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CONTRIBUTORS

Committee on NASA Science Mission Extensions; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

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EXTENDING SCIENCE

NASA's Space Science Mission Extensions and the Senior Review Process

Committee on NASA Science Mission Extensions

Space Studies Board

Division on Engineering and Physical Sciences

A Report of

The National Academies of

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Preface

In fall 2014, NASA Associate Administrator for the Science Mission Directorate John Grunsfeld discussed with members of the Space Studies Board the possibility of a study of the value of NASA's extended science missions and how the agency evaluates mission extension proposals, known as Senior Reviews. NASA's Astrophysics Division has conducted Senior Reviews on a regular basis since the early 1990s; the agency's other divisions started following similar procedures afterwards, and they were formally required by the NASA Authorization Act of 2005, which states:

The Administrator shall carry out biennial reviews within each of the Science divisions to assess the cost and benefits of extending the date of the termination of data collection for those missions that have exceeded their planned mission lifetime.

Although that Act (which was reaffirmed in 2010) requires biennial reviews, it does not define how NASA should conduct them, leaving the details to NASA, which has codified its requirements in internal management and other policy documents.

In summer 2015 NASA formally requested that the National Academies of Sciences, Engineering, and Medicine conduct a study on this subject. The Academies established a committee in fall 2015. The committee held an organizing teleconference in December, and its first in-person meeting was held at the National Academies' Keck Center in Washington, D.C., on February 1-2, 2016. The committee heard from the NASA Associate Administrator for Space Science as well as each of the division directors and other speakers. The committee's second meeting was held at the Beckman Center in Irvine, California, on March 2-4. At this meeting the committee heard from the former chairs of several Senior Review panels, as well as persons in charge of large and small missions currently in their extended phase. The committee's third meeting was held at the National Academy of Sciences Building in Washington, D.C., on April 18-20 and was primarily devoted to writing this report, which was delivered to NASA in late August.

Acknowledgment of Reviewers

This report has been 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 institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Robert Barish, University of Illinois,
J. Bernard Blake, The Aerospace Corporation,
Lisa Gaddis, U.S. Geological Survey,
George M. Gloeckler, University of Michigan,
Guosheng Liu, Florida State University,
H. Jay Melosh, Purdue University,
Jon Miller, University of Michigan,
Clive R. Neal, The University of Notre Dame,
Rebecca Oppenheimer, American Museum of Natural History,
Michael Ryschkewitsch, Johns Hopkins University Applied Physics Laboratory, and
Xubin Zeng, University of Arizona.

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

Contents

SUMMARY	1
1 INTRODUCTION	8
The Science Mission Directorate, 9	
What Is an Extended Mission?, 11	
What Do NASA's Extended Missions Cost?, 12	
How Does NASA Decide What Missions to Extend?, 13	
Reference, 14	
2 THE SCIENTIFIC BENEFITS OF MISSION EXTENSIONS	15
Astrophysics Discoveries During Extended Missions, 15	
Earth Science Discoveries During Extended Missions, 19	
Heliophysics Discoveries During Extended Missions, 23	
Planetary Science Discoveries During Extended Missions, 27	
Conclusions, 31	
References, 32	
3 REVIEW OF EXTENDED MISSIONS BY NASA	36
SMD-Wide Characteristics of Senior Reviews, 37	
Division-Specific Characteristics of Senior Reviews, 37	
Stakeholders, 40	
Incorporation of Lessons Learned into Senior Reviews, 43	
Summary History of Missions Reviewed by the Senior Reviews, 43	
Extension of European Space Agency Science Missions, 44	
Conclusion, 47	
Reference, 47	

4	THE BALANCE OF NEW MISSIONS VERSUS EXTENDED MISSIONS Conclusion, 51 References, 51	48
5	INNOVATIVE COST REDUCTIONS FOR EXTENDED MISSIONS Colocating Operations, 53 Innovative Approaches, 54 Repurposing Extended Missions to Create New Science Missions, 57 Risk Assessment and Acceptance, 58 The Need for Support in Response to Spacecraft Anomalies, 58 Control of Costs and Risks Related to the Introduction of New Procedures, 59 Determining the Lifetime Cost of Science Missions, 59 Conclusion, 60	53
APPENDIXES		
A	Statement of Task	63
B	Scientific Discoveries of the Lunar Reconnaissance Orbiter and <i>Opportunity</i> Rover During Extended Phase	64
C	NASA Science Mission Directorate Budgets by Division for Fiscal Year 2016	68
D	Extended Mission and Senior Review References in Decadal Surveys	70
E	Biographies of Committee Members and Staff	75
F	Acronyms	81

