allocated to solar system targets. The James Webb Space Telescope (JWST) will obtain limited observations of solar system targets but will not have the spectral coverage of HST.

Recommendation: NASA should conduct an assessment of the role and value of space-based astronomy, including newly emerging facilities, for planetary science. This assessment should be finished before the next decadal survey is significantly under way.

The Deep Space Network

Decadal Findings: *Vision and Voyages* recognized the Deep Space Network (DSN) as a critical component of the solar system exploration program. The report specifically recommended that NASA expand the DSN capabilities to comfortably meet the navigation and communications requirements of all the recommended missions, and that all three stations should maintain high-power uplink capability in the X- and Ka-band, and downlink capability in the S-, Ka-, and X-bands. Ka-band provides significantly greater downlink capability; S-band is specifically needed for communications through the Venus atmosphere to the surface; while X-band is needed to communicate through Titan's atmosphere and for spacecraft emergencies.

Assessment: Progress has been made toward the *Vision and Voyages* recommendations. Two new 34-meter antennas with X- and Ka-band capability have been commissioned in Canberra, Australia, with two more under construction in Madrid. Developments to support higher data rates include Ka-band antenna arraying and high data rate capability, Delay Tolerant Networking, and common platform implementation. The DSN is also working to create international protocols to facilitate use of international antennas.

The recommendation for Ka-band uplink and downlink at all stations has not yet been met. Ka-band downlink is available at all 3 stations, but Ka-band uplink is available only at Goldstone. The plan is to incorporate Ka-uplink at all stations in the next few years, but this is not yet a committed capability that missions in development can count on as it is not listed in the Space Communications and Navigation (SCAN) catalog.

The projected needs from planetary missions for DSN capabilities have only increased since *Vision and Voyages* was written. The DSN currently supports over 35 missions and maintains 99 percent reliability. The plethora of spacecraft at Mars offers a particular challenge. There are eight missions currently operating at Mars, with at least three NASA or ESA missions and possibly several more international missions planned to arrive in the 2020-2021 time period. Other demands include outer solar system missions that require 70-meter or equivalent antenna coverage, and high data rate instruments in the inner solar system. Thus, maintaining adequate resources for maintenance and expansion of the DSN is necessary to fully implement *Vision and Voyages* recommendations and keep pace with new, evolving demands. (See Figure 3.12.)

Recommendation: The committee endorses the *Vision and Voyages* recommendation that all three DSN complexes should maintain high-power uplink capability in the X- and Ka-band, and downlink capability in the S-, X-, and Ka-bands.

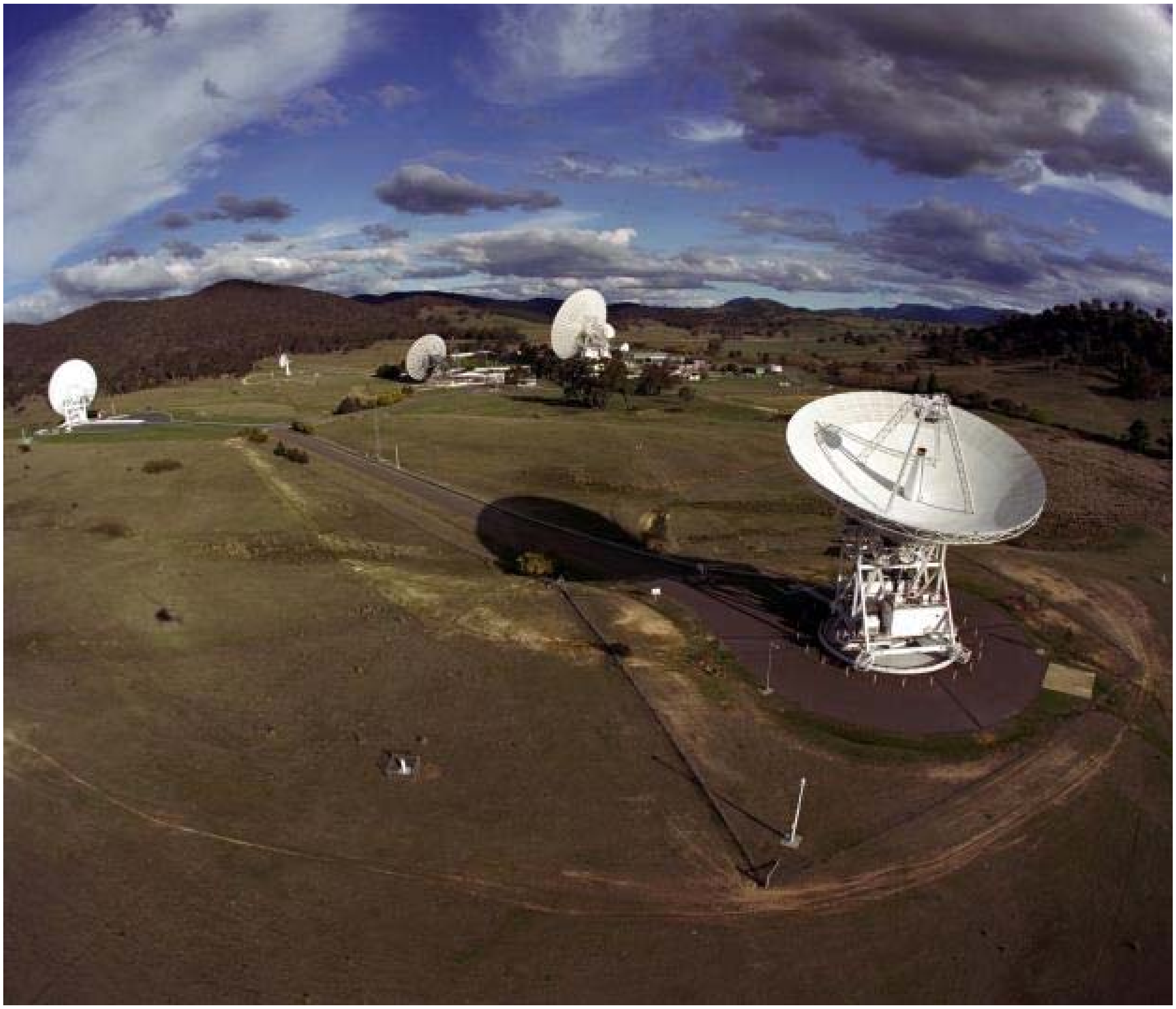

FIGURE 3.12 Canberra complex antennas in Australia. SOURCE: NASA Jet Propulsion Laboratory, "View of the Canberra Complex," https://deepspace.jpl.nasa.gov/gallery/; courtesy of NASA.

Sample Curation and Laboratory Facilities

Sample return missions from other planetary bodies and astromaterial sample collections here on Earth (e.g., Antarctic meteorites, cosmic dust) have been a vital part of NASA's science vision since nearly its inception. Sample studies continue to provide fundamental insight into how our solar system and its constituent bodies formed and evolved over the past 4.5 billion years. New generations of scientists and instrumentation are poised to address many ever-evolving scientific questions with returned samples. Careful curation is vital to the long-term viability of any sample return mission: curatorial efforts must begin at mission conception. *Vision and Voyages* states: "Sample curation facilities are critical components of any sample return mission, and must be designed specifically for the types of returned materials and handling requirements. Early planning and adequate funding are needed so that an adequate facility is available once samples are returned and deemed ready for curation and distribution." *Vision and Voyages* recommended that "every sample return mission flown by NASA should explicitly include in the estimate of its cost to the agency the full costs required for appropriate initial sample curation," and put forward the establishment of a single advisory group to provide input on all aspects of extraterrestrial sample curation. Last, *Vision and Voyages* advised that "well before planetary missions return samples, NASA should establish a well-coordinated and integrated program for development of the next generation of laboratory instruments."

Finding: The Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) committee fulfills the decadal requirements for a single advisory group to provide input on curation and management of planetary samples. In addition to its allocation responsibilities for all extraterrestrial samples under NASA control, CAPTEM is a community-based, interdisciplinary forum for discussion and analysis of matters concerning the collection and curation of extraterrestrial samples, including planning future sample return missions. As such, it provides a crucial function for the sample community to participate in planning activities. However, the Mars 2020 project is proceeding with its own sample-advisory board; although this board may be coordinating with Johnson Space Center curation, the board itself is operating outside of CAPTEM.

Finding: NASA established the Laboratory Analysis of Returned Samples (LARS) program to advance sample analysis techniques and develop analytical capabilities for future sample return missions. The recent report on the reorganization of R&A funding (*Review of the Restructured Research and Analysis Programs of NASA's Planetary Science Division*) showed that sample-based studies continue to have a home for funding within NASA R&A programs as well. NASA recently commissioned a study by the National Academies of Sciences, Engineering, and Medicine on the available laboratory facilities for sample analysis and strategies for continued investment. This study is ongoing at the time of writing.

Finding: The 2014 Discovery AO and 2017 New Frontiers AO require early planning and coordination for sample return missions. The actual costs for all aspects of curation, from planning through distribution and storage, including all required laboratory construction or modification, are required to be borne by the mission from inception to two years following sample return. Therefore, curation activities (and their associated costs) during phases A-D fall under the AO cost cap, and activities during phase E fall under the principal investigator (PI)-Managed Mission Cost (but not the AO cost cap). Whereas long cruise missions can defer such costs to phase E, this situation penalizes short missions that have to include curation and laboratory costs in phases B-D.

Recommendation: NASA should consider the budget for curation by samplereturn missions, as developed in the AO-required Curation Planning documents, a phase E cost, regardless of the phase in which the costs are actually incurred. This would ensure that sample return missions are on equal footing with other mission proposals and discourage unrealistically low budgets for sample curation.

Recommendation: NASA should ensure that all constituencies relating to sample return missions, both competed and directed, be coordinated through the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) to optimize communication, avoid duplication of effort, and maximize existing expertise.

Education and Outreach

Vision and Voyages highlighted the importance of effective outreach by the planetary community, noting that planetary exploration is among the "most exciting and accessible" science activities funded by NASA or any government agency. *Vision and Voyages* further stated that the NASA planetary program has a special responsibility to reach out to the public. *Vision and Voyages* stressed the value in the near instant availability of images from planetary missions and the global access to planetary data, noting that "interested members of the public can be informed of discoveries and mission events as they happen through social media." *Vision and Voyages* recommended that "Efforts to integrate effective outreach should be directly embedded within each planetary mission," and strongly endorsed NASA's informal guideline that a minimum of 1 percent of the cost of each mission be set aside from the project budget for education and public outreach activities.

Since the publication of *Vision and Voyages*, major changes have been made to the way NASA's SMD carries out its education and outreach activities in an effort to eliminate duplication of efforts and increase efficiency. Informed by National Academy of Sciences and stakeholder recommendations, in 2016 the SMD restructured its program of STEM Science Activation to fund activities that are "closely aligned with learners' needs." These consist of 27 multiyear cooperative agreements that leverage "SMD's Astrophysics, Earth, Heliophysics and Planetary content and experts into the learning environment through leveraging community-based partners." These are activities that "occur primarily in out-of-school settings and for learners of all ages."

Finding: The intent of the *Vision and Voyages* endorsement of 1 percent of mission budgets going toward education and public outreach activities was to have scientists who are involved in NASA's missions directing and participating in public education and outreach activities. Currently, the STEM Activation program is not uniformly engaging NASA missions; some missions are not being engaged at all. Furthermore, the STEM Activation program is not utilizing the mission scientists to define or provide science content; therefore, the critically important connections between the mission scientists and these education programs have been greatly reduced. While NASA center-managed public engagement efforts are connecting with some missions, in other cases there is no direct tie between missions that are producing results for the programs and the work of the NASA education program.

Recommendation: In order to enable the excitement of space exploration to be fully communicated to the broader public, the STEM Activation program should work with all NASA planetary missions to define science content and program implementation. NASA's Planetary Science Division should link education and outreach activities directly to the missions that are providing the science content for them, interfacing through the PIs for competed missions, and through the project scientists for directed missions. Education experts within the STEM Activation program should work directly with the mission scientists and engineers (subject matter experts, or SMEs) to ensure a strong connection to NASA's mission results. NASA had previously provided funds equal to 1 percent of the overall project budget to support these activities. New funding at this level would provide robust support for project engagement in these education and outreach activities.

Partnerships

Understanding our solar system requires a multidisciplinary approach to leverage investment. Progress over the last few decades and more recently suggests benefits to NASA of developing partnerships within and outside SMD and external to NASA.

Science Mission Directorate Partnerships

Within NASA's Science Mission Directorate, there are numerous options for partnering to enhance the planetary science program. The Planetary Science Division and Heliophysics Science Division can partner to further the understanding of how magnetospheres and planets and their satellites work as a system. The Planetary and Astrophysics Science Divisions can partner to further the comparison of exoplanetary systems and our solar system, the search for life within our solar system, and the investigation astronomically in searching for extra-solar systems capable of containing life. They can also partner to facilitate the understanding of how solar systems form. Planetary, Helio, Astro, and Earth Science Divisions can all work together to understand rocky planet evolution and habitability.

Such partnerships have taken many forms in the past, including hosting instruments from other divisions on planetary spacecraft, joint research funding, and other collaborations. For example, although Kepler was a Discovery mission funded by the Planetary Science Division, it has been operated by the Astrophysics Science Division.

Non-SMD NASA Partnerships

It is also possible for PSD to cooperate with other parts of NASA outside the Science Mission Directorate, and this has been advantageous for the planetary science program. For example, the Lunar Reconnaissance Orbiter was primarily funded by the Human Exploration Operations Mission Directorate (HEOMD) at NASA, but included a substantial suite of planetary science missions and is now operated by PSD. STMD and HEOMD have also funded heat shield instrumentation on the MSL Curiosity and the Mars 2020 missions, and are sponsoring the MOXIE in situ resource utilization experiment on Mars 2020.

International Partnerships

NASA has engaged in international partnerships on flagships and smaller PI-led missions with JAXA, ESA, Russia, and India. The Planetary Science Division has sought to develop long-reaching strategies and joint missions not possible within any single country. The committee notes that missions under study by potential partners are not substitutes for actually meeting the science goals established in the decadal survey. For example, although Russia and NASA have jointly studied the Venera-D Venus mission, where NASA would potentially contribute instruments, there is no indication that Russia is fully funding this mission.

Commercial Partnerships

Perhaps the most exciting new development in the larger space field is the emergence of new commercial space actors with interest in operations beyond low Earth orbit. SpaceX has indicated an interest in Mars exploration, and other companies have been formed to engage in asteroid mining or sending spacecraft to the Moon. These plans are at very early stages of formulation and are uncertain. (As an example, the committee sought a briefing by SpaceX on its plan to launch two Red Dragon spacecraft to Mars, but the project was canceled soon after the committee began its work.) Despite the uncertainty, this newly emerging sector holds great promise for providing new opportunities for NASA.[9]

National Science Foundation (NSF)

Vision and Voyages assessed the contribution to planetary science research made by ground-based astronomical facilities and laboratory facilities and investigations under the auspices of the National Science Foundation (NSF). Reviewing the progress of NSF toward meeting these recommendations was beyond the scope of this committee; however, the committee reiterates the importance of the *Vision and Voyages* recommendations, including the following:

[9] SpaceX has indicated ambitious plans for future human exploration of Mars. See Musk (2017, 2018).

- The committee supports the National Observatories' ongoing efforts to provide public access to its system of observational facilities, and believes that there is a synergy between ground-based observations and in situ planetary measurements for which the National Observatories could play a key role, perhaps through coordinated observing campaigns on mission targets. The committee notes that there are certain key elements of concern for planetary science, such as actions by NSF to divest itself from older observatories that are used also by NASA.
- The ground-based observational facilities supported wholly or in part by NSF are essential to planetary astronomical observations, both in support of active space missions and in studies independent of (or as follow-up to) such missions. Their continued support is critical to the advancement of planetary science. The committee also believes that expansion of NSF funding for the support of planetary science in existing laboratories, and the establishment of new laboratories as needs develop could be beneficial to the overall planetary science community.

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Planetary Science Technology

Vision and Voyages found that continued success of the NASA planetary exploration program depends on two major elements: (1) careful selection of flight projects that answer the highest-priority questions in solar system science, and (2) an ongoing, robust, stable technology development program that is aimed at the missions of the future, especially those missions that have great potential for discovery and are not within existing technology capabilities. Early investment in key technologies reduces the cost risk of complex projects, allowing them to be initiated with reduced uncertainty regarding their eventual total costs.

TECHNOLOGY INVESTMENT BUDGET

Decadal Findings: Because the future of planetary science depends on a well-conceived, robust, stable technology investment program, the survey strongly recommended that a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources. They recommended that the program should be consistently funded at approximately 6 to 8 percent of the total NASA Planetary Science Division (PSD) budget, should be targeted toward the planetary missions that NASA intends to fly, and should be competed whenever possible.

Assessment: The PSD technology investments have been between 6.9 and 9.9 percent, with an average of slightly under 8 percent for FY 2011 to FY 2016, and meet the 6-8 percent annual investment recommended by the decadal survey. The current budget estimates for the years FY 2018 through FY 2022 are showing technology funding at ~ $200 million, which represents about 10 percent of overall expected annual PSD budget of slightly greater than $1.9 billion.

Finding: The PSD has to date met and is expected to continue to fully meet the decadal survey's technology investment recommendation.

TECHNOLOGY PROGRAM TACTICAL AND STRATEGIC INVESTMENT BALANCE

Decadal Findings: *Vision and Voyages* strongly recommended that NASA strive to achieve balance in its technology investment programs by addressing the near-term missions cited specifically in this report, as well as the longer-term missions that will be studied and prioritized in the future. *Vision and Voyages* also identified the candidate set of "Key Capabilities" for technology development shown in Table 4.1 and that would provide this balance.

Assessment: PSD has been very responsive to the recommendations of the survey to improve integration of disparate technology programs, fill gaps in the technology readiness level maturation, fund high-priority technologies needed for future missions, and ensure a reasonable balance across the various technology areas. As part of their efforts, after the decadal survey PSD initiated a technology road-mapping exercise incorporating inputs from various sources to identify technologies that enable innovative science, in more extreme environments on smaller missions on a more frequent cadence. These technology requirements were then integrated into the 2015 NASA Technology Roadmap and the 2017 NASA Technology Investment Plan.

Table 4.1 shows the mapping of the current PSD Technology Priorities to the decadal survey recommendations.

TABLE 4.1 Current NASA Technology Roadmap Priorities Mapped Against Decadal Survey Recommended Needs

Mission Objectives	Decadal Survey Recommendations for Key Capability Required	NASA Technology Priorities
Inner Planets Venus climate history Venus/Mercury interior	High-temperature survival Atmospheric mobility	High-temperature compatible Electronics/Power Systems High-temperature electronic packaging for extreme environments High-temperature diamond-based electronic sensors and actuators High-temperature electric motors and position sensors exploration
Lunar volatile inventory	Advanced chemical propulsion Sample handling Long-duration high-temperature subsystems Autonomy and mobility Cryogenic sampling and instruments	Power/Propulsion for Small Spacecraft Ice Sample Return High-performance low-power computing and FPGAs System Autonomy (GNC, Prox. Ops, C&DH, Sampling Ops, FIDH) Low-temperature compatible electronics, actuators and mechanisms
Mars Habitability, geochemistry, and geologic evolution	Ascent propulsion Autonomy, precision landing In situ instruments Planetary protection	Planetary Ascent Vehicle for Sample Return Autonomous precision landing technology System Autonomy (GNC, Proximity Operations, C&DH, Sampling Ops, FIDH) Sample acquisition systems (ice penetration melt, drills; plume sampling; sample cache, delivery and processing) Subsurface ice (>2 m) acquisition and handling Motor controller, rover wheels Landing Hazard Avoidance Systems Planetary Protection Techniques/material and component compatibility Ice Sample Return
Giant Planets and Their Satellites Titan chemistry and evolution Uranus and Neptune/Triton	Atmospheric mobility Remote sensing instruments In situ instruments—cryogenic Aerocapture Advanced power/propulsion High-performance telecommunications Thermal protection/entry	High-performance low-power computing and FPGAs System Autonomy (GNC, Proximity Operations) Low-temperature compatible electronics, actuators, and mechanisms Low-mass low-power instruments for cold high-radiation Ocean Worlds Advanced Solar Arrays, MMRTGs, and Next Generation Electric Propulsion Sample acquisition systems (ice penetration melt, drills; plume sampling; sample delivery and processing) Next Generation Optical Communications High-temperature electronic packaging for extreme environments Heat Shield Technology for Planetary Entry and Sample Return

Mission Objectives	Decadal Survey Recommendations for Key Capability Required	NASA Technology Priorities
Primitive Bodies Trojan and Kuiper belt object composition Comet/asteroid origin and evolution	Advanced power/propulsion Advanced thermal protection Sampling systems Verification of samples—ices, organics Cryogenic sample preservation Thermal control during entry, descent, and landing	Advanced Solar Arrays, MMRTGs, and Next Generation Electric Propulsion **HEEET:** 3D-woven thermal protection system **LWRHUs:** Lightweight Radioisotope Heater Units Sample acquisition systems (ice penetration melt, drills; plume sampling; sample delivery and processing) Surface Cryogenic Ice sample acquisition and handling Heat Shield Technology for Planetary Entry and Sample Return

In addition to the technologies identified above, PSD is working closely with the Space Technology Mission Directorate (STMD) to co-fund technologies that enable planetary missions. These include the following:

- Spacecraft Technology
  - Heat Shield for Extreme Entry Environment Technology
  - Extreme Environment Solar Power
  - Deep Space Engine
  - Bulk Metallic Glass Gears
- Core Technology
  - High-Performance Spaceflight Computing
  - Entry System Modeling
- Instruments
  - Mars Science Laboratory Entry Descent and Landing Instrument II
  - VEMCam

Finding: The NASA technology priorities are responsive to the list established in *Vision and Voyages* and the Science Mission Directorate (SMD) and the Space Technology Mission Directorate (STMD) are working collaboratively to advance these technologies toward meeting mission needs. Such partnerships can benefit the Science Mission Directorate.

TECHNOLOGY DEVELOPMENT MANAGEMENT, TRL MATURATION, AND MISSION INSERTION

Decadal Findings: In assessing the state of technology *Vision and Voyages* found that in the past, NASA planetary exploration technology programs have overemphasized TRLs 1-3 at the expense of the more costly but vital midlevel efforts necessary to bring the technology to flight readiness. As a result the decadal survey recommended that the Planetary Science Division's technology program should be responsible for continuing the development of the most important technology items through TRL 6.

The decadal survey also emphasized that in the announcement of opportunities (AOs) for Discovery and New Frontiers missions, PSD should make newly developed technology available for transfer to proposers along with providing cost and risk mitigation support.

Assessment: NASA has continued to invest in multimission technologies and as part of the competed Discovery and New Frontiers AOs released since the decadal survey. NASA has taken steps as part of the 2014 Discovery AO and 2016 New Frontiers AO to both incentivize the use of new technology and to reduce the principal investigator (PI)'s programmatic risk for flying new technology by providing technologies. As noted below, to reduce PI mission risk NASA has provided this technology as government furnished equipment (GFE) with technical and monetary incentives, or by transferring NASA technology to a commercial provider who has brought it up to TRL 6 or above. In addition, they have initiated workshops to increase the awareness of the PI teams of the available technology such as that initiated in June of 2016 in support of the New Frontiers AO.

The 2014 Discovery AO NASA included the following:

- Government Furnished Equipment (Technology)
  - DSAC: Deep Space Atomic Clock—NASA offered a $5 million incentive for use and the fabrication of a copy of the as-demonstrated unit to be funded by the mission, including any modifications needed.
  - HEEET: 3D-woven thermal protection system—NASA to cover up to $10 million of the HEEET material and the labor costs for the HEEET team to work with the mission.
- Commercial Partners
  - Advanced Solar Arrays—Available from two vendors, ATK and DSS.
  - Green Propellant—Available from Aerojet-Rocketdyne.

These four items were all made available to SMD missions following significant development efforts and investment by STMD.

The 2016 AO for New Frontiers included the following:

- Government Furnished Equipment
  - NEXT-C: Commercialized version of the NEXT ion propulsion system—NASA to provide two thrusters and two PPUs.
  - DSOC: Next-generation optical communications—NASA to provide the hardware and labor costs for DSOC team's participation in integration and operations, and a $30 million incentive.
  - LWRHU: Lightweight Radioisotope Heater Unit—NASA to provide up to 30 units.

These three items were all made available to SMD missions following significant development efforts and investment by NASA's Space Technology Mission Directorate and the Human Exploration Operations Mission Directorate (HEOMD). Partnering in this manner has benefited the Science Mission Directorate.

Finding: NASA has implemented cost-effective ways to bring the new technology up to TRL 6 and above, including taking proactive steps to educate PI teams on the available technology and providing incentives in the announcement of opportunity for the incorporation of the technology in their proposed missions.

TECHNOLOGY DEVELOPMENT PROGRESS ASSESSMENT

To cost effectively meet the breadth of environmental and mission enabling systems challenges, the decadal survey committee emphasized the need for continued investment in advancing multimission core technologies that address the following needs:

- Reduced mass and power requirements for spacecraft and their subsystems;
- Improved communications capabilities yielding higher data rates;
- Increased spacecraft autonomy;
- More efficient power and propulsion for all phases of the missions;
- More robust spacecraft for survival in extreme environments;
- New and improved sensors, instruments, and sampling and sample preservation systems; and
- Mission and trajectory design and optimization.

This committee focused on the subset of these core technologies that are mission enablers with long lead development challenges. The development status of these technologies is discussed in the following sections.

Radioisotope Power

Decadal Findings: *Vision and Voyages* expressed a significant concern for the very limited availability of plutonium-238 (Pu-238) for planetary exploration. As a result *Vision and Voyages* had recommended that Advanced Sterling Radioisotope Generators (ASRGs) be the highest priority advanced power system technology investment. Due to the NASA termination of their support of the ASRG, and increased confidence in the availability of Pu-238, this did not happen and NASA has chosen Multi-Mission Radioisotopic Generator (MMRTG) as a higher priority technology investment and also to invest in longer term developments of advanced energy conversion techniques.

Assessment: The PSD has made dramatic progress in reestablishing a viable production source for Pu-238. NASA and DoE have established a long-term relationship where NASA will fund the establishment and maintenance of a constant production line for Pu-238. This arrangement will reduce mission risk by maintaining a qualified work force and making targeted equipment investments across the production chain. By fiscal year 2019 production rate will begin at 400 g/yr. By fiscal year 2021 additional production redundancy will be added, and by 2025 DoE will be able to produce 1.5 kg/yr. with a surge capability to 2.5 kg/yr. (See Figure 4.1.)

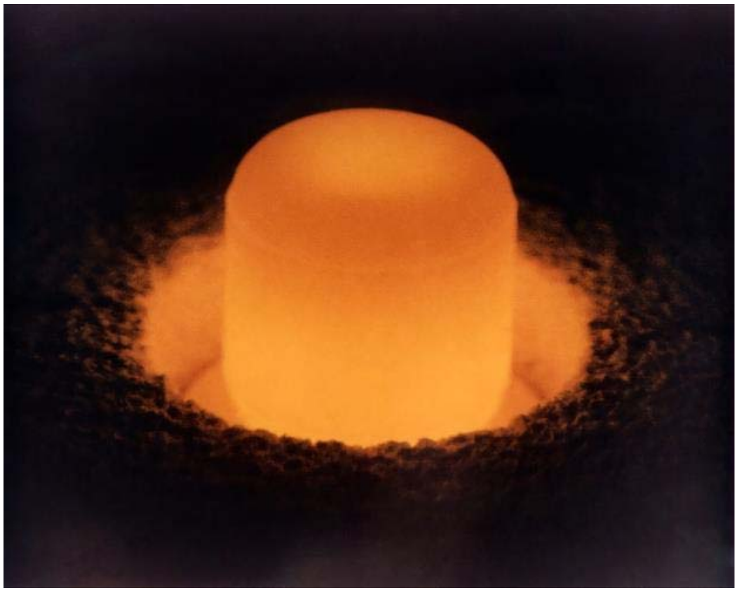

FIGURE 4.1 Pellet of Pu-238 for RTG use. SOURCE: The Planetary Society, “Plutonium-238 Fuel Pellet,” http://www.planetary.org/multimedia/space-images/spacecraft/plutonium-238-fuel-pellet.html; courtesy of the U.S. Department of Energy.

Clads are the basic building blocks of MMRTGs. Approximately the size and shape of a marshmallow, they contain the plutonium fuel that provides heat that is converted to electricity. Each MMRTG requires 32 clads, each containing 151 mg of Pu-238 (plutonium dioxide). The currently forecasted clad availability and capability to assemble MMRTGs along with NASA's expected mission needs are shown in Figure 4.2.

In March 2018, based on this renewed confidence in the availability of Pu-238 and MMRTG development maturity and community pressure, NASA announced it would allow MMRTGs for missions proposed in response to the 2019 Discovery AO.

Finding: The currently forecast Pu-238 and clad production rates are expected to fully meet with margins the NASA currently envisioned mission needs for MMRTGs over the next 10-15 years.

Recommendation: NASA should continue to work closely with the DoE to ensure that the schedules for Pu-238 and clad production and the development of the MMRTG are maintained. It is also important that NASA continue the longer term developments of advanced energy conversion techniques.

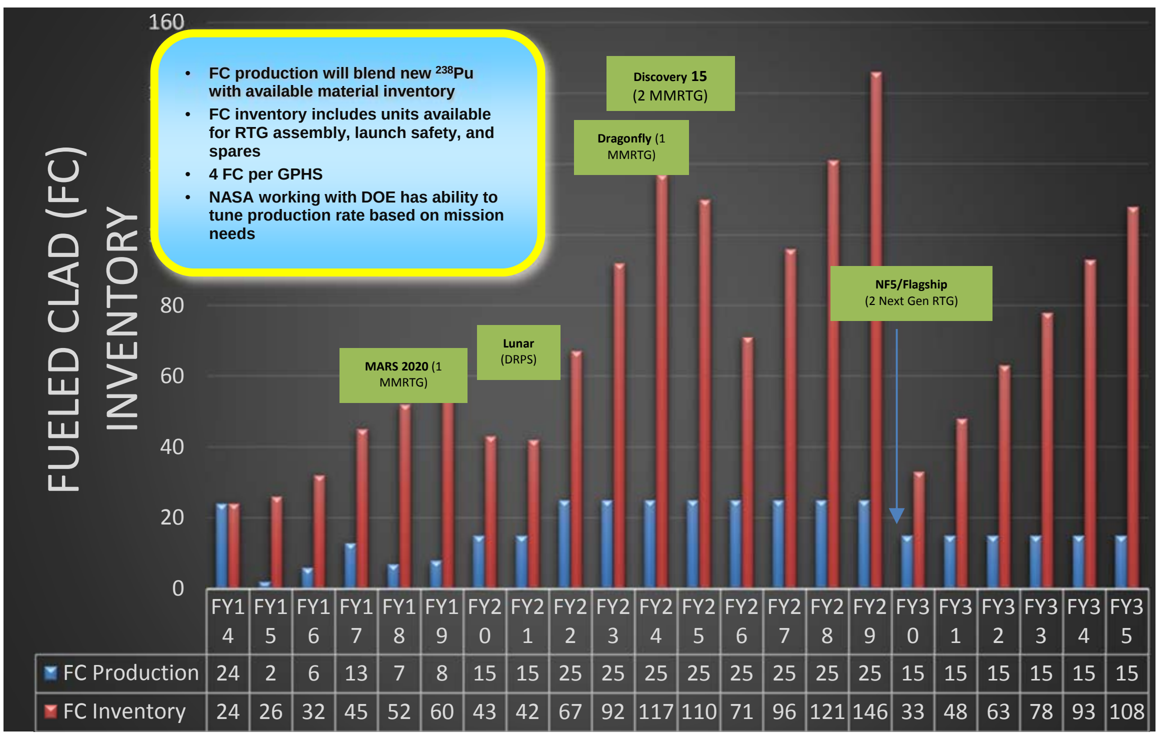

FIGURE 4.2 Expected Pu-238 availability versus NASA's expected mission needs. NOTE: GPHS = General Purpose Heat Source. SOURCE: NASA.

Electric Propulsion and Advanced Solar Arrays

Decadal Findings: *Vision and Voyages* emphasized the importance of NASA continuing to invest in capability-driven technology such as electric propulsion to increase propulsion systems efficiency especially for outer planet and primitive body missions. *Vision and Voyages* also recommended that

NASA consider making equivalent systems investments in the advanced Ultraflex solar array technology that will provide higher power at greater efficiency.

Assessment: SMD is working with the Glenn Research Center to develop the next-generation Xenon thruster and the necessary power processing units. This activity, the NASA Evolutionary Xenon Thruster-Commercial (NEXT-C) Gridded Ion Thruster System, is intended to take this hardware from a TRL 5/6 to a TRL 8, where it is ready for use in future planetary missions as well as commercial spacecraft. (See Figure 4.3.)

The STMD is also working with Glenn Research Center to develop critical technologies to extend the length and capabilities of new science and exploration missions using solar electric propulsion (SEP). STMD is funding the development of 12.5 kW Hall Effect thrusters and 20 kW-class flexible blanket solar arrays.

Finding: NASA has fully embraced the *Vision and Voyages* recommendations concerning electric propulsion and advanced solar arrays, and is making significant technology development progress in both.

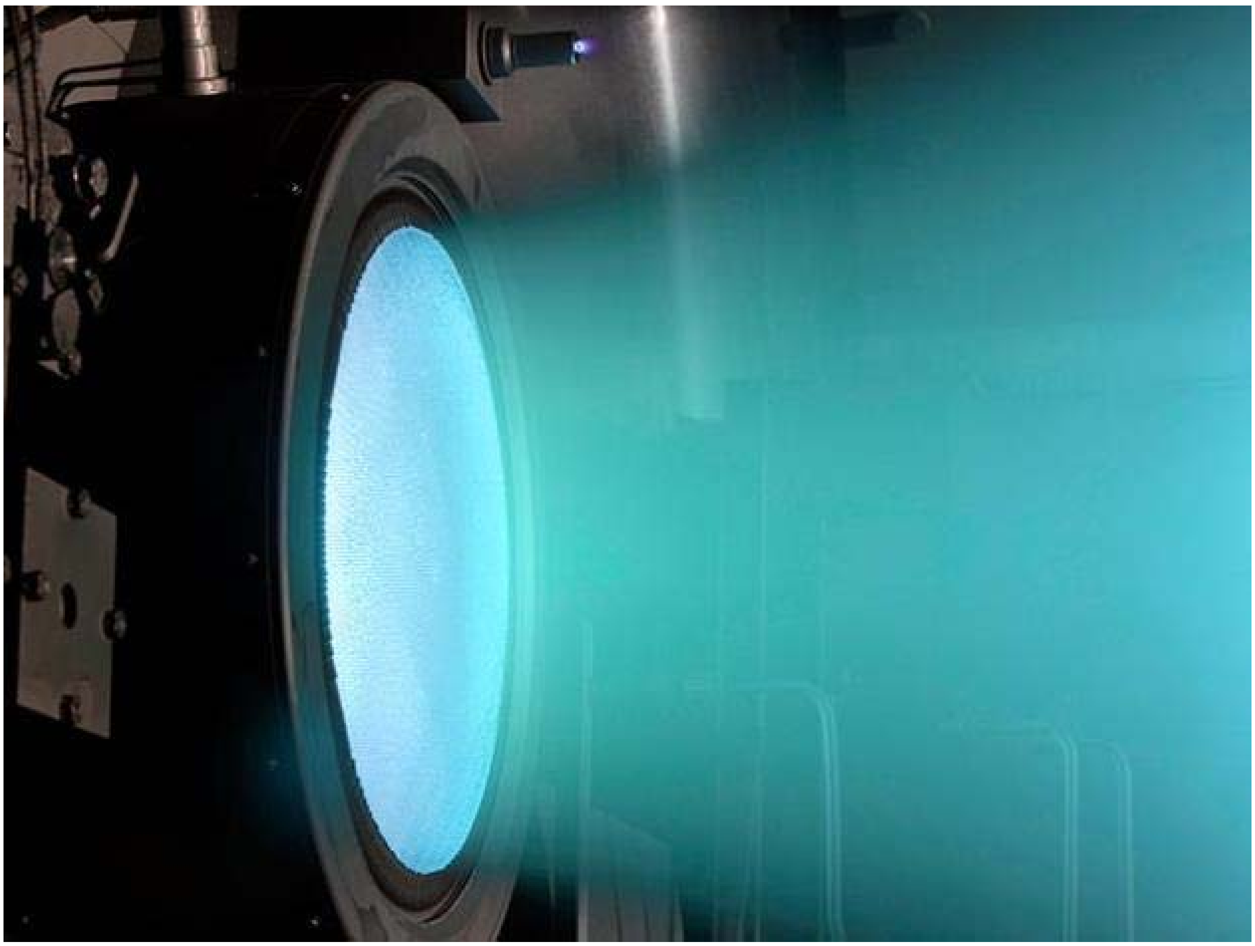

FIGURE 4.3 NEXT-C ion thruster during test. SOURCE: NASA Glenn Research Center, "NASA's Evolutionary Xenon Thruster (NEXT) Project has developed a 7-kilowatt ion thruster for deep space missions," https://www1.grc.nasa.gov/facilities/epl/.

Aerocapture

Decadal Findings: *Vision and Voyages* recommended that NASA consider making equivalent systems investments in aerocapture to enable efficient orbit insertion around bodies with atmospheres.

Assessment: NASA continues to recognize the potential of aerocapture to reduce propellant mass/volume needs, transit time, and launch costs, as noted in the 2016 NASA/JPL Report *An Assessment of Aerocapture and Applications to Future Missions*. NASA has continued work in aerocapture technologies, including a concept study with Georgia Tech on the feasibility of SmallSat flight demonstrations, but it is not currently a major technology investment within NASA's portfolio.

Finding: NASA is investing in the underlying technologies for aerocapture, including a potential flight demonstration. Aerocapture system-level design and development however, is destination-specific, and when there is a specific mission requirement, the investment will need to be increased.

Communications and Data Bandwidth

Decadal Findings: *Vision and Voyages* recommended that NASA invest in increasing communications, optical communications, and data link bandwidth, which would be of major benefit for planetary exploration.

Assessment: SMD is working several different avenues for increasing communications and data bandwidth. The recently selected Discovery mission, Psyche, will fly a deep space optical communication system developed by STMD that was offered as a government furnished system with no technology risk penalty. This system is intended to provide order-of-magnitude higher data rates with the same mass and power as state-of-the-art telecommunication systems and no additional demand on a spacecraft.

In addition STMD is currently planning technology demonstrations that will pave the way for use of this technology in future deep space missions. The Laser Communications Relay Demonstration (LCRD) sponsored by NASA's Space Technology and Human Exploration and Operations Mission Directorates is the next technology demonstration. It follows the Lunar Laser Communications Demonstration, a very successful pathfinder mission that flew aboard the Lunar Atmosphere Dust and Environment Explorer (LADEE) in 2013. Launch of LCRD is currently planned for 2018. To enable future missions to fully utilize the promise of increased data rate, a comprehensive ground support system will be required.

Finding: NASA has fully embraced the *Vision and Voyages* recommendation and is making meaningful investment in advanced communications technology development and flight demonstration.

Science Instruments and Detectors

Decadal Findings: *Vision and Voyages* recommended that a broad-based, sustained program of science instrument technology development be undertaken, and that this development include new instrument concepts as well as improvements in existing instruments. This instrument technology program should include the funding of development through TRL 6 for those instruments with the highest potential for making new discoveries.

Assessment: SMD has formed two programs to help advance the state of the art in science instrumentation: Planetary Instrument Concepts for the Advancement of Solar System Observations

(PICASSO) for concepts from TRL 1-3, and Maturation of Instruments for Solar System Exploration (MatISSE) for instruments at TRL 4-6.

PICASSO currently has 54 funded activities under way that cover a wide variety of instruments, detectors, and targets. Eighteen of these 54 are directly relevant to life detection, and the portfolio includes atmospheres, chromatography, dust, gamma ray/neutron, gravity, heat flow, magnetometers, plasma, raman, sampling, seismometers, THz spectrometers, and UV-VIS imagers. These cover the range of TRLs from TRL 2 to TRL 5. Twenty-seven of the 54 funded tasks are directly relevant to small spacecraft less than 3U, 10 kg, and 10 W. The portfolio covers many of the same areas as for the life detection activities.

MatISSE has 21 funded activities that cover spectrometers (imaging, raman, mass, gamma ray), deep core drill technology, subsurface microwave/optical/electromagnetic sensor suite, fluorescence imager, genome sensor for landers; spectrometers (microwave, sub-mm, visible, UV), imagers (sub-mm, UV), subsurface radar, organics analyzer, and atmospheric lidar; and comet penetrator/sample extractor, cosmic dust analyzer, and vector magnetometer for flyby/rendezvous.

Although between the MatISSE and PICASSO there are 75 funded technology developments under way, the history of proposals for these programs indicates that less than 15 percent were able to be funded.

- MatISSE; 2012: 17%
- PICASSO 2013: 11%
- MatISSE 2014: 11%
- PICASSO 2014: 13%
- PICASSO 2015: 11%
- MatISSE 2016: 13%
- PICASSO 2016: 14%

Finding: NASA created the PICASSO and MatISSE programs to provide a sustained, broad-based science instrument development through TRL 6, as recommended by *Vision and Voyages*. The high number of proposals submitted to these programs, relative to the funding available, shows a strong community demand for these programs.

Extreme Environments

Decadal Findings: *Vision and Voyages* recommended that, as part of a balanced portfolio, a significant percentage of the Planetary Science Division's technology funding be set aside for expanding the environmental adaptability of existing engineering and science instrument capabilities.

Assessment: SMD has funded two specific programs targeted at technologies for extreme environments: Concepts for Ocean Worlds Life Detection Technology (COLDTech), for Europa, Titan, Enceladus, Callisto, Ganymede, and Ceres; and Hot Operating Temperature Technology (HOTTech), for Venus, Mercury, and gas giant interiors.