Summary

NASA operates a large number of space science missions, approximately three-quarters of which are currently in their extended operations phase. They represent not only a majority of operational space science missions but also a substantial national investment and vital national assets. They are tremendously scientifically productive, making many of the major discoveries that are reported in the media and that rewrite textbooks. For example, the Spitzer Space Telescope together with the Hubble identified a very distant galaxy where star formation proceeds much more rapidly than previously known in the early universe. The Aqua Earth observing spacecraft showed that the melting of the Greenland ice sheet in 2012 was the most extensive surface melting measured to date. The STEREO spacecraft obtained the first 360 degree images of the Sun. The Mars Exploration Rovers *Spirit* and *Opportunity* identified habitable hydrothermal environments on Mars. (These and many other scientific discoveries made by missions in their extended phase are discussed in Chapter 2.)

The NASA Authorization Act of 2005 established a requirement for NASA to conduct reviews of missions in extended phase every 2 years. After a decade of this requirement, in summer 2015 NASA asked the National Academies of Sciences, Engineering, and Medicine to conduct a study on its extended science missions. In response, the Academies created the Committee on NASA Science Mission Extensions, which met in person and via conference call several times starting in December 2015. The committee was asked to evaluate the following:

- The scientific benefits of mission extensions,
- The current process for extending missions,
- The current biennial requirement for mission extensions,
- The balance between starting new missions and extending operating missions, and
- Potential innovative cost-reduction proposals for extended missions.¹

NASA currently operates approximately 60 space science missions, of which approximately 45 have finished their prime mission phase and have entered their extended phase.² Extended missions provide a substantial return

¹ The full statement of task is included in Appendix A.

² Missions can consist of more than one spacecraft, and it is possible in some cases for one or more spacecraft that is/are part of a mission to be extended while other/s is/are not. For various reasons it is difficult to obtain exact numbers of NASA missions in prime and extended phases. This is due in part to how NASA counts its missions and the fact that some missions (e.g., WISE/NEOWISE) have changed status over time. Also, the numbers are always in flux as new spacecraft are launched or change status. Thus, the numbers in this report should be considered approximations and will have changed by publication.

on investment for NASA and U.S. taxpayers, considering the very high science productivity of these extended missions at relatively low cost.

Extended science missions have made major contributions to scientific discovery over many decades. They are valuable assets in NASA's portfolio because they are already operating successfully and no longer require development or launch costs but still provide excellent science at low incremental cost, needing only funding to conduct their operations and collect, process, and analyze their data. Approximately 75 percent of NASA's space science missions operate on approximately 12 percent of the space science budget (Figures S.1 and S.2).

Many extended science missions have made important discoveries via new destinations, observation types or targets, and/or data analysis methods. Moreover, continuous coverage, long-baseline data sets, and statistically significant observations of infrequent events require continuity of measurement over years or decades and are best provided through missions in extended phase. NASA's extended missions commonly achieve science objectives identified by the decadal surveys while providing unique insights for determining priorities and approaches for future exploration. Based on its assessment, the committee concluded that extended-phase science missions are a vital part of NASA's overall science effort.

The NASA Science Mission Directorate (SMD) undertakes a Senior Review process for astrophysics and planetary science missions in even-numbered years and Earth science and heliophysics missions in odd-numbered years. For spacecraft missions that continue to operate beyond their prime phase, the Senior Review is a valuable peer review process for recommending future support based on assessments of the scientific accomplishments