The COLDTech portfolio is a spacecraft-based instruments and technology program for surface and subsurface exploration of ocean worlds with emphasis on the detection of evidence of life, sample acquisition, delivery and analysis systems, and technologies required to access oceans. The HOTTech portfolio primarily encompasses electrical and electronic systems for the robotic exploration of high-temperature environments (>=500°C). There are 21 awards totaling $27 million of investment in the COLDTech portfolio and 8 awards totaling $4.5 million of investment the HOTTech portfolio over three years. The specific technologies funded in each portfolio are shown in Table 4.2.

Finding: NASA is making a focused investment in the COLDTech and HOTTech programs to address the spacecraft bus, instrument, and in situ systems survival and operations in extreme environment as recommended by *Vision and Voyages*.

TABLE 4.2 NASA Planetary Science Division Extreme Environment Technology Investment Portfolio

COLDTech	In Situ Exploration and Core Technologies	Autonomous precision landing technology Sample acquisition systems (ice penetration melt, drills; plume sampling; sample delivery and processing) Motor controller, rover wheels Nuclear magnetic resonance detection of extant life
	Instruments and Sensors	Seismometers and sounders Imagers (luminescence, visible) Microfluidic wet chemistry laboratory Supercritical CO_2 extraction and chiral supercritical fluid chromatography Nano motion sensor Nanopore sequencing Molecular sensor
HOTTech	Electronics	High-temperature electronic packaging for extreme environments Nano-triode vacuum devices for high-temperature environments High-temperature oscillators and clocks for wireless communications
	Sensors, Actuators, and Motors	SiC electronics and sensors for high-temperature environments High-temperature diamond-based electronic sensors and actuators High-temperature electric motors and position sensors for Venus exploration
	Power Generation	Lithium-combustion-based power generation in high-temperature environments Low-intensity high-temperature solar cells for extreme environments

Technology for Flagship Missions in the Next Decade

Decadal Findings: *Vision and Voyages* recognized that NASA's comprehensive and costly flagship missions are strategic in nature and have historically been assigned to NASA centers rather than competed. The survey pointed out that flagships, as with Discovery and New Frontier Missions, can benefit from, and in fact are enabled by, strategic technology investments such as those shown in Table 4.3. (Note that this list is not all-inclusive.)

TABLE 4.3 Technology Investments for Flagship Missions

Flagship Mission	Recommended Technology Development
Mars Astrobiology Explorer-Cacher (Mars Sample Return)	Sample acquisition, processing, and encapsulation Mars ascent End-to-end sample containment Planetary protection for restricted sample return Precision landing Autonomous rendezvous and guidance for return orbiter
Jupiter Europa Orbiter (JEO)	Spacecraft and instrument technology for high-radiation environment Planetary protection
Uranus Orbiter and Probe	Long-lived (>15 yr), flight-qualified ASRGs Lightweight materials for structure and subsystems Thermal protection systems for probes Inexpensive solar-electric propulsion Aerocapture
Enceladus Orbiter	Long-lived (>15 yr), flight-qualified ASRGs Planetary protection
Venus Climate Mission	Packaging of spacecraft, mini-probe and dropsondes Entry flight system

SOURCE: *Visions and Voyages* (2011).

Assessment: MAX-C was deemed too expensive, and the *Vision and Voyages* committee recommended that the mission be de-scoped to a cost of no more than $2.5 billion. The Mars 2020 mission was redesigned with the *Vision and Voyages* science objectives in mind while staying within the proposed funding limitations. In order to meet this cost target, this mission was designed to use as much heritage hardware from the Mars Science Lab as possible to reduce the cost. However, the sample acquisition, processing and encapsulating system is still the most demanding technological development. Fortunately, Mars 2020 has successfully completed all the technology demonstrations, and the mission is now in integration and testing. In addition, the mission has developed an approach to planetary protection and contamination control that will ensure that the samples that may eventually be returned are uncontaminated. Last, the Mars 2020 mission is also developing additional technologies that will enable future missions. The landing system is including Terrain Relative Navigation that will allow the rover to be diverted to a safer spot if the terrain exceeds the rover's landing parameters. This technology has also passed its technology demonstration and is being integrated into the mission.

Jupiter Europa Orbiter (JEO)

Like MAX-C, the JEO mission was deemed too expensive by the decadal survey, and the mission was redesigned to achieve as much of the JEO science as possible by developing a Jupiter orbiter with over 40 flybys of Europa. This new mission, named Europa Clipper, is currently in the middle of its preliminary design reviews (PDRs), with the overall mission PDR scheduled for fall 2018. Since Europa Clipper is a flyby mission as opposed to an orbiter, it will receive significantly less radiation than the JEO mission would have received. As a result, the project has not had to push technology beyond the current state of the art and is using radiation vaults to protect most susceptible components.

Uranus Orbiter and Probe and Enceladus Orbiter

These missions both require nuclear power because of their tremendous distances from the Sun. As noted above, the ASRG development has been terminated by DoE, and only some residual technology development on the Sterling converter technologies remains. NASA has now focused its nuclear power technology development on an enhanced MMRTG, and is proceeding with a technology decision planned in 2019. The remaining technologies required by these missions have been prioritized by NASA as part of its technology development process. The only required technology not included in this list is aerocapture, which could be enhancing for an ice giants mission. (See Figure 4.4.)

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FIGURE 4.4 Artist concept of a Uranus orbiter. SOURCE: *All About Space*, “Destination Ice Planet: Uranus,” cover, Issue 30, 2014.

FIGURE 4.5 Testing of a balloon concept for the Venus Climate Mission. SOURCE: NASA.

Venus Climate Mission

The decadal survey indicated that extensive technology was not required for the Venus Climate Mission. However, the mission functionality may benefit from technology developments achieved via HOTTech and potentially other technology efforts. (See Figure 4.5.)

Finding: The Planetary Science Division has embraced the decadal survey's technology recommendations, and they have constructed a rational and comprehensive technology portfolio that can enable new and more challenging planetary science missions in the next decade.

Recommendation: NASA should continue investment in development of the mission-enabling technologies at the 6-8 percent level.

Small Satellite Technology

Decadal Findings: At the time of the decadal survey the scientific mission capabilities of Micro- and CubeSats sensors for space science were in the relatively early phase of development and were not addressed in *Vision and Voyages*. Subsequent to the *Vision and Voyages* report, the National Academies convened a Committee on Achieving Science Goals with CubeSats that released its report *Achieving Science with CubeSats: Thinking Inside the Box*.

Assessment: Since *Vision and Voyages* was written, significant progress has been made in the capabilities of Micro- and CubeSats along with sensor capabilities. MicroSats are typically in the 100 kg range, and CubeSats are composed of one or more 10 cm <1.33 kg cubes. *Achieving Science with CubeSats: Thinking Inside the Box* recognized the potential value of CubeSats to space and Earth science observational and exploration programs. In particular, for planetary science the report concluded that "in situ investigation of the physical and chemical properties of planetary surfaces and atmospheres" could be accomplished by deployable (daughter-ship) CubeSats and could expand the scope of the mother-ships with complementary science or site explorations.

The MARCO CubeSats were recently launched to Mars on the InSight mission. They will return data from InSight during its entry into the atmosphere before they fly past Mars.

Space Launch System (SLS) and Commercial Launch Vehicles

Decadal Findings: *Vision and Voyages* pointed out that the costs of launch services pose a challenge to NASA's program of planetary exploration. Launch costs have risen in recent years for a variety of reasons, and launch costs today tend to be a larger fraction of total mission costs than they were in the past. These increases pose a threat to formulating an effective, balanced planetary exploration program.

Assessment: The NASA Launch Services Program (LSP) provides for commercial launch vehicle services in support of all NASA missions. The commercial launch vehicle industry is in great transition, as some launch vehicles from the LSP family are being retired, and new and in many cases less costly launch vehicles are becoming available (e.g., the Falcon Heavy from SpaceX, which is not yet approved by the NASA Launch Services Program). The Launch Services Program has existing contracts in place, with launch options at multiple pricing to provide both the launch vehicles and supporting services required to meet current and expected launch needs. As new vehicles become available and qualified, the LSP develops opportunities to add them to NASA launch vehicle services options.

In addition to the commercial launch vehicles, NASA's new Space Launch System (SLS) is under development and could be an attractive option for some applications, as it has the capability to reduce interplanetary cruise time for science missions to the outer planets by 3-5 years, and potentially increase payload size.

CONCLUSION

Since the publication of the planetary science decadal survey, NASA has made impressive progress at meeting its technology development goals. In the past, technology development has often been sacrificed to meet the demands of programs in development. By partnering with STMD and HEOMD, the NASA Planetary Science Division's ability to achieve the funding goals of the decadal survey despite substantial cuts to its budget is commendable.

5

Mars Exploration Architecture

MARS EXPLORATION PROGRAM BACKGROUND

Mars has been a high-priority exploration objective and holds a special place in the solar system because it addresses aspects of three important *Vision and Voyages* themes. It is the only terrestrial planet besides Earth that preserves a readily accessible record of environments where life could have developed. Whether life did or did or not develop there has implications for the size of the habitable zone and for the prevalence of life among small extrasolar terrestrial planets.

Study of Mars's early history and evolution informs the theme "Building New Worlds," including the questions of what governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets, the evolution of their atmospheres, and the role played by large impacts; the theme "Planetary Habitats," including the questions of primordial sources of organic matter and whether organic synthesis continues today; and the theme "Solar System Workings," including the questions of how the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time.

These *Visions and Voyages* themes are echoed in the first three goals of the Mars Exploration Program Analysis Group (MEPAG) Science Goals document: (1) to study preservation of biosignatures in past habitable environments and the possible presence of extant life in subsurface or transient near-surface habitable environments; (2) to study the history of ancient climate and the processes that changed ancient wetter into modern drier Mars, and martian climate change in the recent past; and (3) to study the history of Mars's crust and its interaction with water, and the evolution of Mars's crust and interior.

Furthermore, Mars is the only terrestrial planet beyond the Earth-Moon system that humans may visit or occupy in the foreseeable future. This fact maps to the fourth MEPAG goal, preparing for human exploration by providing knowledge of Mars sufficient to design and implement a human mission.

Mars exploration advanced rapidly from 1965 to 1976, with a regular cadence of missions including Mariners 4, 6, 7, and 9 and Vikings 1 and 2. Inability to follow up from Viking due to high cost and lack of political will led to a stagnation of Mars science. The eventual follow-up eighteen years later, Mars Observer, failed during Mars orbit insertion. (See Figures 5.1 and 5.2.)

After the failure of Mars Observer, NASA sent additional spacecraft to Mars. Key missions include Pathfinder/Sojourner, Mars Global Surveyor (MGS), Mars Odyssey, the Mars Exploration Rovers (MERs) Spirit and Opportunity, Mars Reconnaissance Orbiter (MRO), Phoenix, then Mars Science Laboratory (MSL) Curiosity, and the Mars Atmosphere and Volatile Evolution Mission (MAVEN). There were two high-profile setbacks in the late 1990s with the failures of Mars Polar Lander and Mars Climate Orbiter. The success of the Mars Exploration Program (MEP) has resulted from pursuit of a *logical sequence of science and mission objectives*, where new findings stimulate new investigations. For example, MGS identified crystalline hematite, possibly formed through aqueous processes on the surface. That exposure was selected as the landing site for MER/Opportunity, which characterized that ancient aqueous environment. MRO has used high-resolution imagery to find a plethora of ancient aqueous environments and certify sites for safety. The Mars Odyssey THEMIS instrument, along with MRO's HiRISE instrument, paved the way for landing site selection for Phoenix in 2008, and these orbital assets have been essential for selecting landing sites for MSL in 2011, and ExoMars and Mars 2020. (See Figure 5.3.)

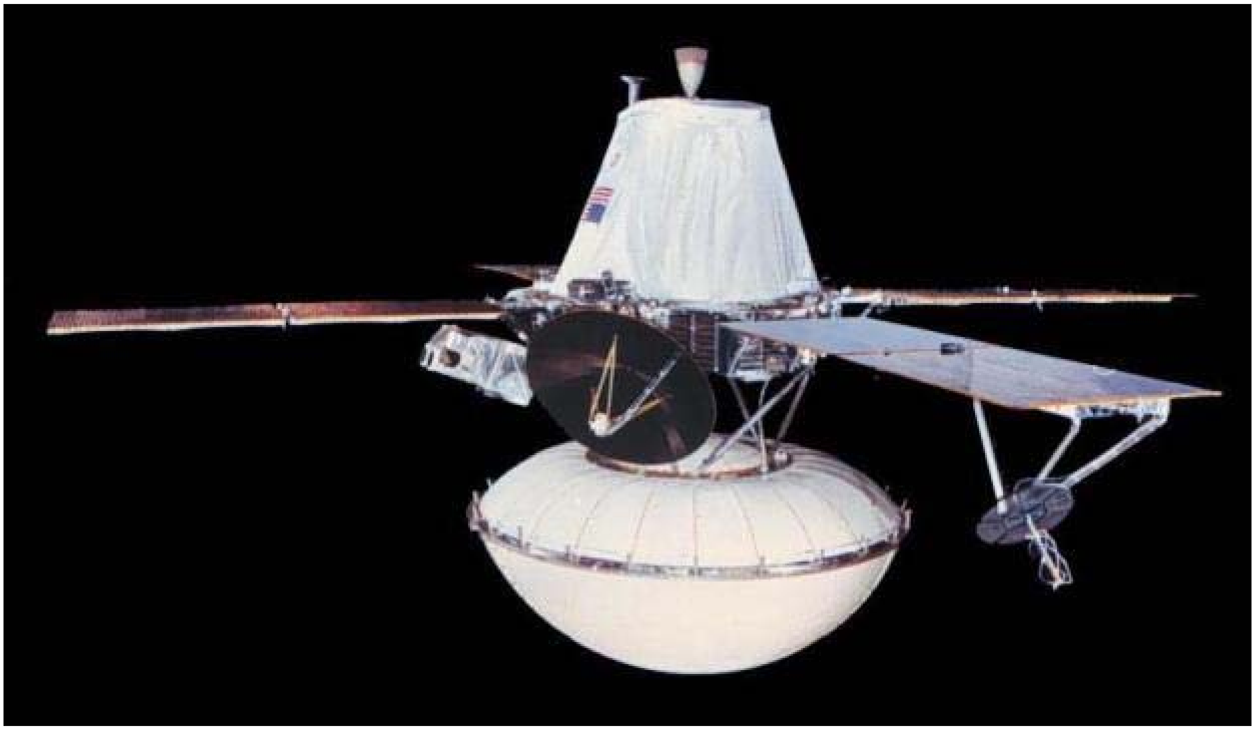

FIGURE 5.1 Mockup of the Viking spacecraft, which consisted of both an orbiter and a lander. SOURCE: NASA/JPL.

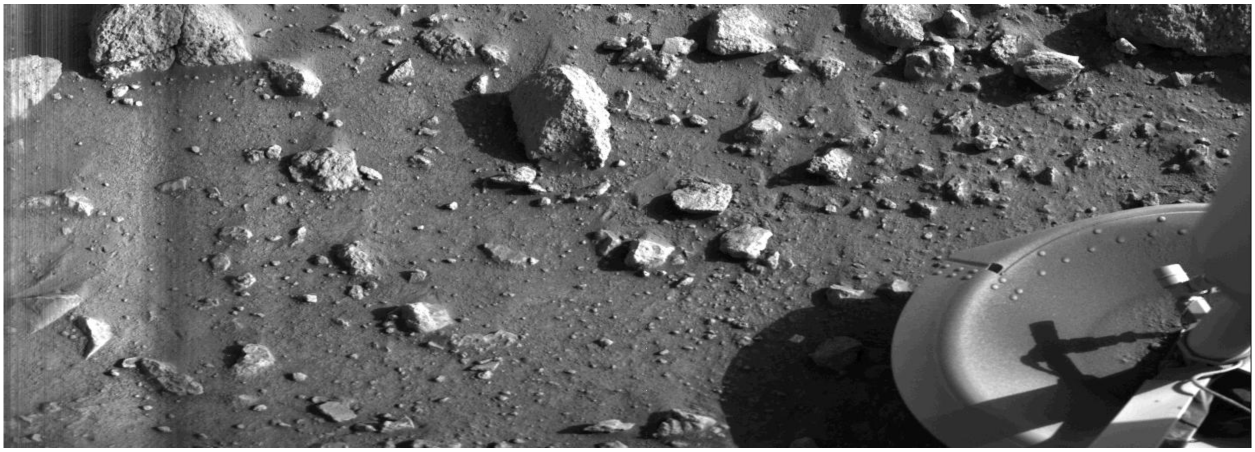

FIGURE 5.2 Image taken by Viking on Mars. SOURCE: NASA/JPL.

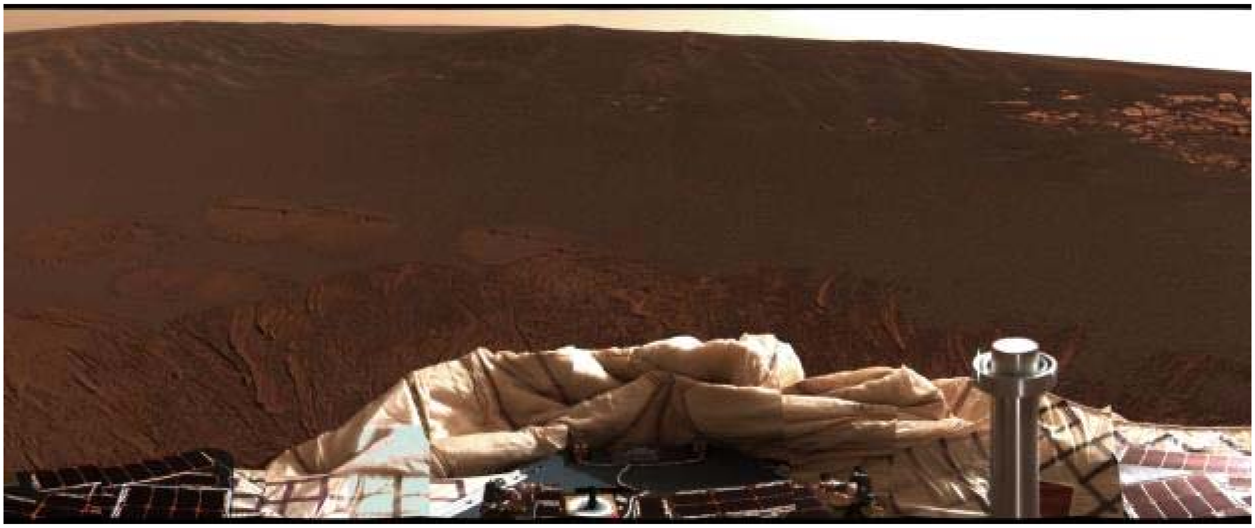

FIGURE 5.3 Image taken by Opportunity rover on Mars. SOURCE: NASA/JPL.

The MEP's discovery of widespread sedimentary and hydrothermal deposits that formed in apparently habitable environments, with the potential to preserve biosignatures, led to the identification of MAX-C as the highest priority flagship mission in *Vision and Voyages*. Specifically, a three-flagship mission sequence was envisioned to complete Mars sample return (MSR): (1) MAX-C, a geology/caching rover, to collect, document, and cache samples from an ancient habitable environment with strong potential to have preserved biosignatures; (2) a fetch rover to collect the sample cache coupled with a Mars Ascent Vehicle (MAV) to place the cache in Mars orbit; and (3) retrieval of the cache and return to Earth or near-Earth space by a round-trip Sample Return Orbiter. *Vision and Voyages* also recommended technology development for the fetch rover, Mars Ascent Vehicle, Sample Return Orbiter, and a curatorial/containment facility for returned samples.

In addition, *Vision and Voyages* made a number of associated recommendations:

1. New Frontiers (NF) mission concepts were considered that would characterize polar deposits and volatiles, or that would deploy a global geophysical network. Neither was included as a recommended NF mission.
2. Earlier studies such as the National Academies' *An Astrobiology Strategy for the Exploration of Mars* endorsed in situ studies as an important component of exploration for past martian life. Nevertheless, *Vision and Voyages* did not recommend additional rovers conducting in situ investigations. Instead, it was the Decadal Survey Committee's judgment that the more complete and detailed information possible from analysis of returned samples in terrestrial laboratories warranted making sample return the predominant thrust of Mars exploration.
3. It was recommended that Discovery be opened to include all solar system targets, including Mars. This was implemented, and the next Discovery mission—Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport (InSight)—is a single-node Mars geophysical investigation. (See Figure 5.4.)

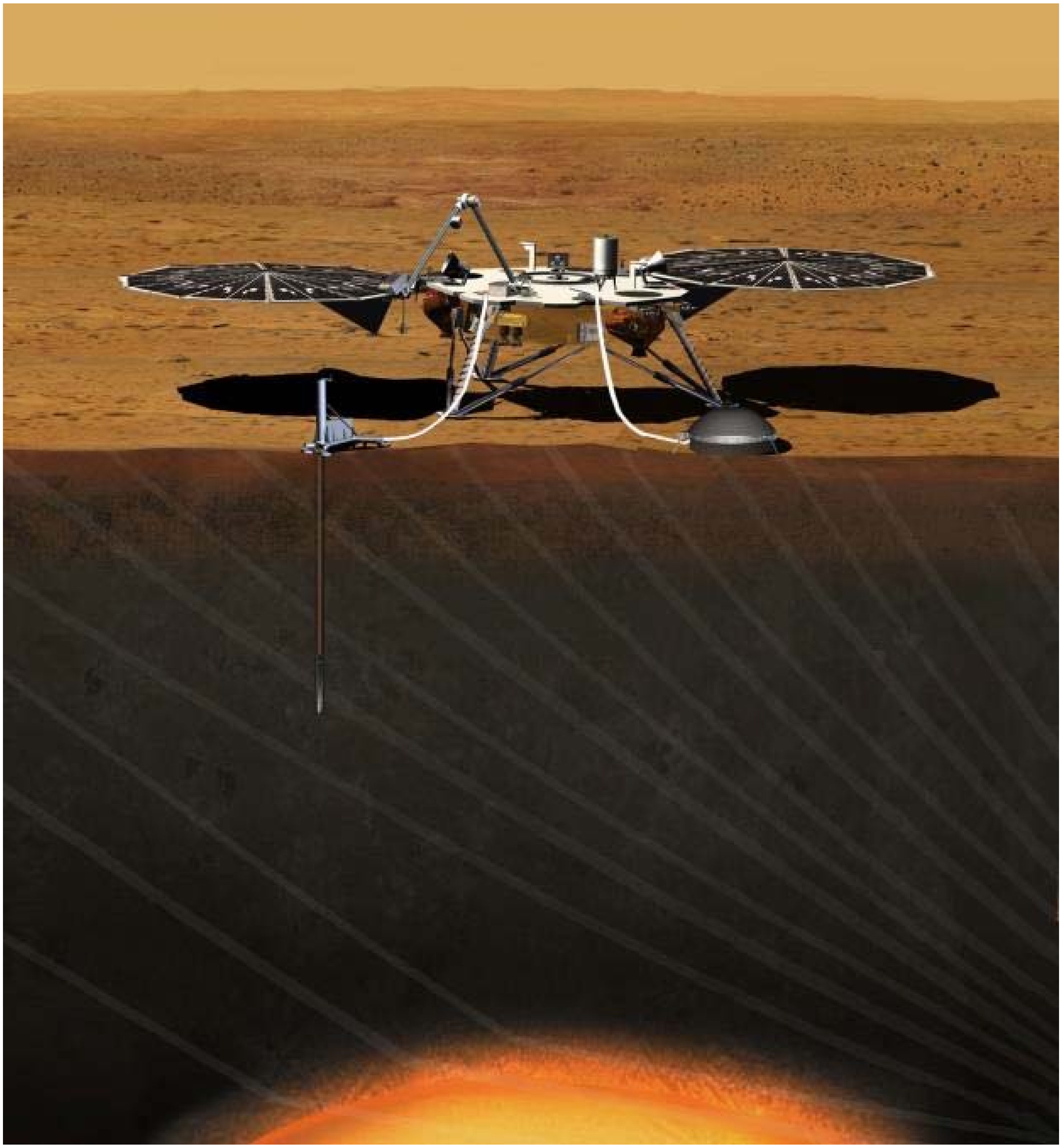

FIGURE 5.4 Concept image of InSight on the surface of Mars, probing the ground. SOURCE: NASA/JPL.

Since *Vision and Voyages* was written, scientifically compelling new discoveries about Mars have continued to be made. These significantly change the scientific understanding of Mars as a planet from what it had been in ~2010 during the writing of *Vision and Voyages*:

1. Modern Mars is dynamic, with active aeolian sedimentation, unexplained release and consumption of methane, recurrent slope lineae (RSL) formed by a mechanism that may involve extant brines or deliquescence, and fluvial-like sedimentation driven by ablation of seasonal CO_2 ice—a process with no Earth analog.

2. Ancient Mars contained at least a dozen distinct liquid water environments, of which half were possibly habitable. This is a much greater diversity than was recognized by *Vision and Voyages*. They are recorded by a surprising abundance and diversity of hydrated mineral assemblages and landforms indicative of lacustrine, pedogenic, alluvial, and hydrothermal environments. A single sample return mission will explore only one or, at most, two of these environments.
3. There is widespread, shallow pure ice at midlatitudes, possibly the remnant of late Amazonian ice ages, or possibly the result of mobilization and concentration of ground ice.
4. A reservoir of frozen CO_2 is buried in the polar caps. If released, it could double atmospheric pressure.
5. A thicker ancient atmosphere was lost to space, primarily by solar-driven processes.

The newly discovered water resources bound in minerals and as shallow segregated ground ice represent a profound overlap in the objectives of scientific investigation of Mars and preparation for future human exploration.

PRESENT STATUS OF THE MARS EXPLORATION PROGRAM

NASA's Mars Exploration Program (MEP) is a science-driven, technology-enabled study of Mars as a system meant to understand the following:

- The formation and early evolution of Mars as a planet;
- The history of geological and climate processes that have shaped Mars through time;
- The potential for Mars to have hosted life (its "biological potential"); and
- The surface environments and resources relevant to future exploration of Mars by humans.

The MEP's evolving science strategy is meant to be consistent with the priorities outlined in *Visions and Voyages*, which are formed into specific requirements applied to individual missions. It receives science input from interactions with the planetary and Mars science community (primarily through MEPAG).

Mars Exploration Program History and Organization

The MEP was begun in 1994, initially under the name Mars Surveyor Program. NASA assigned the lead role for the MEP implementation to the Jet Propulsion Laboratory (JPL). The MEP explores Mars on behalf of NASA's Science Mission Directorate (SMD). It currently operates rovers and orbiters on and around Mars, supports Mars missions conducted by U.S. and international partners, and is formulating and developing future missions. MEP missions are organized into a program, and mutually support each other. Scientific discoveries by one mission drive the formulation of the scientific foci of future missions. Acquired data crucially inform the implementation of future missions. For example, orbital missions like MGS, Odyssey, and MRO provide data for identifying, characterizing, and certifying landing sites for future missions like Phoenix, MSL, ExoMars, and Mars 2020, and landed assets provide ground truth for orbital remote sensing. (See Figures 5.5, 5.6, and 5.7.) Measurements of the atmosphere made by orbiters are crucial to supporting the entry, descent, and landing (EDL) of surface vehicles. Observations by landed assets are interpreted and placed into context using research results from orbital measurements, thus informing an understanding of Mars as a system. In addition, MEP missions develop and demonstrate engineering capabilities that enable future missions, and MEP orbiters enhance the scientific return of landed missions by serving as telecommunication relays, enabling significant increases in data return.

FIGURE 5.5 Artist rendering of Mars Reconnaissance Orbiter. SOURCE: NASA.

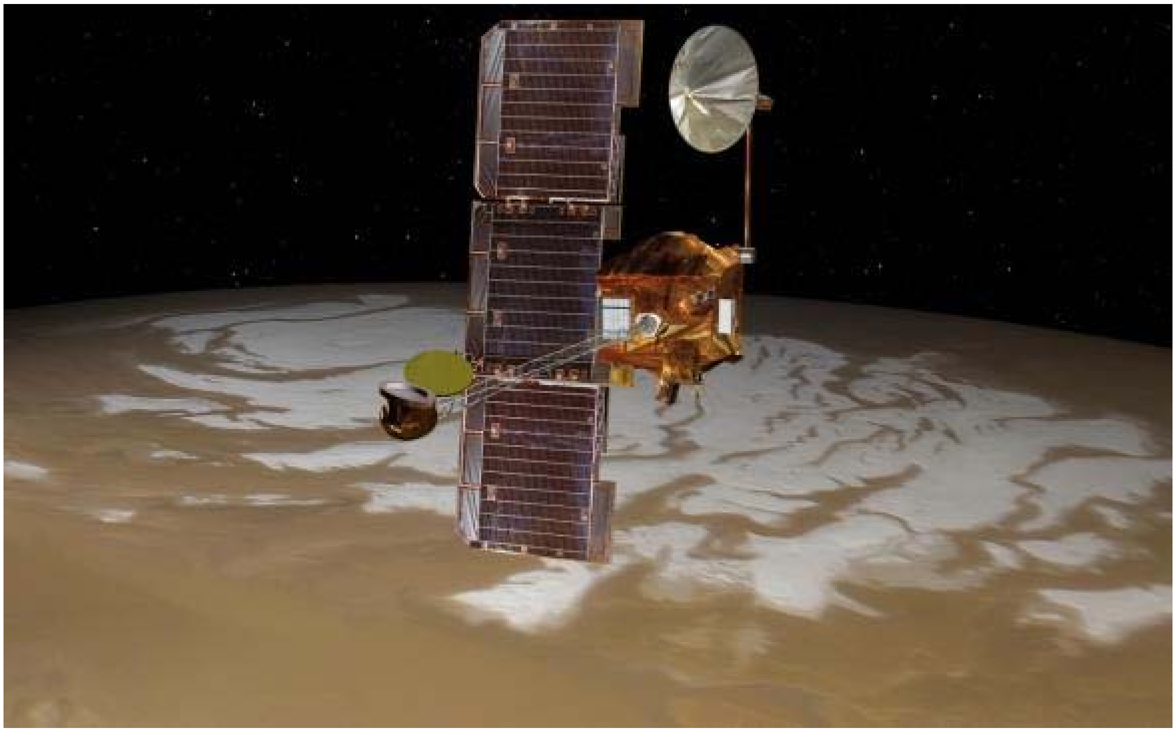

FIGURE 5.6 Artist rendering of Mars Odyssey above Mars. SOURCE: NASA.

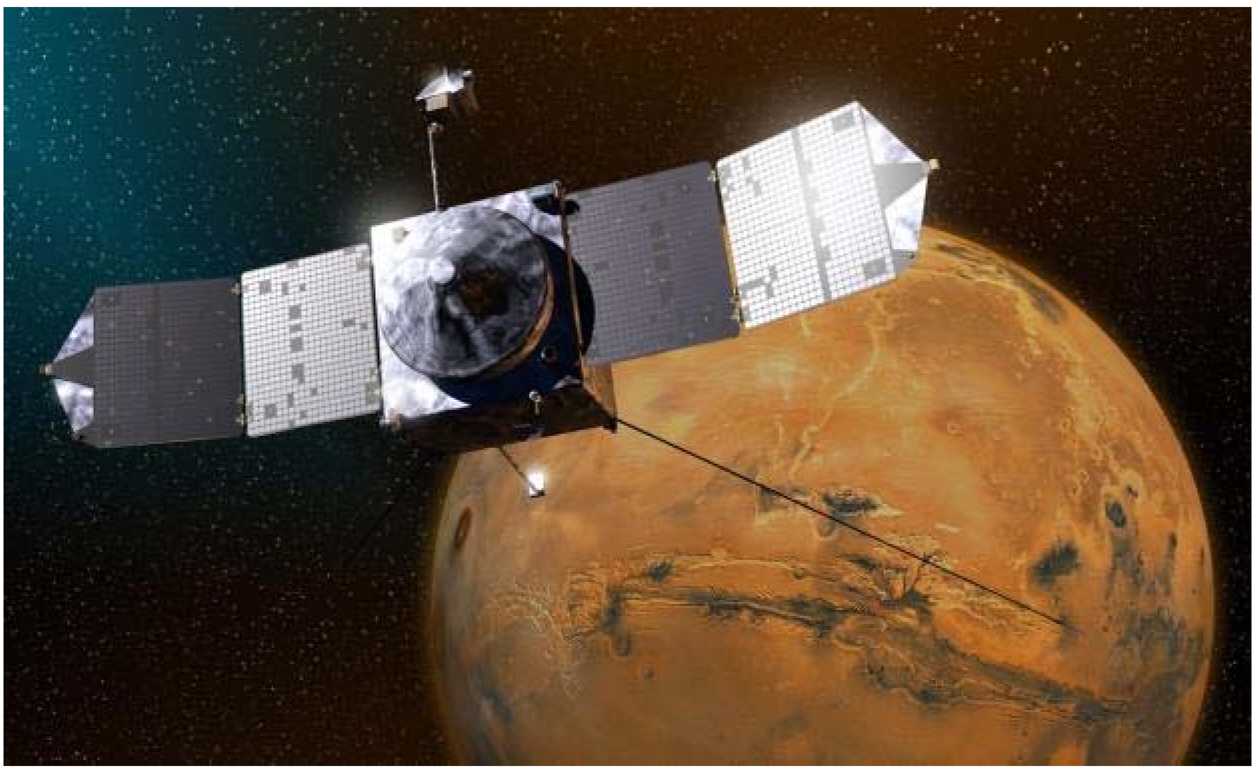

FIGURE 5.7 Artist rendering of MAVEN above Mars. SOURCE: NASA.

To support an integrated program structure, the MEP carries out a number of activities that provide long-term investments for the future, including the following:

- The Mars Data and Analysis Program (MDAP) is a research and analysis effort that sponsors detailed studies of data returned from Mars missions that yield fundamental scientific results and help shape future MEP missions. Research conducted through MDAP formulates new science questions for Mars and tests current hypotheses.
- The Program Formulation Office conducts advanced studies of future missions. Studies and planning for these missions, as well as identification of technology needed to implement them, are the focus of long-range technology investments. Advanced studies also address Mars telecommunication capabilities and other programmatic needs (e.g., meteorological measurements for landers, landing site certification). These needs can be met through a mixture of directed and competed missions. Future mission concepts also address preparations for the future human exploration of the martian system.
- The MEP supports implementation of both directed and competed missions. The latter have included the Phoenix mission, which landed in the northern polar region of Mars to study ice, and the MAVEN mission, which is quantifying the rate of escape of atmospheric gases from the planet and implications for the ancient martian climate. Both were selected for flight under the former Mars Scout program.

Mars Exploration Program Missions in Flight and Development

The history of MEP missions illustrates the benefits of an organized program and funding line for conducting hypothesis-driven science, where one mission's results inform results of the other missions. For example, Mars Pathfinder pioneered the airbag landing system later used by the MER rovers Spirit and Opportunity, and its Sojourner rover helped in the development of rover operations. MGS achieved Mars orbit in 1997. It carried the Thermal Emission Spectrometer (TES), Mars Orbiter Laser Altimeter (MOLA), Mars Orbiter Camera (MOC), and Magnetometer (MAG) and Electron Reflectometer (ER). Its accomplishments included the first global map of mineralogy of surface materials, the beginning of acquisition of a climatological record of atmospheric dust and ice aerosols and water vapor, a highly accurate global topographic map, thousands of high-resolution images, and a map of magnetization of crustal rocks. These data enabled discovery of widespread sedimentary rocks, including the hematite-rich materials explored by MER/Opportunity. MOC images revealed active formation of gullies by some type of fluid flow, initially hypothesized to involve water. MAG mapping of crustal magnetization showed that early Noachian rocks formed in a magnetic field that subsequently shut down.

Mars Odyssey orbiter entered orbit in 2001. Its Gamma Ray Spectrometer mapped elemental composition of surface materials, and its Neutron Spectrometer detected large amounts of hydrogen in the upper meter of regolith at high latitudes that can only be explained by a high abundance of subsurface ice. That ice was later explored by Phoenix. Odyssey's Thermal Emission Imaging System (THEMIS) discovered olivine-rich igneous rocks, chloride-rich sedimentary deposits, and midlatitude mantles interpreted as relict layers of ice-rich airfall deposits formed during a late Amazonian period of high obliquity.

In 2004 the MER rovers Spirit and Opportunity landed at Gusev crater and Meridiani Planum, respectively, to investigate a paleolake basin known from Viking images and hematite-rich sediments found by TES. Spirit found no lake sediments, but on its traverse to older terrain found sulfate- and silica-rich materials likely formed in a hydrothermal system. Opportunity found that the hematite resides in late Noachian sulfate-rich sedimentary deposits interpreted to have been precipitated from discharge of saline groundwater. It then traversed to clay-bearing early Noachian rocks discovered by MRO, and found that those rocks formed by partial alteration of a basaltic protolith in a subsurface groundwater environment.

MRO, in orbit since 2006, is equipped with the High-Resolution Imaging Science Experiment (HiRISE), Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), Shallow Radar (SHARAD), Mars Climate Sounder (MCS), and Mars Color Imager (MARCI). MRO has made numerous discoveries about Mars, including exposures of aqueously altered rocks that record a dozen diverse ancient wet environments, deposits of shallow, nearly pure water ice present at mid- and high latitudes, active migration of dunes at rates that indicate Earth-like sand fluxes, a buried deposit of CO_2 ice in the north polar layered deposits that—if released—would double atmospheric pressure, interannual and seasonal characteristics of atmospheric temperature and aerosols, and dynamic processes in the residual and seasonal CO_2 ice caps. MRO's MCS, MARCI, and CRISM instruments—together with Mars Odyssey/THEMIS—have extended the climatological record begun by MGS to over 10 Mars years. Perhaps the most provocative MRO finding is the presence of recurring slope lineae (RSL), downslope flow features that appear in summer and may involve brine or deliquescent salts, but could also be dust avalanches.

In 2008 Phoenix landed in the north polar region of Mars after an extensive search for a safe site by HiRISE. Its robotic arm dug into the Martian soil, and the presence of shallow, nearly pure water ice was confirmed. It also discovered that perchlorate salts are prevalent in the regolith. Perchlorates are powerful freezing point depressants and are hypothesized to be involved in formation of RSL; they can react with organics and may explain the nondetection of organics by the Viking landers.

The MSL rover Curiosity landed at Gale crater in August 2012 at a site selected primarily using MRO data. Its investigations include the ChemCam laser chemical sampler that can deduce the make-up of rocks at a distance of up to 7 meters using laser-induced breakdown spectroscopy (LIBS), the CheMin and Sample Analysis at Mars (SAM) compositional experiments, and the Mars Hand Lens Imager (MAHLI). MSL's mineral and chemical analyses of the Sheepbed mudstone conclusively demonstrated the presence of a habitable lake environment on early Mars, with low salinity, moderate pH, biologically necessary elements, and an energy source in the form of mixed oxidation state Fe- and S-bearing phases that could support chemolithotrophic metabolism. SAM initially detected a lower methane abundance than could be explained given meteoritic carbon inputs, followed by elevated then promptly decaying methane abundances. Either a geologic or a biologic source is episodically releasing the gas.

MAVEN reached Mars in 2014 with the objectives of observing and quantifying the influence of the Sun on upper-atmospheric structure and behavior, and of measuring the present-day escape rates of atmospheric species. These results plus modeling enable inference of the past history of atmospheric escape and the total amount of gas that has been removed to space through time. Results and modeling to date suggest that a half bar or more of atmosphere has been removed since the early Noachian, providing an explanation for the change in climate inferred from observations of the geology and mineralogy of the surface.

The final approved MEP mission is the Mars 2020 rover, a version of the Mars Astrobiology Explorer/Cacher (MAX-C) that was prioritized within the decadal survey, modified to reduce its cost. Mars 2020 will take the first step toward Mars Sample Return by collecting and caching small core samples from a site containing the two highest priority materials for sample return, unaltered volcanic materials and either lacustrine or hydrothermal sediments emplaced in a past habitable environment that may be capable of preserving biosignatures. Careful documentation of the samples' geologic context will be provided by a combination of remote and contact investigations. The remote investigations include Mastcam-Z, a panoramic and stereoscopic camera system with the ability to zoom; SuperCam, which provides imaging, chemical analysis from LIBS, and mineralogy from reflectance and Raman spectroscopy; and the Radar Imager for Mars's Subsurface Experiment (RIMFAX), a ground-penetrating radar that will provide centimeter-scale resolution of the shallow subsurface. Contact investigations include the Planetary Instrument for X-ray Lithochemistry (PIXL) to determine fine-scale elemental composition, and Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC), which will employ fine-scale imaging and an ultraviolet (UV) Raman to determine fine-scale mineralogy and search for organic compounds.

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FIGURE 5.8 The MEP budget, adjusted for inflation, since 2000 (red). Values from 2000 to 2016 are "actual" amounts spent, and 2017 is the "enacted" amount. Note the large fluctuations beginning in FY 2009 and FY 2013, which correspond in large part to gaps between missions in development. The increased gaps between missions exacerbated the challenge of managing these missions as an integrated program. The cost of continued operation of extended missions is nontrivial and in the 2010s has comprised typically ~20-40 percent of the MEP budget. Figure does not include the cost of the InSight mission, which was part of the Discovery budget. SOURCE: Adapted from Callahan and Dreier (2017) and provided by Jason Callahan.

Permission Pending

FIGURE 5.9 The MEP as a percentage of NASA's total budget (blue) and as a percentage of the Science Mission Directorate's budget (green). Values from 2000 to 2016 are "actual" amounts spent, and 2017 is the "enacted" amount. Note the large fluctuations beginning in FY 2009 and FY 2013, which correspond in large part to gaps between missions in development. The cost of continued operation of extended missions is nontrivial and in the 2010s has comprised typically ~20-40 percent of the MEP budget. Figure does not include the cost of the InSight mission, which was part of the Discovery budget. SOURCE: Adapted from Callahan and Dreier (2017) and provided by Jason Callahan.