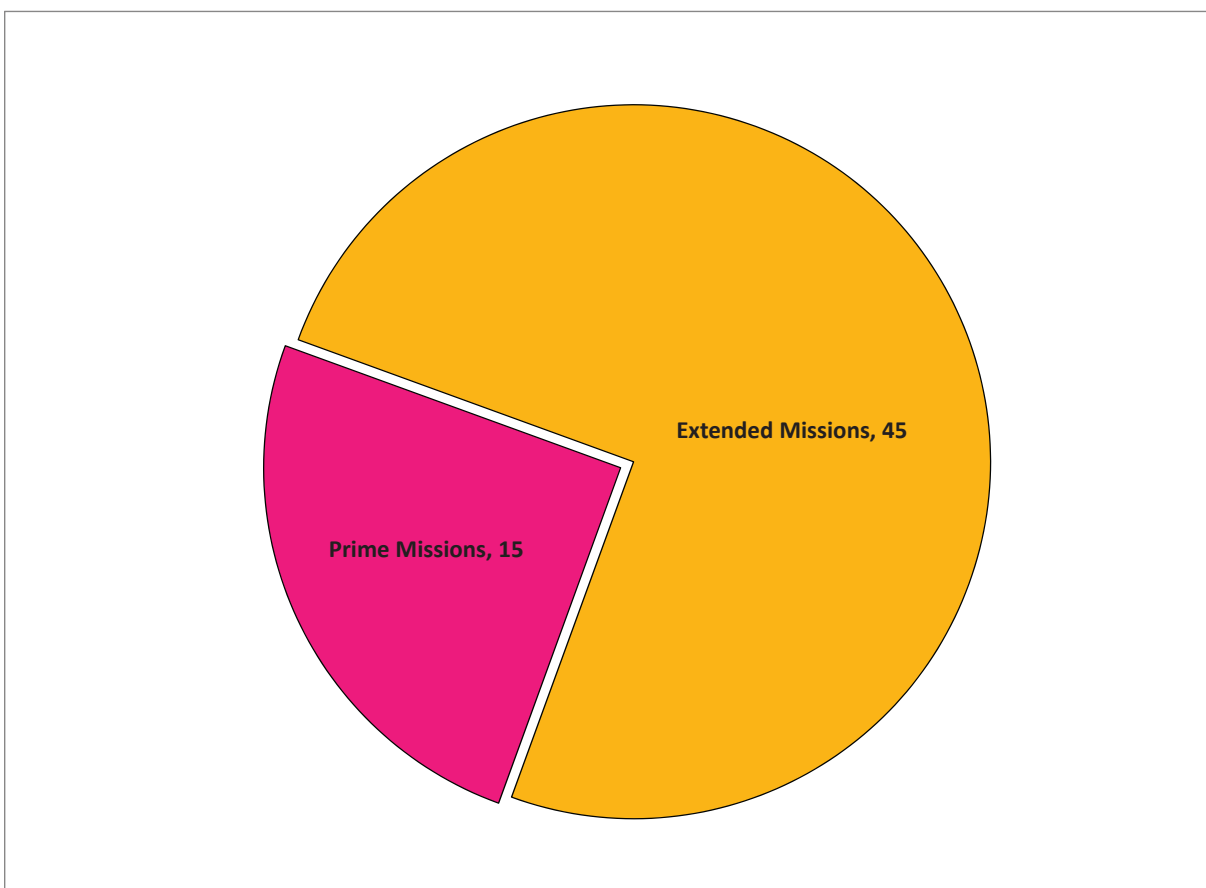


FIGURE S.1 Number of prime versus extended missions in the NASA Science Mission Directorate fiscal year 2016 budget. SOURCE: Data from the NASA Science Mission Directorate.