Mars Exploration Program Future Plans

Figures 5.8 and 5.9 illustrate the MEP budget from 2000 to present. The MEP budget includes costs for spacecraft development, operation of existing spacecraft, and analysis of returned data. During the 2010s, operation of missions beyond their nominal durations into extended missions has been highly beneficial and cost-effective, with major new discoveries being made after the prime mission using existing flight hardware. During the same period, the MEP has shifted to more expensive, large-rover missions to address scientific questions posed by orbiter missions, while simultaneously shouldering the cost of operating existing Mars spacecraft. A combination of the focus on MSR, the constrained budget to formulate it, and the lack of formal approval for the Fetch Rover/MAV and Sample Return Orbiter has resulted in lack of a defined schedule and budget to implement Mars Sample Return and lack of a long-term plan besides sample return. The net effect has been two main consequences:

1. All Mars surface missions listed above—plus the InSight Discovery mission—rely on Mars orbital missions now in flight for a UHF relay to return data to Earth. Of all NASA orbiters with this capability, only MAVEN has been operating less than 12 years. MRO is the major relay asset, and it is aging. The lack of a new orbiter in development means that the Mars telecommunications infrastructure is not being renewed, and is subject to aging and potential failure.
2. Chapter 2 described a variety of new Mars discoveries since the publication of *Visions and Voyages*, including the diversity of wet environments on ancient Mars beyond the one or possibly two that will be sampled by Mars 2020, the occurrence of widespread shallow, nearly pure ice, and the possibility of modern briny flows. There are no current Mars Exploration Program plans for follow-up investigation of these or other findings, either for hypothesis-driven science that has been the hallmark of the MEP, or for assessment of resources for future human exploration.

MEPAG has been keenly aware of these shortcomings in future plans, and in 2015 developed a concept for a Next Mars Orbiter to replenish the Mars telecommunications infrastructure and perform follow-up investigations of new discoveries since *Vision and Voyages*. NASA has not yet been successful in including such a mission in its budget.[1]

[1] Such an orbiter would cost on the order of a Discovery-class mission, although it could cost more or less depending on requirements and whether it includes scientific instruments.

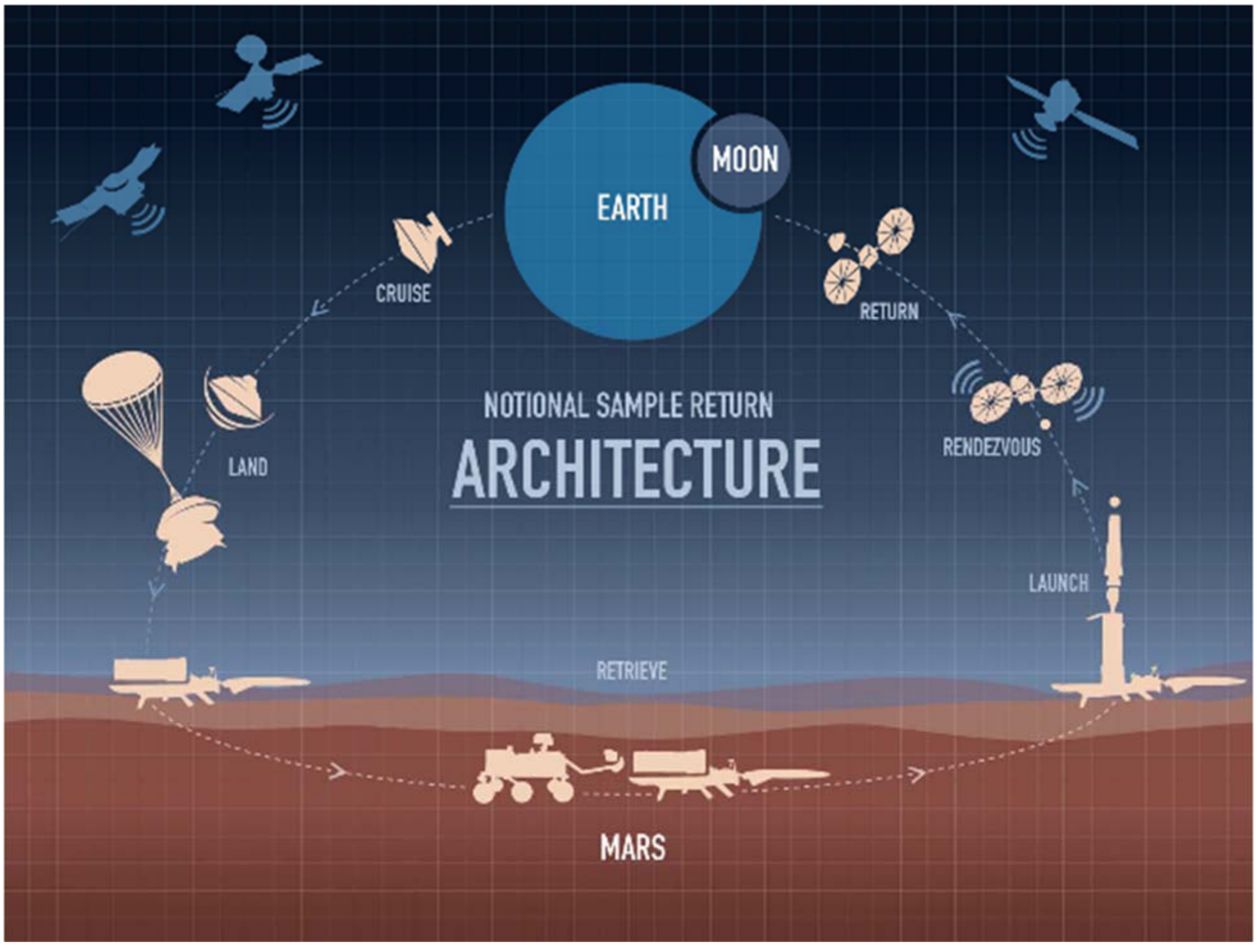

FIGURE 5.10 Notional concept image for implementation of the two future missions required to complete Mars Sample Return, a Fetch Rover and Mars Ascent Vehicle, and a Sample Return Orbiter. SOURCE: NASA.

The Prospect of "Lean and Rapid" Mars Sample Return

In August 2017 NASA Associate Administrator Thomas Zurbuchen announced a concept for a "lean and rapid" Mars Sample Return. (See Figure 5.10.) The "lean and rapid" nickname is based on the strategy of focusing future mission development on completing the two remaining steps to Mars Sample Return in the decade of the 2020s, following the Mars 2020 mission. Notionally, it is enabled fiscally by (1) making the completion of Mars Sample Return the sole MEP scientific objective for the 2020s, and (2) implementing the concept with strong international participation. In the "lean and rapid" concept, there would be no Next Mars Orbiter; existing assets (Odyssey, MRO, MAVEN, Trace Gas Orbiter) would continue to provide telecommunications interfaces for landed assets through Mars 2020 (also including MSL, InSight, and ExoMars).[2] A U.S. Fetch Rover/MAV mission would launch at the same opportunity as a Sample Return Orbiter (SRO) provided through international collaboration, nominally in 2026. Telecommunications support for the Fetch Rover/MAV would fly on the SRO itself, mitigating the risk of aging infrastructure *for the Fetch Rover/MAV*. The fetch rover would have a 240-sol mission duration to retrieve samples, deliver them to the MAV's sample return capsule (SRC), and address any

[2] The possibility of a commercial communications architecture has also been discussed.

anomalies before the MAV would launch. The SRO would collect SRC containing the cached samples, and return it either directly to Earth or to cis-lunar space for astronaut retrieval.

Presentations to the committee by JPL engineers provided comprehensive descriptions of the conceptual design of the Fetch Rover/MAV. Extensive trade studies have been carried out, leading to a point design. A hybrid MAV propulsion module (oxidizer and paraffin-based fuel) is in an advanced stage of testing. (See Figures 5.11, 5.12, 5.13, 5.14, 5.15, and 5.16.) The SRC conceptual design meets all *Vision and Voyages* science requirements for sample return, by including with the cached sedimentary or hydrothermal and volcanic samples receptacles for fetch rover-collected regolith and an atmospheric gas sample. The scenario for capture of the SRC by the SRO has been designed and analyzed, and appears to be within current technological capabilities.

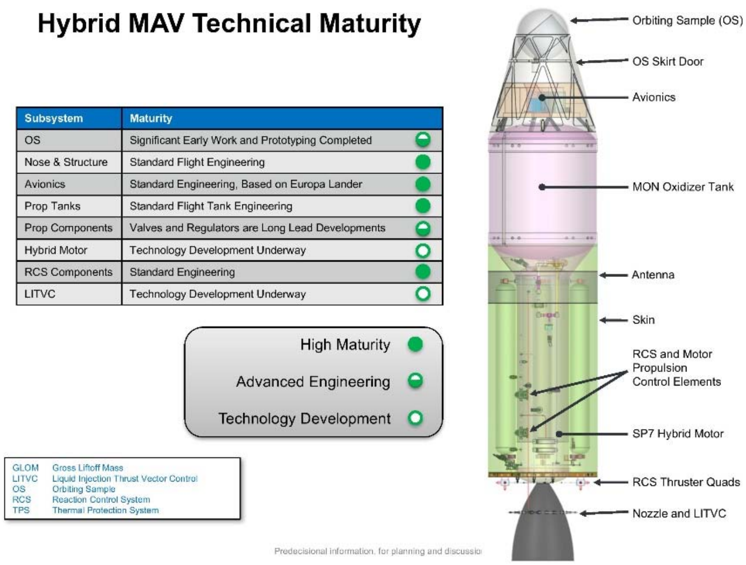

FIGURE 5.11 Schematic image of the Mars Ascent Vehicle (MAV) currently under study. MAV technology is finally making substantive progress. SOURCE: JPL.

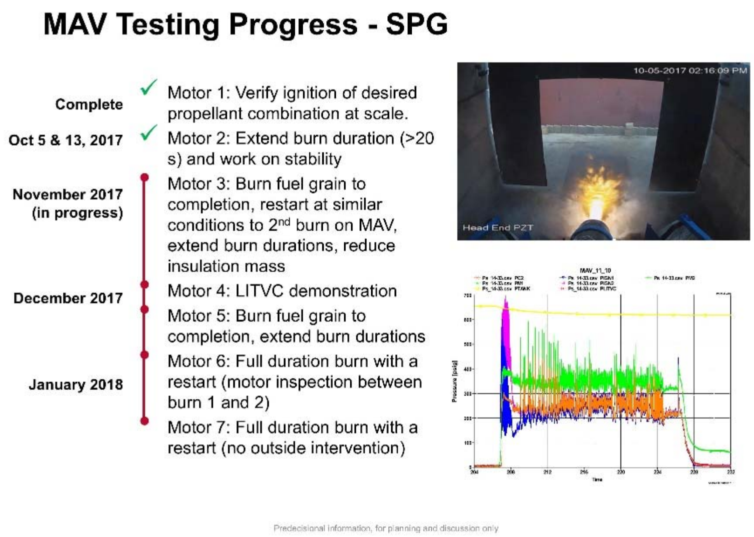

FIGURE 5.12 Test of one of the MAV hybrid rocket motor engines in fall 2017. SOURCE: JPL.

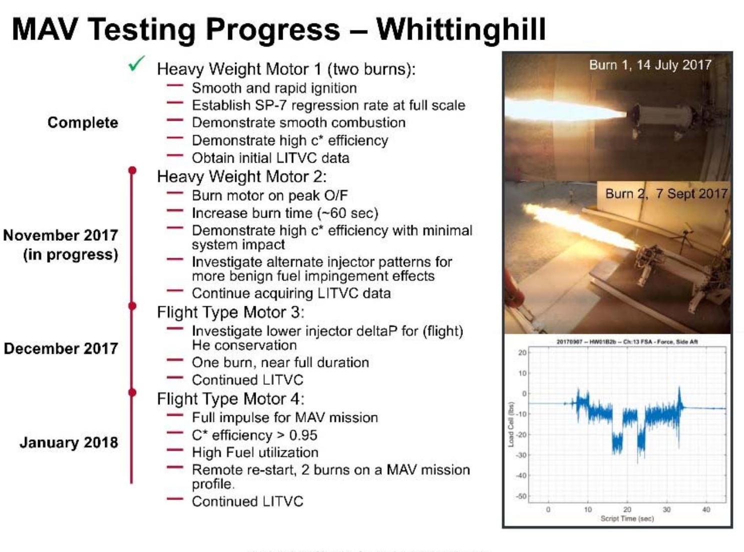

FIGURE 5.13 Test of one of the MAV hybrid rocket motor engines in fall 2017. SOURCE: JPL.

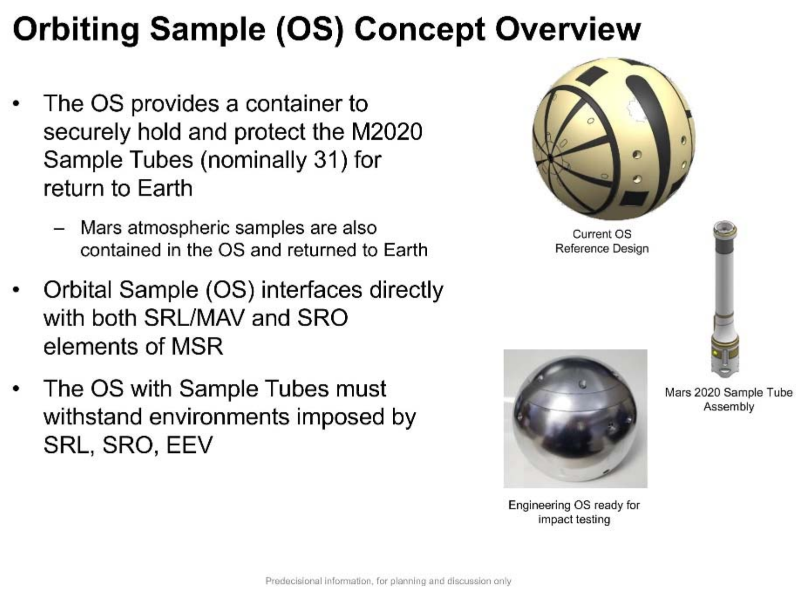

FIGURE 5.14 Concept design for the Orbiting Sample vehicle that would carry samples collected by the Mars 2020 rover. SOURCE: JPL.

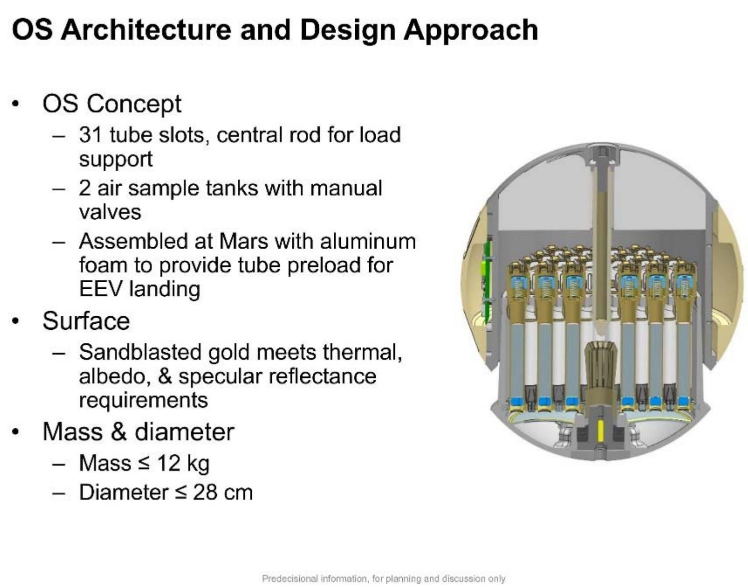

FIGURE 5.15 Concept design for the Orbiting Sample vehicle that would carry samples collected by the Mars 2020 rover. SOURCE: JPL.

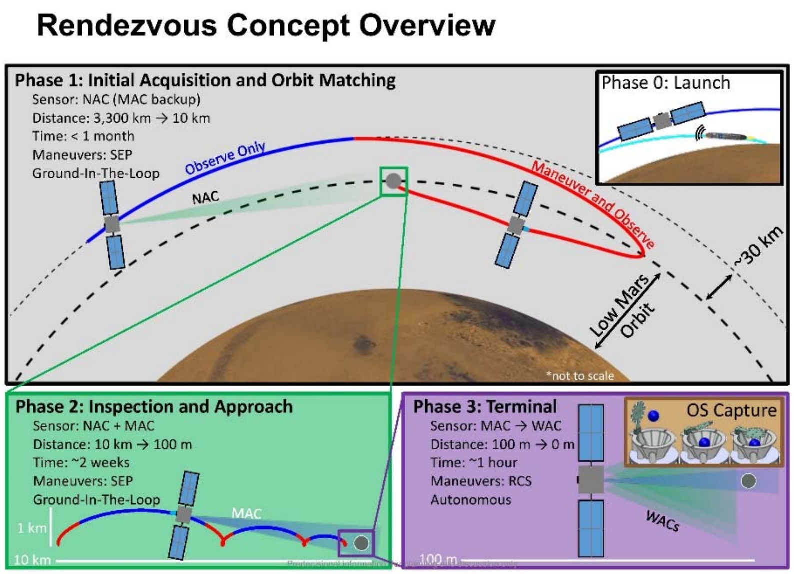

FIGURE 5.16 Rendezvous concept for the Orbiting Sample vehicle that would carry samples collected by the Mars 2020 rover. SOURCE: JPL.

Assessment of the Current Status of the Mars Program

Based on considerations of the state of published Mars science summarized in Chapter 2, the material summarized in this chapter and the committee's direct knowledge of the Mars program, an assessment of the Mars program status is given below. Subsection headings reiterate the subjects this committee was charged to assess.

Mars exploration architecture and its responsiveness to the strategies, priorities, and guidelines put forward by the National Academies' Vision and Voyages *and other relevant National Academies Mars-related reports*

Decadal Findings and Assessment: *Vision and Voyages* recommended de-scoping the MAX-C mission concept if necessary to ensure that it would cost ≤$2.5 billion, and proceeding to collect at least the minimum number of samples defined by advisory groups (>20, baseline 31), from the highest priority classes of materials for sampling. In the current MEP architecture, Mars 2020 is within the cost goal and can accomplish the first two high-priority sampling objectives (lacustrine or hydrothermal sediments, unaltered volcanic rock). The Fetch Rover/MAV are being designed to collect the remaining sample types recommended by *Visions and Voyages* (regolith, atmosphere).

Vision and Voyages also recommended robust in situ measurements to aid in selecting the samples to be collected and to put them into context. Such measurements can be completed by the selected Mars 2020 science investigations. In fact, the selected payload provides redundancy in each type of characterization measurement recommended by the Mars 2020 Science Definition Team (chemistry, mineralogy, geologic setting).

Vision and Voyages recommended major investment in design work on a MAV, thus making significant progress on the second step for sample return. The new solid rocket motor design can survive long-term exposure to low temperature, and is being tested to qualify it for flight, thus maturing that aspect of the required technology.

Vision and Voyages also recommended continuation of ongoing missions that address evolving science objectives through a Senior Review process. Operating missions have developed and address new science objectives that respond to emerging findings, meeting this recommendation.

Although not formally part of the MEP, the InSight Discovery mission is addressing questions about Mars's interior that were prioritized in National Academies reports on Mars prior to *Vision and Voyages*.

Finding: Mars 2020 will fulfill the mandate of *Vision and Voyages* that "a critical next step [to Mars Sample Return] … would be provided through the analysis of carefully selected samples from geologically diverse and well characterized sites."

Finding: The "lean and rapid" conceptual approach to a Fetch Rover/MAV and an SRO described by NASA to the committee is on track to be fully responsive to completing the *Vision and Voyages* highest-priority flagship-class science, Mars sample return (MSR). The detailed architecture including specific international involvement is still under conceptual development. The FY 2019 budget, approved by Congress and signed by the president during the writing of this report, appears to provide funding to continue development and plan implementation.

Finding: NASA is making substantial progress on technology development that will be required for MSR. This includes, but is not limited to, the MAV propulsion system, the Sample Return Capsule, and the approach to orbital rendezvous and capture. A sample analysis and curation facility will also be required.

Recommendation: NASA should continue planning and begin implementation of its proposed "lean and rapid" architecture to return samples from the Mars 2020 mission to achieve the highest-priority decadal survey flagship-class science for consideration for the next decadal survey.

The long-term goals of the Planetary Science Division's Mars Exploration Program and the program's ability to optimize the science return, given the current fiscal posture of the program

Decadal Findings and Assessment: The Mars 2020 mission will be a significant first step toward MSR and will accomplish in situ science in addition to sample collection. Mars 2020 also hosts MOXIE, a demonstration of in situ resource utilization (oxygen extraction), which will make a meaningful step toward preparing for future human exploration.

Successful operation of MSL, InSight, the ExoMars lander, Mars 2020, and any subsequent directed or competitively selected Mars landed mission depends on orbital communications infrastructure to return adequate data to Earth. The loss of even one of the three U.S. orbiters capable of relay communications (Mars Odyssey, MRO, MAVEN) would create tactical challenges (e.g., reduction of daily passes to support operations) for continued operation of current (MER, MSL) and planned (InSight, ExoMars, Mars 2020) landed missions through the mid-2020s. Mars Odyssey is not expected to survive to the mid-2020s, MRO has experienced hardware anomalies that challenge the mission to survive until the (possibly optimistic) SRO launch date of 2026, and MAVEN already is past its nominal design lifetime.

In the program architecture described by NASA, there is no plan to replenish orbital communications infrastructure, except temporarily via the SRO associated with MSR. This lack of a long-term telecommunications infrastructure risks extended mission operations of InSight and Curiosity without international assistance. It risks or precludes extended mission operations of Mars 2020 after Earth return of the SRO, when the highly capable rover could continue in situ exploration of exobiologically relevant geologic formations, as well as any follow-up exploration by Discovery or New Frontiers missions, or by non-U.S. missions that currently are supported by U.S. telecommunications assets.

Finding: There is a risk that ongoing and soon-to-be landed assets on Mars will be left without telecommunications support because of the aging orbiters. The Mars telecommunications relay network is marginally able in its present form to service current and planned surface missions. The system is fragile and aging. The loss of even one of the three U.S. orbiters capable of relay communications (Mars Odyssey, MRO, MAVEN) would create tactical challenges for continued operation of current and planned landed missions beyond 2021, and compromise the ability of the MEP to continue its science return. The committee was not presented with and did not evaluate the possibility of commercially provided telecommunications capabilities to supplant telecommunications capabilities being used. Also, despite the hardware capability, there is no plan for the European Space Agency (ESA)'s Trace Gas Orbiter (TGO) to be used as a relay asset in the immediate future.

Recommendation: NASA should ensure the longevity of the telecommunications infrastructure at Mars to support the science return from current and planned landed assets (e.g., MSL, Insight, ExoMars, Mars 2020), to mitigate the risks associated with the existing aging assets. This should not be accomplished by sacrificing the science being conducted by existing orbiters.

The Mars exploration architecture's relationship to Mars-related activities to be undertaken by foreign agencies and organizations

Decadal Findings and Assessment: Mars missions are being undertaken both by NASA and by several non-U.S. space agencies. Most of the missions feature one or more international collaborations, both on foreign-led missions with U.S. participation or collaboration, and on U.S.-led missions with foreign participation or collaboration. These collaborations dramatically enhance the overall scope of Mars science being conducted, both in terms of investigations flown and investigators analyzing the returned data.

Examples of international cooperation span many nations and objectives. Mars Express (ESA) includes U.S. participating scientists on the MARSIS radar from Italy, which was developed with JPL participation, and on the OMEGA imaging spectrometer from France. MRO (U.S.) hosts the SHARAD radar from Italy, and that team contains a strong contingent of U.S. scientists, some in leadership roles. InSight (U.S.) hosts the SEIS seismometer from France and the HP3 heat flow probe from Germany. Mars HOPE (UAE) is working with U.S. partners who will develop instruments and subsystems. The University of Colorado/Laboratory for Atmospheric and Space Physics is partnering in development of the Emirates Exploration Imager (EXI), the Emirates Mars Ultraviolet Spectrometer (EMUS), the spacecraft, and mission operations. Arizona State University is partnering in development of the Emirates Mars Infrared Spectrometer (EMIRS), and the Johns Hopkins Applied Physics Laboratory is providing the telecommunications sub-system. The Mars Moons Explorer mission (MMX, Japan) is hosting the NASA-funded MEGANE neutron and gamma-ray spectrometer being provided by the Johns Hopkins Applied Physics Laboratory. The Mars 2020 rover (U.S.) hosts the MEDA meteorological package (Spain), the RIMFAX ground-penetrating radar to provide additional context for collected samples (Norway), and SuperCam (France), which provides microscopic imaging, LIBS measurements of chemistry, and Raman and reflectance spectroscopic measurements of mineralogy. Last, the ExoMars rover (ESA) hosts the MOMA experiment (U.S.) to search for and characterize even trace levels of organic molecules.

In addition, there are several notable examples of close international collaborations between teams that pursue complementary or related scientific objectives. The Mars Express/OMEGA and MRO/CRISM teams, the Mars Express/MARSIS and MRO/SHARAD teams, and the MAVEN, Mars Express, and TGO teams have all collaborated closely.

Undeniably, there have been issues with international partnerships. Late delivery of SEIS caused a two-year delay in the launch of InSight. A U.S. component of the ExoMars Trace Gas Orbiter payload was solicited and selected but then canceled due to lack of adequate U.S. funding. Limitations on funding by the Italian Space Agency led to temporary suspension of SHARAD operations and data product generation.

On balance, international collaborations have been positive. The MEP can benefit from many planned international collaborations and missions over the coming decades. Perhaps the largest impending collaboration would be on Mars Sample Return. In a recently signed Letter of Intent, NASA and ESA described a potential international collaboration in which ESA might provide a Fetch Rover for the MAV, and NASA would provide the SRC for an ESA-led SRO. Maintaining political support for that collaboration would benefit from strong incentives such as sharing of the returned samples. There is precedent for distributing returned samples among nations who contribute to a sample return mission. Returned samples are traditionally allocated to individual researchers among the full international community after a period of preliminary examination.

Finding: Missions to Mars being led by non-U.S. entities (including ExoMars, Trace Gas Orbiter, Mars HOPE, and Mars Moon Explorer) benefit and significantly augment the U.S. Mars Exploration Program and lead to a broader scientific exploration of Mars.

Recommendation: NASA should immediately work to reinvigorate international cooperation to help implement Mars exploration more effectively and affordably. This could involve international contributions of instruments, other hardware, or whole missions that complement what the United States is providing or leading, as suggested in *Visions and Voyages* and as proposed in the "lean and rapid" concept for Mars Sample Return.

The extent to which the Mars exploration architecture represents a reasonably balanced mission portfolio

Decadal Findings and Assessment: Major new science questions have emerged since *Vision and Voyages* that will not be addressed by Mars Sample Return or any U.S. mission now in development or operation. These questions center on ancient habitable environments, Amazonian climate change, and the dynamic nature of present-day Mars:

- *Ancient Mars:* In which, if any, of the ancient habitable environments did life exist? If in some but not others, why? What do the answers imply for emergence of life on small terrestrial exoplanets?
- *Amazonian Mars:* What are the distribution and characteristics of shallow ground ice? What processes formed shallow, excess ice? What is the history of climatic variations recorded in excess ice? How do those climatic variations relate to obliquity variations possibly recorded in polar deposits, and to release or refreezing of CO_2 ice buried in the polar caps?
- *Modern Mars:* What processes form RSL and what is the role of brines or deliquescence, if any? If water is involved, what is its source? What is the source of methane releases, and why are they episodic? Why does the methane appear and disappear so quickly? What is the relationship between atmospheric processes observed to operate seasonally and annually and climate change operating on the 10^4- to 10^7-year time scales?

A majority of high-priority Mars science questions that have emerged since *Vision and Voyages* cannot be fully addressed by single, stand-alone missions. The science and exploration arguments for an ongoing Mars program include (1) that Mars science questions cut across multiple important decadal survey science themes; (2) the potential for life to exist or have existed on Mars and the inability of a single mission to definitively determine in what environments it existed and did not exist, and (3) the need to prepare for potential future human missions to Mars.

Science questions and preparation for human exploration overlap. For example, investigating the distribution of shallow excess ice will quantify an important resource to provide astronauts with water and oxygen (Dundas et al., 2018). Improved understanding of the hydrated mineral assemblages that record ancient habitable environments will characterize their recoverable water contents; water resources recoverable from those deposits are highly uncertain at present (Murchie et al., 2016; Bishop et al., 2017).

Programmatic arguments for an ongoing program include the requirement for technology development for future missions and the scientific and technical interplay among missions. A prime example of the latter is the need for meteorological measurements and high-resolution orbital remote sensing to support surface missions. At the present time, NASA has no plans to replenish the capabilities of MRO for high-resolution imaging that have proven so important for landing-site certification, including monitoring of the meteorology required for entry, descent, and landing, and high-resolution imaging to support strategic planning of landed science.

The European Space Agency's ExoMars Trace Gas Orbiter will follow up on the recent confirmation of methane. However, the U.S. Mars Exploration Program has no mechanism beyond the Discovery Program to investigate other compelling new discoveries since the last decadal survey, either scientifically or to assess resource potential for future human exploration.

Finding: There are strong arguments for continuing Mars exploration through a program rather than as a series of independent, unconnected missions. Although the current MEP has a broad focus across most areas of Mars as a system, the program going forward beyond Mars 2020 is focused entirely on sample return. There is currently no vision for a program beyond sample return, either for scientific investigation or to prepare for future human exploration.

Finding: There are no plans at present to replace the site characterization and monitoring capabilities of MRO that have proven important for landing-site certification and strategic planning of landed science.

Finding: The MEP has not yet put forward a complete architecture and attendant strategic plan that addresses the long-term goals of Mars exploration and optimizes science return across the spectrum of past, current, and future missions.

Recommendation: NASA should develop a comprehensive MEP architecture, strategic plan, management structure, partnerships (including commercial partnerships), and budget that address the science goals for Mars exploration outlined in *Visions and Voyages*. The architecture and strategic plan should maximize synergy among existing and future domestic and international missions, ensure a healthy and comprehensive technology pipeline at the architectural (vs. individual mission) level, and ensure sustenance of foundational infrastructure (telecommunications, imaging for site certification, etc.). This approach of managing the MEP as a *program*, rather than just as a series of missions, enables science optimization at the architectural level. This activity should include assurance that appropriate NASA/MEP management structure and international partnerships are in place to enable Mars Sample Return.

SUMMARY OF THE CURRENT STATUS OF THE MARS EXPLORATION PROGRAM

NASA has been exploring Mars for over 50 years. (See Figure 5.17.) Mars is a high priority for scientific study because of its strong relevance to all of the science themes of *Visions and* Voyages, and because it is a destination for future human explorers. The Mars Exploration Program has made additional discoveries since *Visions and Voyages* that reinforce this high priority and pose important new science questions. Mars 2020 will take the important first step toward the highest science priority in *Vision and Voyages*, Mars Sample Return, by collecting and caching carefully selected and well documented samples. The MEP currently lacks, and should promptly develop, a comprehensive plan, architecture, management and international partnering approach, and funding profile to implement the next steps in Mars exploration including and beyond completion of Mars Sample Return.

FIGURE 5.17 Mariner 4, launched in 1964, performed the first successful flyby of Mars. NASA has had a long and impressive planetary exploration program. SOURCE: JPL.

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6

Preparing for the Next Decadal Survey

Currently, the next planetary science decadal survey is planned to begin in late 2019. The plan is to have a statement of task from NASA by the end of that year, announce a chair by March 2020, and begin meetings by spring-summer 2020. The goal is to deliver the final report by spring 2022. NASA, the National Academies, and the planetary science community will all have to prepare for the next decadal survey, often in collaboration with each other. Some of this preparation, such as meetings of the various planetary Analysis Groups (AGs) is already under way.

The National Academies Committee on Astrobiology and Planetary Science (CAPS) has been designated the "keeper of the decadal survey" and will be involved in shaping the statement of task prior to the start of the study.

There are many subjects that CAPS and NASA will have to consider as they prepare for the next decadal, including the following:

- Changes in civil space policy between now and the decadal survey, including such issues as the Lunar Orbital Platform-Gateway, the Commercial Lunar Payload Services request for proposals, and the development of commercial spaceflight capabilities.
- How to structure the decadal survey panels:
  - By planetary body—for example, the past decadal survey's panels "inner planets," "Mars," "gas giants," "satellites," and "primitive bodies" (comets, asteroids, and Kuiper belt objects), or
  - By topical areas such as "the search for life," "solar system formation," and so on.
- How the community may respond to science that comes out after the decadal survey is released.
- New mission studies prior to (or even during) the decadal survey.
- The creation of new program lines, such as an Ocean Worlds program line.
- The emergence of SmallSats.
- How cost and schedule have affected implementation of the decadal survey.
- The role of planetary protection.
- The role of the virtual institutes.

NATIONAL CIVIL SPACE INITIATIVES

When the last decadal survey started, NASA was pursuing the Constellation program to return humans to the Moon. By the time *Vision and Voyages* was released, Constellation had been canceled and the human spaceflight program had been shifted toward the objective of sending humans to Mars, with a nearer-term goal of sending humans to an asteroid. Soon thereafter, the goals of the human spaceflight program were focused on the Asteroid Redirect Mission. By 2018 NASA was focusing on sending humans to the vicinity of the Moon and the possibility of using commercially developed landers to land on the lunar surface. These changes in the goals of the human spaceflight program—which is not guided by a decadal survey—serve to highlight the value of the decadal process in providing stability and clarity to the planetary science program.

In addition, there have been significant developments in nongovernment spaceflight such as the emergence of new launch providers and private initiatives to explore beyond low Earth orbit. Many of these new actors remain unproven, and their impact upon the planetary science program is therefore hard to determine. The next decadal survey will have to consider how to plan for the consequences of commercial and human space flight on the ability to do planetary science, on the Moon and on Mars. This will raise difficult questions such as how to take advantage of newly emerging capabilities, as well as how to prioritize science versus the interests of other stakeholders. This is a long-term planning issue for planetary scientists, filled with both opportunities and disadvantages. Can science exploration and human activities coexist? This will raise questions such as how to take advantage of newly emerging capabilities, as well as how to prioritize science versus the interests of other stakeholders.

PROCEDURES TO DEAL WITH UNANTICIPATED SITUATIONS

Vision and Voyages was released in March 2011 and covered the period of 2013-2022. Scientific discoveries and policy changes were occurring even before the implementation of the decadal survey. This experience demonstrates that in the future, opportunities may present themselves that were not considered in the last decadal survey. These can take the form of new programmatic objectives (e.g., Europa lander), new technological capabilities (CubeSats and other SmallSats, new instrument capabilities), or scientific developments and discoveries (e.g., ocean worlds, exoplanet discoveries).

The challenge for those conducting the next decadal survey is to find methods of both taking advantage of new opportunities while not abandoning the carefully laid-out plans and strategies from the decadal.

The committee concluded that there is a middle ground in which NASA and the science community would give thoughtful consideration to potential deviations from the decadal plan. New opportunities should be considered, but will need to be consistent with the general philosophy and approach of the decadal survey. Appropriate input from the science community should be solicited and incorporated into the decision process, including on the scientific value of possible deviations as well as the priorities relative to the previously established directions.

The Committee on Astrobiology and Planetary Science underwent a change in its charter starting in 2017 that enabled it to write letter reports—without recommendations—provided that the subject matter was consistent with issues raised in the decadal survey. This has been an important development for the community. The first CAPS report, *Getting Ready for the Next Planetary Science Decadal Survey*, was produced in 2017. Its next report, reviewing the Planetary Science Division's plans for the lunar and exploration initiative and determining if NASA's plans are consistent with *Vision and Voyages* and other National Academies reports, was in process as this report went to review. Consulting CAPS can serve as an effective method to evaluate the consistency of NASA and other plans with the decadal survey. (See Figure 6.1)

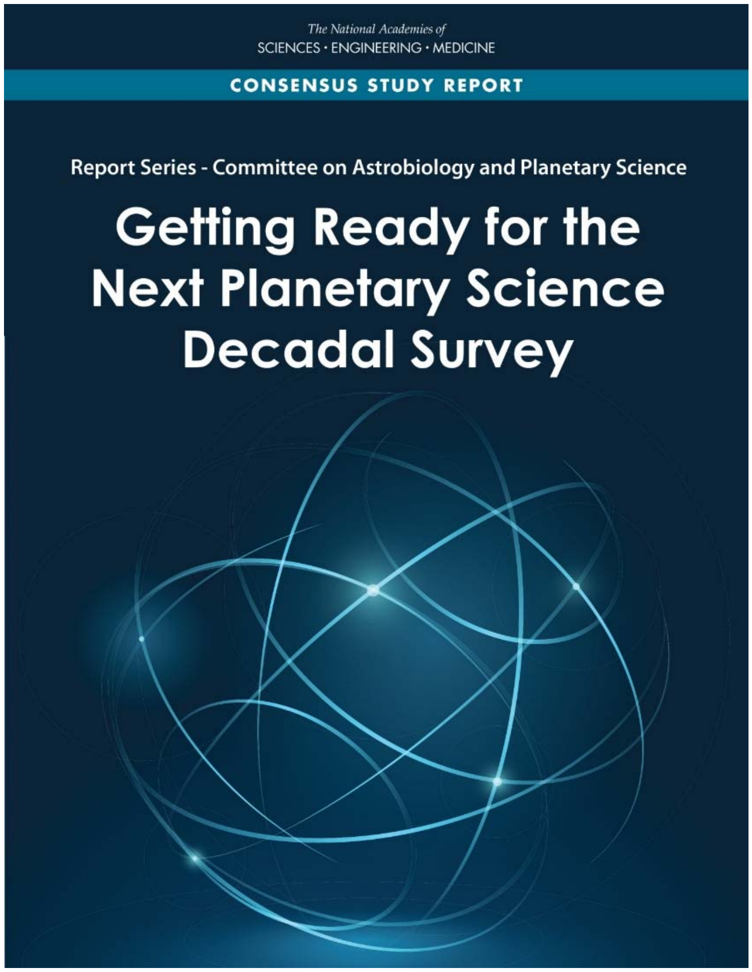

FIGURE 6.1 "Getting Ready for the Next Planetary Science Decadal Survey" was produced in summer 2017 by the Committee on Astrobiology and Planetary Science. It provides guidance for, among other things, mission studies that NASA can conduct that will be used for the decadal survey. SOURCE: NASEM (2017b).

Getting Ready for the Next Planetary Science Decadal Survey reviewed studies of possible future flagship- and New Frontiers-class missions that have been completed in the years since *Vision and Voyages*. The report also identified a list of priority areas that are candidates for large- or medium-class mission studies. Several of the concepts address new, high-priority science findings since *Vision and Voyages*. To maintain programmatic balance between different classes of missions, these new concepts—summarized below—warrant study to determine their science value per dollar and technical and cost feasibility as New Frontiers-class missions:

- Additional Venus concepts beyond Venera-D. High-priority new science that could be addressed could include tessera composition and whether an ocean persisted late into Venus's history.
- A Lunar Geophysical Network was recommended by *Vision and Voyages* for inclusion in New Frontiers 5. The concept can be revisited to consider incorporation of new approaches from InSight.
- A Lunar Polar Volatiles Mission to determine the nature of volatiles trapped in permanently shadowed polar regions remains a high science priority. Although the concept presents technical challenges, a reexamination of innovative technical approaches to such a mission is warranted.

- A medium-class Mars Rover would be much smaller than MSL or Mars 2020. The rover would conduct in situ studies of deposits formed in habitable environments not sampled by Mars 2020, complementing and providing context for the more detailed results possible from Mars Sample Return. (See Figure 6.2)
- A Mars Volatiles Orbiter would be a de-scoped version of the Next Mars Orbiter concept studies by NEX SAG, which addressed high-priority new Mars science involving recurrent slope lineae (RSL), shallow excess ground ice, and modern dynamical processes including volatile cycling.
- A Ceres Lander would conduct in situ investigations of Ceres's composition, geology, and geophysics to determine whether it records a past ocean or extant liquid water environment. (See Figure 6.3)
- An Io Observer was recommended by *Vision and Voyages* for inclusion in New Frontiers 5. The concept can be revisited to consider how best to address new results and incorporate innovative technical approaches.
- A Kuiper-Belt Mission beyond New Horizons would take the next steps in exploration of the Kuiper belt. Possible mission concepts include a New Horizons-like flyby of a different large Kuiper belt objects (KBOs) than Pluto and at least one smaller KBO, to assess KBO diversity; or a detailed rendezvous study of the Pluto system or Triton to study one or more KBOs in depth.
- A Dedicated Telescope for Solar System Science would conduct detailed studies of dynamical processes on numerous solar system objects that are now precluded by demands for observing time in large telescopes and at wavelengths inaccessible from the ground. Objectives would include Io volcanism, Titan weather, active processes at Europa and Enceladus, and characterization of outer planet satellites and KBOs.

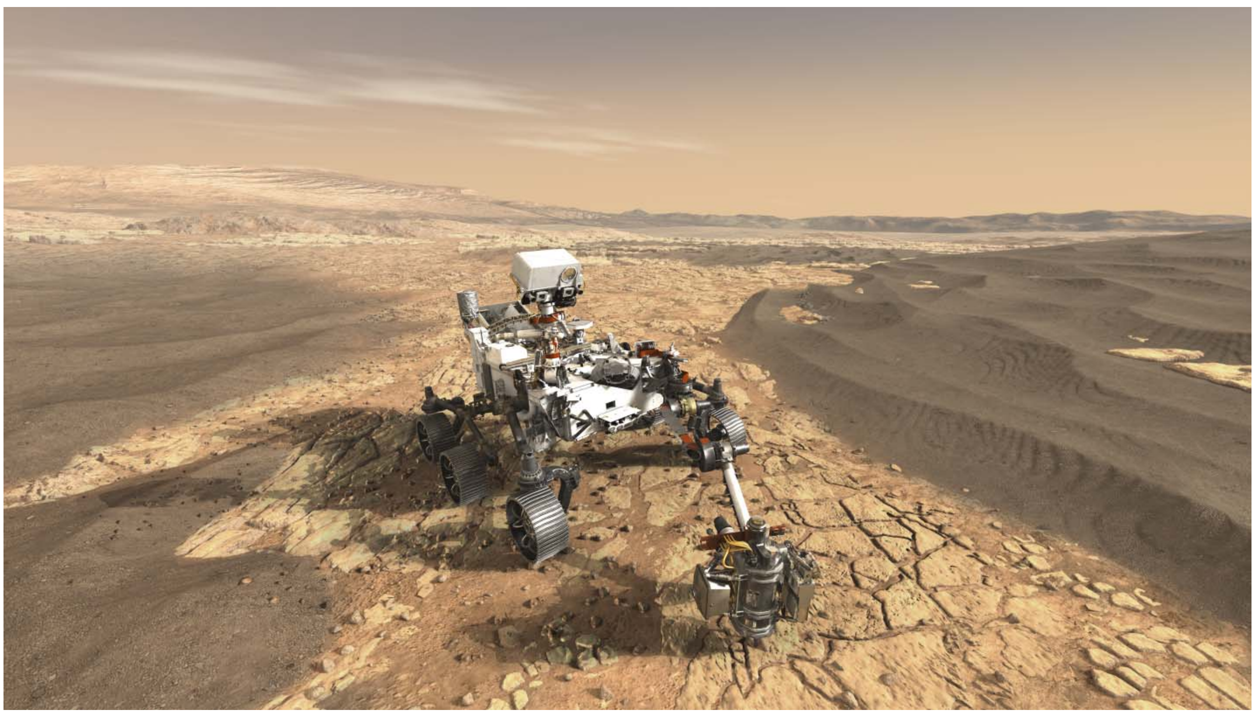

FIGURE 6.2 Artist concept of the Mars 2020 rover. This mission will collect samples on the surface of Mars for later return to Earth. The rover is based upon the proven Curiosity design. Smaller and less expensive rovers are possible in the future. SOURCE: NASA.