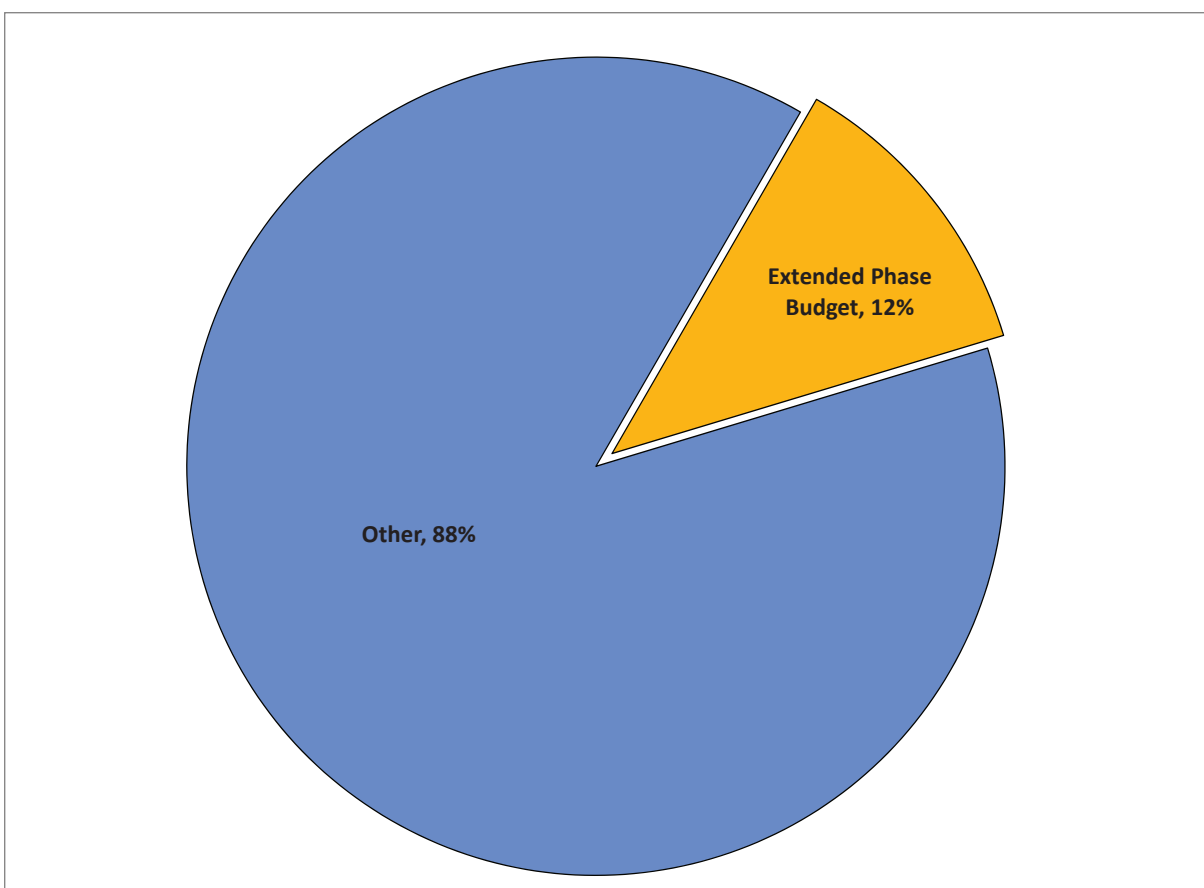


FIGURE S.2 Percentage of the NASA Science Mission Directorate fiscal year 2016 budget devoted to extended phase missions. SOURCE: Data from the NASA Science Mission Directorate.

and future projections, as well as the practical utility in meeting national and related interagency needs. NASA uses Senior Review recommendations as a major consideration when deciding on mission extensions. However, given budget constraints and uncertainties, the Senior Review may need to recommend termination of otherwise highly productive missions, although it is likely to express support for continuation of such missions if additional resources can be identified and allocated. The committee noted that the current NASA approach provides some flexibility in how the agency ultimately implements recommendations for mission termination, which at times allows for additional recommended missions to be continued. For example, in rare instances, non-government support for continuing missions has been provided by universities.

The exact manner in which NASA conducts its Senior Reviews is based on the specific needs of each division. For example, NASA Earth Science Division missions and some Heliophysics Division missions have potential or realized non-research utility—meaning that they can be used to support other NASA or national needs. So in addition to the primary criterion of continued scientific productivity, evaluating the applied and operational use of NASA Earth science missions is a secondary factor in Earth Science Senior Review evaluation and extension decisions. In addition, the Astrophysics Division deems a few missions (currently the Hubble Space Telescope and Chandra X-ray Observatory) to be multipurpose observatories with broad scientific capabilities and has decided to review them separately from other missions in the division. Also, Planetary Science Division missions have variable transit times to their destinations, some taking many years before the beginning of the prime mission,

which requires that the Senior Review process be applied to such missions on a case-by-case basis. These differing needs of the divisions highlight the need to allow the divisions flexibility in how they conduct their Senior Reviews, and no single template can be effectively applied to all of the divisions.

Senior Review teams are established by NASA and consist of volunteers who issue their recommendations independent of the agency but rely on NASA to establish the timeline for conducting the review. At times, the Senior Review process has become too compressed, and NASA has allocated insufficient time for some of the stages that are essential for an effective Senior Review. In particular, it is essential that

- The Senior Review panels have adequate time to review the proposals,
- Adequate time is also allocated to formulate questions for the mission teams, and
- The proposal (mission) teams have sufficient time to respond to questions from the panels.