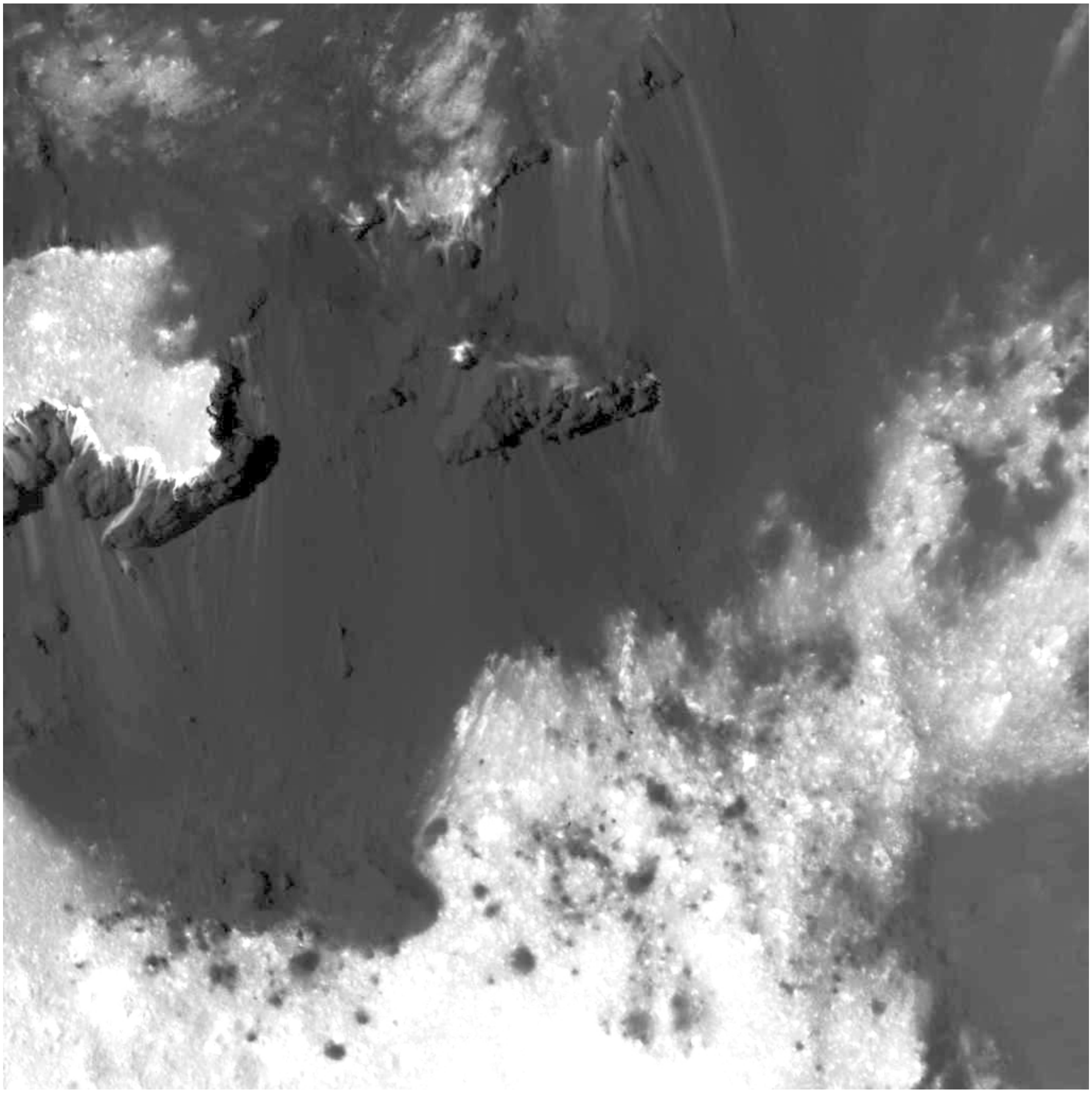

FIGURE 6.3 A prominent mound located on the western side of Cerealia Facula on Ceres can be seen in the upper left of this image obtained by NASA's Dawn spacecraft in June, 2018. Future missions may land on Ceres. SOURCE: JPL.

The next decadal survey will develop a new list of New Frontiers mission candidates that will likely include many of the missions previously included in prior decadal surveys. The addition of two to three of these new concepts to the New Frontiers list by the next decadal survey could replenish the list of candidate missions after selection of New Frontiers 4; identify new directions for large missions; and provide intermediate-term new, high-priority Mars science before the long-term objective of Mars Sample Return is completed.

Finding: Even though the actual implementation of a flagship or New Frontiers mission may differ substantially from a mission concept, a concept study has value for the decadal survey. It enables science objectives to be defined, the overall mission scope (i.e., whether it is a flagship- or a New Frontiers-class mission) to be determined, and the community to begin preparing for the next funding opportunities.

Recommendation: NASA should sponsor 8 to 10 mission concept studies based on the list produced by the Committee on Astrobiology and Planetary Sciences, prioritized with input from the assessment and analysis groups, prior to the next decadal survey. Mission concept studies for flagship-class missions should include options as described in the National Academies report *Powering Science—NASA's Large Strategic Science Missions*.

In Chapter 3 the committee recommended that NASA redo the ice giants study. The 8 to 10 mission concept studies recommended above should be in addition to the redo of the ice giants study.[1]

OCEAN WORLDS

Since the release of *Vision and Voyages*, the topic of Ocean Worlds has grown in importance/popularity/significance, owing to advances at Enceladus and Titan by the Cassini mission, along with Hubble Space Telescope (HST) observations of possible plume activity at Europa. (See Chapter 2.) The 2016 Congressional Commerce, Justice, Science, and Related Agencies Appropriations Bill directed NASA to create an Ocean Worlds Exploration Program, using a mix of programs already funded within NASA. The direction for this program was to seek out and discover extant life in habitable worlds in the solar system "using a mix of Discovery, New Frontiers and flagship class missions consistent with the recommendations of current and future Planetary decadal surveys."

Community-based efforts (e.g., the Outer Planets Assessment Group [OPAG]'s Roadmaps to Ocean Worlds group) are under way to define the goals and objectives and potential mission strategies and technologies needs of an Ocean Worlds Program. Results of these efforts will be fed into the next decadal survey. One possibility could be the creation of a new Ocean Worlds program line. The experience of the Mars Exploration Program could provide useful guidance.

SMALLSATS

The Planetary Science Division (PSD) has developed its own effort to enable small satellite concepts and continues to work with the Space Technology Mission Directorate (STMD) to leverage its efforts as well. Technology and subsystem developments within NASA centers and industry are moving toward increasingly more capable small platforms—SmallSats (<500 kg) and CubeSats that have potential for deployment as secondary or "rideshare" payloads on launches beyond low Earth orbit.

As discussed in Chapter 4, NASA has taken meaningful steps to begin to understand the potential for this scale of platform to address specific, limited, but useful planetary science objectives in the forms of the Small Innovative Missions for programs. PSD has invested $6 million over one year on 19 awards for concept studies for Planetary Science Deep Space SmallSats (PSDS3) to scope science capability and cost of small secondary missions, and include studies focused on Venus, the Moon, small bodies, Mars, and icy bodies and outer planets.

Finding: Aside from requirements derived from the competitively selected SIMPLEx and PSDS3 mission concepts, there is not a clear pathway for prioritizing development of the key CubeSat and SmallSat technologies and planetary deployment and operational architectures that would enable operations beyond the Earth-Moon environment. These include, but are not limited to, destination

[1] At the time this report was being written, NASA was beginning a Ceres mission study.

delivery approaches, propulsion, telecommunications, and deployable elements to provide power generation or instrument aperture.

Recommendation: In preparation for the next decadal survey, NASA should consider priorities and pathways for advancing the state of the art of CubeSats and SmallSat technology, and how science-driven planetary small mission concepts that leverage emerging capabilities are identified and possibly implemented for flight.

The committee notes that by the time of the next decadal survey, NASA will have some experience with planetary science SmallSats such as the MARCO spacecraft that were launched along with InSight to Mars. (See Figures 6.4 and 6.5)

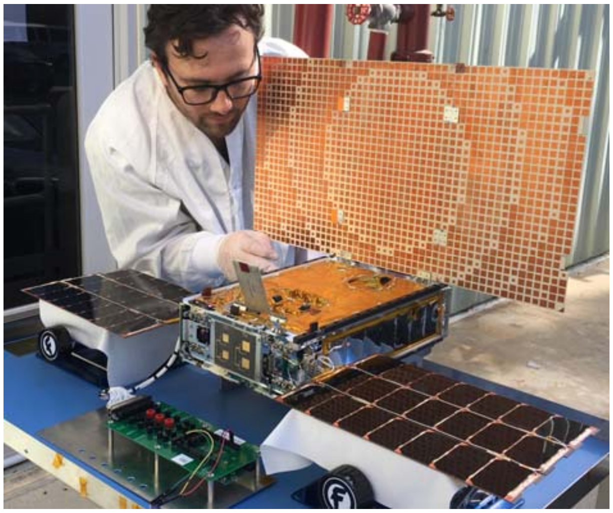

FIGURE 6.4 One of the MARCO CubeSats developed for the InSight mission to Mars. SOURCE: NASA.

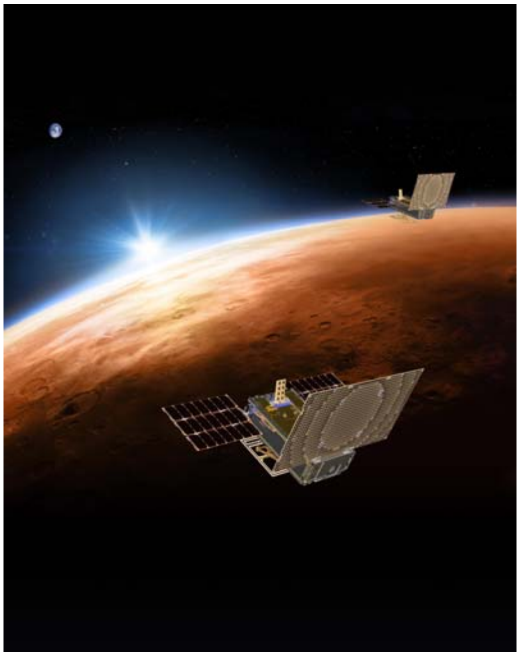

FIGURE 6.5 Artist concept of the MARCO CubeSats developed for the InSight mission to Mars. SOURCE: NASA.

COST AND SCHEDULE PERFORMANCE

The objective of the cost and technical evaluation (CATE) process is to perform a cost and technical risk analysis for a set of concepts that may have a broad range of maturity, and to ensure that the analysis is consistent, fair, and informed by historical data. Typically, concepts evaluated via the CATE process are early in their life cycles, and therefore are likely to undergo significant subsequent design changes. Historically, such changes have resulted in cost growth. Therefore, a robust process is required that fairly treats a concept of low maturity relative to one that has undergone several iterations and review. CATEs take into account several components of risk assessment. Because the CATE is best suited to the comparative evaluation of a family of pre-phase A concepts, it was the methodology used in the planetary decadal survey and is best suited to the early phase analysis of strategic missions.

The CATE process was successfully used in the *Vision and Voyages* decadal survey. The decadal survey's top two flagship missions, MAX-C and the Jupiter Europa Orbiter (JEO), had independent cost estimates prepared using the CATE process, and the resulting estimates showed that both missions were too expensive as proposed. As a result the decadal survey recommended that both missions be re-scoped. NASA revised the missions to fit within these boundaries, and now both are approved and in development.

The 2017 National Academies report *Powering Science—NASA's Large Strategic Science Missions*, included recommendations on how to adjust the CATE process to provide for a range of cost and science levels for large strategic (i.e., flagship) missions. These recommendations were heavily based upon the experience with the MAX-C and Jupiter Europa Orbiter concepts in *Vision and Voyages*, as well as NASA's efforts to follow the de-scoping options in the decadal survey. The committee believes that this can be a useful lesson for the next decadal survey. (See Figure 6.6)

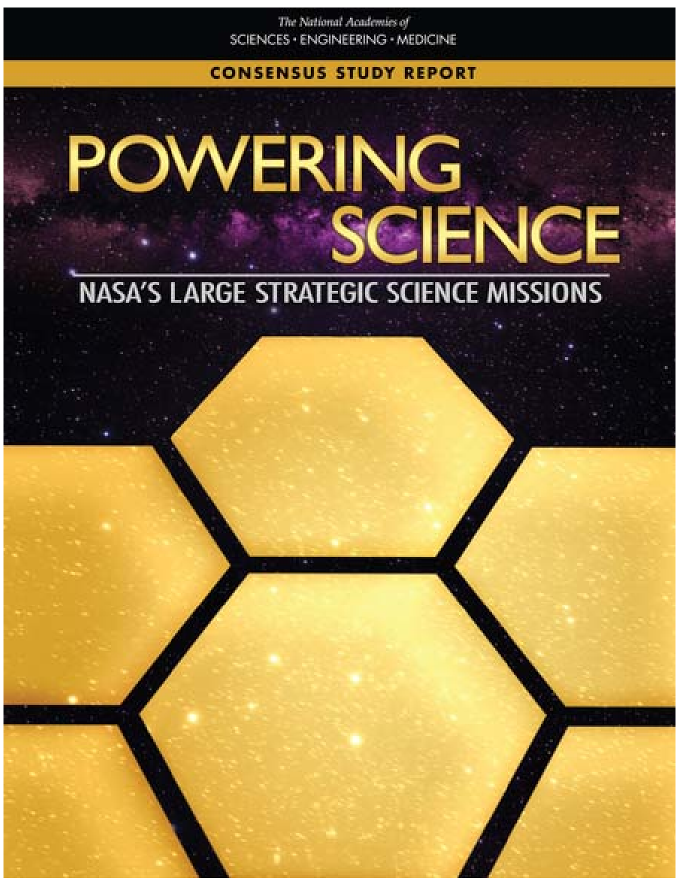

FIGURE 6.6 "Powering Science" was released in summer 2017 and provided recommendations for NASA's large strategic ("flagship") missions. SOURCE: NASEM (2017a).

PLANETARY PROTECTION ISSUES

A National Academies study was under way at the time of this report to recommend improvements to the planetary protection policy process. The international consensus planetary protection policy maintained by COSPAR is designed to promote rather than impede the exploration of the solar system. These policies are motivated by the twin rationales of preserving extraterrestrial environments for future scientific studies and the protection of Earth's biosphere from the unlikely, but not irrefutable, hazards posed by the introduction of alien organisms.

The implementation of planetary protection policies can complicate and add expense to the design and construction of spacecraft and their instruments and, in certain cases, impose operational restrictions on their intended use. In order to be effective, planetary protection regulations have to be formulated using the most up-to-date understanding of the relevant scientific and engineering issues, and these policies must be reviewed and updated regularly. The next decadal survey will have the results of the upcoming National Academies study on planetary protection and NASA's response to it.

THE ROLE OF THE VIRTUAL INSTITUTES

Vision and Voyages devoted relatively little attention to the two NASA virtual institutes: the NASA Astrobiology Institute (NAI) and the Solar System Exploration Research Virtual Institute (SSERVI, formerly the NASA Lunar Science Institute). The committee determined that the breakdown of NAI investment as a percentage of overall R&A spending (from keyword analysis) is:

- FY 2011: 10%
- FY 2012: 12%
- FY 2013: 10%
- FY 2014: 8%
- FY 2015: 8%
- FY 2016: 9%

This demonstrates that the NAI alone represents a significant proportion of planetary R&A spending.

The National Academies last conducted a review of the NAI in 2008 (*Assessment of the NASA Astrobiology Institute*), prior to the start of the decadal survey. The National Academies has not conducted a review of SSERVI. An independent review of the role and performance of both NAI and SSERVI prior to the next decadal survey could be of value to that study.

Recommendation: A formal assessment by NASA of how well the program structure and funding of the virtual institutes are aligned with the Planetary Science Division's science goals should be conducted on a regular basis, appropriately phased to the cycle of decadal surveys and midterm reviews.

Such a review could include (but not be limited to) an assessment of administration costs, the effectiveness of the institute in terms of publications, the difficulty of individual principal investigators (PIs) to get into the institutes (where many are funded as teams), and issues of diversity among institute teams.

In addition, the committee notes that there have been substantial developments in communications and computer technology, such as the emergence of "cloud computing." These are impacting many areas of science, including planetary science. The committee concluded that the next decadal survey should devote specific attention to them.

Recommendation: The next decadal survey committee should assess NASA's ability to respond to new needs for data archiving and interoperability from spacecraft, laboratories, and publications.

There are likely to be many further science discoveries in the years before and during the next decadal survey. For example, the New Horizons spacecraft will fly past a Kuiper Belt Object on January 1, 2019. These new discoveries will shape the decadal survey, but both the community and NASA have much to do to prepare. (Figure 6.7)

FIGURE 6.7 NASA's New Horizons spacecraft is scheduled to fly past the Kuiper Belt Object 2014 MU69, which the New Horizons team has nicknamed Ultima Thule. The flyby will occur on January 1, 2019. SOURCE: NASA.

REFERENCES

NASEM (National Academies of Sciences, Engineering, and Medicine). 2017a. *Powering Science: NASA's Large Strategic Science Missions*. The National Academies Press, Washington, DC.

NASEM. 2017b. *Report Series: Committee on Astrobiology and Planetary Science: Getting Ready for the Next Planetary Science Decadal Survey.* The National Academies Press, Washington, DC.

Appendixes

A

Statement of Task

The National Academies of Sciences, Engineering, and Medicine shall convene an ad hoc committee to review the response of NASA's Planetary Science program to the 2011 decadal survey, "Vision and Voyages for Planetary Sciences in the Decade 2013-2022" (V&V). The committee's review will include the following tasks:

- Describe the most significant scientific discoveries, technical advances, and relevant programmatic changes in planetary sciences over the years since the publication of the planetary decadal survey (Vision & Voyages or V&V);
- Assess the degree to which NASA's current planetary science program addresses the strategies, goals, and priorities outlined in the V&V and other relevant NRC and Academies reports and assess NASA progress toward realizing these strategies, goals, and priorities, and effectiveness in maintaining programmatic balance;
- With respect to the Mars program within the planetary science program, the committee's assessment will include:
    - the Planetary Science Division's Mars exploration architecture and its responsiveness to the strategies, priorities, and guidelines put forward by the National Academies' V&V and other relevant National Academies Mars-related reports;
    - the long-term goals of the Planetary Science Division's Mars Exploration Program and the program's ability to optimize the science return, given the current fiscal posture of the program;
    - the Mars exploration architecture's relationship to Mars-related activities to be undertaken by foreign agencies and organizations; and
    - the extent to which the Mars exploration architecture represents a reasonably balanced mission portfolio.
- Recommend any actions that could be taken to optimize the science value of the planetary science program including how to take into account emergent discoveries since the decadal in the context of current and forecasted resources available to it;
- Provide guidance about implementation of the decadal's recommended mission portfolio and decision rules for the remaining years of the current decadal survey, but do not revisit or redefine the scientific priorities or mission recommendations from the V&V; and
- Recommend any actions that should be undertaken to prepare for the next decadal survey, such as community discussion of science goals, potential missions, and programmatic balance, and NASA support of potential mission concept studies.

B

Committee Biographical Information

LOUISE M. PROCKTER, Co-Chair, is the director of the Lunar and Planetary Institute in Houston, Texas—a small scientific-community nonprofit soft-money organization that runs one of the two large annual planetary sciences conferences. Dr. Prockter has been involved in robotic planetary missions throughout her career. She served as an imaging team associate on the Galileo and Near-Earth Asteroid Rendezvous (NEAR) missions; was a deputy project scientist and co-investigator on the MESSENGER mission; was a deputy project scientist for the Europa Clipper mission, and is currently a co-investigator on that mission's camera team. Dr. Prockter's scientific research focuses on the geomorphology and structural tectonics of icy satellites and other solar system bodies. She is a fellow of the Geological Society of America and has served on NASA's Planetary Science Subcommittee. Dr. Prockter earned her Ph.D. in planetary geology from Brown University. She has participated in numerous advisory panels within the National Academies—including the Committee for Planetary Exploration (COMPLEX), the Space Studies Board, and the Planetary Decadal Survey—as well as NASA Advisory Council's Planetary Science Subcommittee. Dr. Prockter is a past member of the Space Studies Board and several National Academies ad hoc committees and is very familiar with National Academies processes. Dr. Prockter was formerly involved in the Europa flyby mission when she worked at the Johns Hopkins University Applied Physics Laboratory (APL). She left that position in summer 2016. She is still associated with the science team for an imager instrument for the Europa mission; however, she receives no money from her association other than travel funding, and she has no decision-making involvement in the instrument or the mission.

JOSEPH H. ROTHENBERG, Co-Chair, is an independent consultant who has retired from NASA. He has over 52 years of space program management and engineering experience. He retired from Google, where he was the director of engineering for the Terra Bella (formerly Skybox) Remote Sensing Satellite division. Prior to joining Google he was president of Universal Space Network. Mr. Rothenberg retired from NASA in 2001 where he served in a number of positions including NASA's associate administrator for space flight and director of the Goddard Space Flight Center. Mr. Rothenberg has extensive NASA program management experience and is widely recognized for leading the Hubble Space Telescope's first Servicing Mission. Mr. Rothenberg has a B.S. in engineering science and a M.S. in management engineering from C.W. Post College of Long Island University. He has served on the National Academies Committee on NASA's Beyond Einstein Program: An Architecture for Implementation, the Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies, the Committee on Assessment of Options for Extending the Life of the Hubble Space Telescope, and the Committee on Human Spaceflight Crew Operations. He is a national associate of the National Academies.

DAVID A. BEARDEN is general manager of the NASA and Civil Space Division within Vaeros Operations at The Aerospace Corporation. He is responsible for management and technical leadership of the company's support to NASA headquarters and centers as well as civil space agencies. Dr. Bearden leads a multidisciplinary team of scientists and engineers that develops and sustains technical consulting business from civil agencies, commercial companies, and international space clients. Dr. Bearden has corporate responsibility for proposal preparation, project planning, and project delivery to NASA programs. Through training courses and daily involvement in the delivery of technical expertise to customers, Dr. Bearden has gained considerable expertise concerning the issues, risks, and potential solutions in many cutting edge technical fields, including technology insertion analysis balancing benefit, cost, and risk, as well as telecommunication and remote sensing. Dr. Bearden is a nationally recognized cost analysis expert, and has over 20 years of technical and management experience in the acquisition and development of advanced technology space systems. After joining The Aerospace Corporation, Bearden led the Hubble Space Telescope Servicing Analysis of Alternatives, which earned him the 2006 Aerospace Corporation's President's Award. In summer 2009, he led an aerospace team that served as the technical arm of the Augustine Committee. Dr. Bearden has led various mission studies, including the Lunar Robotic Exploration Architecture and Mars Sample Return studies. Dr. Bearden was among the recipients of a NASA Group Achievement Award for Technical Support to Aquarius/SAC-D Standing Review Board. In 2015 Dr. Bearden was selected as an associate fellow of the AIAA. He also led an aerospace team that supported the last round of the decadal surveys using the Aerospace-developed cost and technical evaluation (CATE) process. Dr. Bearden was awarded a Ph.D. in aerospace engineering from the University of Southern California, Los Angeles. He has served on the National Academies Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process, the Committee on Assessment of Impediments to Interagency Cooperation on Space and Earth Science Missions, and the Committee on NASA's Beyond Einstein Program: An Architecture for Implementation.

SCOTT BOLTON is an associate vice president at the Southwest Research Institute (SwRI) in San Antonio, Texas. Dr. Bolton also serves as the principal investigator for the Juno mission, a project within NASA's New Frontiers Program. The Juno spacecraft is currently orbiting Jupiter. Dr. Bolton has more than 36 years' experience in the field of aerospace and space science. Prior to becoming director at SwRI, Dr. Bolton was a senior scientist and manager at the Jet Propulsion Laboratory (JPL) for over 25 years. During his tenure at SwRI, Dr. Bolton oversaw the launches of New Horizons and IBEX, the selection of Juno, the confirmation of MMS, and the delivery of hardware for a number of non-NASA programs related to national security. Dr. Bolton also manages the coordination and development of future NASA mission and instrumentation proposals for the Space Science and Engineering Division at SwRI, managing the strategic plan, partnership selection, and proposal quality. He has held a wide range of positions, including those associated with mission design, engineering, scientific research, and program management for various space missions related to NASA's exploration of Earth, the solar system, and the fields of astrophysics and space physics. Dr. Bolton received his Ph.D. in astrophysics from the University of California, Berkeley.

BARBARA A. COHEN is a planetary scientist at NASA's Goddard Space Flight Center. Dr. Cohen serves within NASA representing science interests and capabilities within human spaceflight planning. She is a principal investigator on multiple NASA research projects, a member of the mission teams operating the Opportunity and Curiosity rovers on Mars, and the principal investigator for Lunar Flashlight, a lunar CubeSat mission. Dr. Cohen is also the principal investigator for the Marshal Space Flight Center Noble Gas Research Laboratory (MNGRL) and is developing a flight version of her noble-gas geochronology technique, the Potassium-Argon Laser Experiment (KArLE), for use on future planetary landers and rovers. She has participated in the Antarctic Search for Meteorites (ANSMET) over three seasons, where she helped recover more than a thousand pristine samples for the U.S. collection, and asteroid 6186 Barbcohen is named after her. She received her Ph.D. in planetary sciences from the University of Arizona. Dr. Cohen served on the Planetary Science Decadal Survey: Inner Planets Panel and the Committee on the Scientific Context for the Exploration of the Moon.

ANDREW M. DAVIS is professor and chair in the Department of the Geophysical Sciences at the University of Chicago, where he also serves as professor of geological sciences at the Enrico Fermi

Institute. Dr. Davis's primary research interests are in isotopic and chemical analysis of (1) presolar, circumstellar dust grains recovered from meteorites to study stellar nucleosynthesis, (2) refractory inclusions within primitive meteorites to study the earliest history of the solar system, and (3) samples of cometary and interstellar dust, the Sun, and asteroids returned to Earth by the Stardust, Genesis, and Hayabusa spacecraft (and in future, OSIRIS-REx and Hayabusa 2). He served for many years on the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM), chairing the Genesis Sample Allocation Subcommittee and serving on the Stardust Sample Allocation Subcommittee. Over the past few years, the Chicago Instrument for Laser Ionization (CHILI) has been built in his laboratory. The pyroxene mineral davisite [CaScAlSiO6] and the asteroid 6947 Andrewdavis are named for him. Dr. Davis earned his Ph.D. in geochemistry from Yale University.

MELINDA DARBY DYAR is the Kennedy-Schelkunoff professor and chair of astronomy at Mt. Holyoke College. Her research includes study of both extraterrestrial (lunar and meteorites, including those from Mars) and terrestrial rock types. Dr. Dyar served as a participating scientist on the Mars Science Laboratory mission. She is deputy PI of the Institute for Remote, In Situ, and Synchrotron Studies for Science and Exploration based at Stony Brook University and a member of three other Solar System Exploration Research Virtual Institutes at Brown University, the Applied Physics Laboratory, and the Planetary Science Institute. Dr. Dyar has 36 years of experience in the field of mineral spectroscopy, including optical, FTIR, LIBS, Mössbauer, x-ray absorption (XAS, synchrotron), and many other types of spectroscopy. She received her Ph.D. from the Massachusetts Institute of Technology. Dr. Dyar is a fellow of the Mineralogical Society of America and was the 2016 recipient of the J.K. Gilbert award from the Geological Society of America for her outstanding contributions to the solution of a fundamental problem(s) of planetary geology.

ALAN W. HARRIS is a research scientist with MoreData! Inc., which takes and interprets photometric observations of asteroids and is funded by NASA and the National Science Foundation (NSF). He has served as a member of selection and review committees for NASA Discovery mission calls. Dr. Harris retired from the Jet Propulsion Laboratory after 28 years of service as a senior research scientist and as a principal investigator of NASA-sponsored research grants. He has served on numerous proposal and program review panels for NASA and NSF, as well as international committees. For example, although not a formal member of the National Academies Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies, he presented at one of the meetings and provided expert review of the final report. Dr. Harris received his Ph.D. in earth and space sciences from the University of California, Los Angeles.

AMANDA R. HENDRIX is a senior scientist with the Planetary Science Institute. Dr. Hendrix's research interests focus on moons and small bodies in the solar system to understand composition, activity, and evolution. Dr. Hendrix has led programs and published results in the Hubble Space Telescope, JSDAP, PG&G, OPR, LASER, and CDAP programs, among others. Dr. Hendrix is a co-investigator on the Cassini UVIS and Lunar Reconnaissance Orbiter LAMP teams, was a co-investigator on the Galileo UVS team, and served as the Cassini deputy project scientist. In 2016 she published a book (Penguin/Random House) with co-author Charles Wohlforth, *Beyond Earth: Our Path to a New Home in the Planets*, a discussion of the technological, medical, and social hurdles to overcome in considering a human space establishment in the outer solar system. She earned her Ph.D. in aerospace engineering with an emphasis in planetary science from the University of Colorado. Dr. Hendrix is a co-chair of the Roadmaps to Ocean Worlds group, serves as a steering committee member of the Outer Planets Assessment Group (OPAG), and is a member of the Hubble Space Telescope Europa Advisory committee.

BRUCE M. JAKOSKY is a professor in the Laboratory for Atmospheric and Space Physics (LASP) and the Department of Geological Sciences at the University of Colorado, Boulder. He is also an associate director for science at LASP. Dr. Jakosky's research interests are in the geology of planetary surfaces, the evolution of the martian atmosphere and climate, the potential for life on Mars and elsewhere, and the philosophical and societal issues in astrobiology. He has been involved with the Viking, Solar Mesosphere Explorer, Clementine, Mars Observer, Mars Global Surveyor, Mars Odyssey, Mars Science Laboratory, and Lunar Reconnaissance Orbiter spacecraft missions. Dr. Jakosky headed the University of Colorado's team in the NASA Astrobiology Institute for more than 10 years. He also is the principal investigator of the Mars Atmosphere and Volatile Evolution (MAVEN) mission to Mars. He has published nearly 200 papers in the refereed scientific literature, and has authored or co-authored a number of books, including *The Search for Life on Other Planets* and *Science, Society, and the Search for Life in the Universe*. Dr. Jakosky received his Ph.D. in planetary science and geophysics from the California Institute of Technology. He has served on the National Academies Committee on Origins and Evolution of Life and the Committee on Astrobiology Strategy for the Exploration of Mars.

MARGARET G. KIVELSON is a professor of space physics, emerita, in the Department of Earth, Planetary, and Space Sciences and the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles, and a research professor at the University of Michigan. Dr. Kivelson's scientific interests are magnetospheric plasma physics of Earth, Jupiter, and Saturn, interaction of flowing plasmas with planets and moons, and ultra-low frequency waves. She is currently a co-investigator on the THEMIS and Europa missions, and a collaborator on the fluxgate magnetometer on Cassini. She is the recipient of the Alfven Medal of the European Geophysical Union and the Fleming Medal of the American Geophysical Union. Dr. Kivelson earned her Ph.D. in physics from Radcliffe College. She has served on the National Academies Committee on NASA Science Mission Extensions, the Plasma Science Committee, and the Committee on Planetary Science Decadal Survey: 2013-2022. Dr. Kivelson is a participant on the Europa flyby mission magnetosphere science team, but she is not involved in decision making or as an advocate for the instrument.

SCOTT L. MURCHIE is the Planetary Exploration Group supervisor in the Space Exploration Sector of The Johns Hopkins University Applied Physics Laboratory (APL). His research focuses on the stratigraphy and formation of planetary crusts, how planetary crusts incorporate and are modified by volatiles, and the composition and geologic processes of asteroids and planetary moons. Dr. Murchie's research combines imaging and spectroscopy, synergistically and where possible together with measurements of elemental composition, for multidisciplinary measurement approaches. Currently, he is a co-investigator on the Mapping Imaging Spectrometer for Europa (MISE). As a co-investigator on MESSENGER, he helped to conceive the overall mission concept, and played a leading role in design of the imaging and reflectance spectroscopic investigations of Mercury's crustal composition, stratigraphy, and evolution. As principal investigator of the CRISM imaging spectrometer on MRO, he led the design and implementation of the investigation, analysis of the data, and dissemination of user-friendly CRISM data products, which have supported over 600 refereed publications to date. For these efforts he received the NASA Distinguished Public Service Medal. Dr. Murchie received his Ph.D. in geological and earth science from Brown University.

JUAN PEREZ-MERCADER is a senior research fellow and principal investigator in the Department of Earth and Planetary Sciences at Harvard University. His current research interests are in the experimental physics and chemistry of self-organization, information in non-equilibrium physico-chemical systems, chemical computation, origins of life, theoretical biology, and life detection in planetary environments. Dr. Perez-Mercader previously served as the first director of Spain's Centro de Astrobiologia (CAB), which he founded in 1998 in association with the NASA Astrobiology Institute. He is also Profesor de Investigación in Spain's National Research Council (CSIC) and an external faculty member at the Santa Fe Institute. He has authored about 150 research papers published in recognized journals and five books, including a best-selling popular science book in Spanish. Dr. Perez-Mercader has two patents in biotechnology and one on chemical computers. He is also an elected member of the International Academy of Astronautics and of the European Academy of Sciences and Arts. Dr. Perez-Mercader is the recipient of many honors and distinctions. Among these are one of the prizes given in 1994 by the Gravity Research Foundation, the European Physical Society Lecturer for the 2005 Celebrations in Bern of Einstein's 1905 work there, and the NASA Public Service Medal (NASA's highest honor to a non-NASA employee) and NASA's Group Achievement Award for exceptional achievement on REMS. He received his Ph.D. in theoretical physics from the City College of New York. Dr. Perez-Mercader has served on the National Academies Committee on the Review of NASA's Planetary Science Division's Restructured Research and Analysis Programs.

MARK P. SAUNDERS is an independent consultant. Since retiring from NASA in December 2008, he has been consulting to various NASA offices providing program/project management and systems engineering expertise. This effort has included support to the Office of Chief Engineer, the Office of Independent Program and Cost Evaluation, the Mars Program, and the Science Office for Mission Assessments (at Langley Research Center). Mr. Saunders has participated in the rewriting of NASA's policy on program/project management; advised and supported the agency's independent program/project review process; and supported the review of various programs and projects. At NASA headquarters he served as director of the independent program assessment office, where he was responsible for enabling the independent review of the Agency's programs and projects at life cycle milestones to ensure the highest probability of mission success. At NASA's Langley Research Center he was initially the deputy director and then the director of the Space Access and Exploration Program Office (SAEPO), and had the responsibility for planning, directing, and coordinating the center's research, technology, and flight programs for advanced aerospace transportation and human/robotic exploration systems. Prior to this he was the manager of Exploration Programs and led all LaRC space exploration research and development activities supporting the agency's Aerospace Technology (AST), Human Exploration and Development of Space (HEDS), and Space Science Enterprises (SSE). At the Office of Space Science, Mr. Saunders served as program manager for the Discovery Program, and at the Space Station Freedom Program operations he served as special assistant to the deputy director. He received the Presidential Meritorious Rank Award, the Outstanding Performance award, and the NASA Outstanding Leadership medal. He earned his B.A. at the Georgia Institute of Technology in industrial engineering. Mr. Saunders has served on the National Academies Committee on Astrobiology and Planetary Sciences.

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C

List of Acronyms

3D	three-dimensional
AEC	Advanced Energy Conversion
AG	Analysis Group
AO	announcement of opportunity
ASRG	Advanced Sterling Radioisotope Generators
AVGR	Ames Vertical Gun Range
CAESAR	Comet Astrobiology Exploration Sample Return
CAPS	Committee on Astrobiology and Planetary Science
CAPTEM	Curation and Analysis Planning Team for Extraterrestrial Materials
CATE	cost and technical evaluation
CDA	Cosmic Dust Analyzer
C&DH	command and data handling
CNEOS	Center for Near-Earth Object Studies
COLDTech	Concepts for Ocean Worlds Life Detection Technology
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
DoE	Department of Energy
DRA	Diviner Rock Abundance
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
EDL	entry, descent, and landing
EJSM	Europa Jupiter System Mission
ELSAH	Enceladus Life Signatures and Habitability
ELV	Expendable Launch Vehicle
ER	Electron Reflectometer
ESA	European Space Agency
ESI	Entry Systems Instrumentation
ESSP	Extreme Environment Solar Power
FIDH	
FPGA	field programmable gate array
FY	fiscal year
GFE	government furnished equipment
GHAPS	Gondola for High-Altitude Planetary Science
GNC	guidance, navigation, and control

GPHS	General Purpose Heat Source
GRAIL	Gravity Recovery and Interior Laboratory
GRaND	gamma ray and neutron detector
HEEET	Heat-shield for Extreme Entry Environment Technology
HEOMD	Human Exploration Operations Mission Directorate
HiRISE	High-Resolution Imaging Science Experiment
HOTTech	Hot Operating Temperature Technology
HPSC	High-Performance Spaceflight Computing
HST	Hubble Space Telescope
INMS	Ion and Neutral Mass Spectrometer
InSight	Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport
ISE100	In-Space Engine 100 lbf
JEO	Jupiter Europa Orbiter
JGO	Jupiter Ganymede Orbiter
JPL	Jet Propulsion Laboratory
JUICE	Jupiter Icy Moons Explorer
JWST	James Webb Space Telescope
KBO	Kuiper belt object
KDP-B	Key Decision Point-B
KDP-C	Key Decision Point-C
LADEE	Lunar Atmosphere and Dust Environment Explorer
LARS	Laboratory Analysis of Returned Samples
LCC	life-cycle cost
LCRD	Laser Communications Relay Demonstration
LDEX	Lunar Dust Experiment
LEAG	Lunar Exploration Analysis Group
LIBS	laser-induced breakdown spectroscopy
LPI	Lunar and Planetary Institute
LQ	Lunar Quest
LRO	Lunar Reconnaissance Orbiter
LSP	Launch Services Program
LWRHU	Lightweight Radioisotope Heater Unit
MAG	magnetometer
MAHLI	Mars Hand Lens Imager
MARCI	Mars Color Imager
MatISSE	Maturation of Instruments for Solar System Exploration
MAV	Mars Ascent Vehicle
MAVEN	Mars Atmosphere and Volatile Evolution Mission
MAX-C	Mars Astrobiology Explorer/Cacher
MCS	Mars Climate Sounder
MDAP	Mars Data and Analysis Program
MEP	Mars Exploration Program
MEPAG	Mars Exploration Analysis Group
MER	Mars Exploration Rover
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging

MGS	Mars Global Surveyor
MMRTG	Multi-Mission Radioisotopic Generator
MOC	Mars Orbiter Camera
MOLA	Mars Orbiter Laser Altimeter
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSR	Mars sample return
NAI	NASA Astrobiology Institute
NASA	National Aeronautics and Space Administration
NEOCam	Near Earth Object Camera
NEXT-C	NASA Evolutionary Xenon Thruster-Commercial
NF4	New Frontiers 4
NMS	neutral mass spectrometer
NRC	National Research Council
NSF	National Science Foundation
OPAG	Outer Planets Assessment Group
OS	Orbiting Sample
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PDR	preliminary design review
PDS	Planetary Data System
PI	principal investigator
PICA	Phenolic-Impregnated Carbon Ablator heat shield
PICASSO	Planetary Instrument Concepts for the Advancement of Solar System Observations
PIXL	Planetary Instrument for X-ray Lithochemistry
PSD	Planetary Science Division
PSDS3	Planetary Science Deep Space SmallSats
PSTAR	Planetary Science and Technology from Analog Research
R&A	research and analysis
R&D	research and development
RELAB	Reflectance Lab
RIMFAX	Radar Imager for Mars's Subsurface Experiment
ROSES	Research Opportunities in Space and Earth Sciences
RSL	recurring slope lineae
RTG	Radioisotope Thermoelectric Generator
SAM	Sample Analysis at Mars
SBAG	Small Bodies Assessment Group
SCAN	Space Communications and Navigation
SEP	solar electric propulsion
SHARAD	Shallow Radar
SHERLOC	Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals
SLS	Space Launch System
SMD	Science Mission Directorate
SME	subject matter expert

SPEAR	Supersonic Parachute
SRC	Sample Return Capsule
SRO	Sample Return Orbiter
SSERVI	Solar System Exploration Research Virtual Institute
STMD	Space Technology Mission Directorate
SWIR	shortwave infrared
TES	Thermal Emission Spectrometer
TGO	Trace Gas Orbiter
THEMIS	Thermal Emission Imaging System
TRL	technology readiness level
USGS	U.S. Geological Survey
UV	ultraviolet
VEXAG	Venus Exploration Analysis Group
VICI	Venus In situ Composition Investigations
VIMS	Visual and Infrared Mapping Spectrometer
VIR	visible and infrared
VIRTIS	Visible and Infrared Thermal Imaging Spectrometer
WBS	Work Breakdown Structure
WFIRST	Wide Field Infrared Survey Telescope