Although NASA is required to conduct Senior Reviews every 2 years, the timing for launch of missions and their major events does not always correspond to the regular schedule for Senior Reviews. As a result, flexibility in scheduling the Senior Reviews (e.g., the ability to change the timing of individual reviews to avoid mission-critical events) is valuable for NASA's science divisions. NASA divisions have at times conducted off-year reviews for some missions, determined by individual mission needs, or extended missions beyond the next 2-year cycle if the spacecraft is expected to terminate after the following review (i.e., Cassini). The committee determined that such flexibility has been important for the success of missions.

Regular reviews of operating missions are essential to ensure that missions are productive and scientifically relevant and that the nation is obtaining value for its expenditure on these missions. However, the current 2-year cadence creates an excessive burden on NASA, mission teams, and the Senior Review panels. A 3-year cadence would ease this burden, while still enabling timely assessment of the quality of the data returned from these missions and their potential for continued productivity. The committee judged that a 4- or 5-year cadence might be too long, given potential science developments and also changes in a mission's health or overall capabilities. The committee also determined that other changes, such as reducing the number of pages required for proposals, would have a negligible or even negative effect on reducing the burden on proposal teams and NASA.

An important component of this revised 3-year cadence is conducting regular assessments of the health of the spacecraft and instruments so that both the agency and proposers are aware of any potential issues that might result in shorter useful lifetimes. NASA's science divisions already have provisions for doing this—for example, Earth sciences missions undergo annual technical health assessments. These assessments need only be moderate in scope, assessing changes since the last review, but the committee noted in its recommendation that a regular assessment is necessary in order to ensure confidence in the extension process.

The committee recognizes that NASA alone cannot change this cadence and that it ultimately requires a change of language in NASA authorization bills. The committee believes that NASA can work with Congress to seek a change in the authorization language to allow for a 3-year cadence and that this will have a significant impact on reducing the burden and improving the overall efficiency of NASA's mission extension process.

In some divisions, there is greater prioritization of new or ground-breaking science, whereas in other divisions continuity of observations may be emphasized. Once again, the committee concluded that flexibility was important for NASA to maximize the efficiency and effectiveness of its mission extension process and obtain the maximum return for its investment.

Overall, the committee was impressed with the way NASA SMD conducts its mission-extension review process and how much the four SMD divisions communicate amongst themselves regarding the reviews. With respect to the membership of the Senior Review panels, the committee concluded that there are several criteria that SMD can implement and standardize across the divisions.

As the divisions have performed more Senior Reviews, the details of the process have become more stable from cycle to cycle. Stability includes consistency of information requested, proposal format, timing for the various stages, and so on. Maintaining best practices through regular interactions and feedback between NASA Headquarters, the mission teams, and review panels will help to ensure that this consistency is maintained while also providing opportunities for incremental improvements to the process.

The committee was charged with evaluating the balance between prime and extended missions. Even though there is no formal definition for “optimal” balance, the committee concluded that the current balance between prime and extended missions is excellent, particularly with the high-quality science being returned at relatively modest cost for the extended missions. Extended missions represent only approximately 12 percent of the NASA SMD budget and provide a very high scientific return.

The committee’s task also asked for an assessment of generally applicable current, and as yet unidentified, cost reductions that NASA could implement. In general, the committee concluded that many cost reduction options are already identified and implemented by both prime and extended missions. For example, colocating mission operations centers to a greater extent than is already done might provide added efficiency (and cost savings) in some cases. However, as the committee was told, the location and responsibilities of the science team are also important factors, and there might be added efficiencies and synergies when science and operations centers are colocated, so flexibility is required regarding sites for science and operations centers. Many extended missions have adopted innovative planning and operations approaches that translate to good or best practices (e.g., early awareness of the potential for extended missions while developing ground system and flight procedures, generating staffing plans, and preparing for reduced budgets during the extended phase) that may be applicable to other missions. Each mission has unique features, so no single approach will be optimal for all.

The committee notes that repurposing extended missions to perform new science observations and missions is an extremely cost-effective approach for addressing new scientific opportunities and national interests.

With the expectation that most missions will be eligible for extension, investment in the development of standard procedures and templates during the prime phase can be a highly effective way to control long-term operations costs and limit the risks introduced by implementing new procedures specifically developed for extended operations. Some NASA divisions permit missions entering into or already in extended phase to accept increased risk, which is an inevitable consequence for aging spacecraft and science instruments and at least for some divisions, an acceptable option in the context of reduced budgets. The committee supports NASA’s current approach to establishing requirements and designs for prime phase and budgeting for extended missions, finding that it has many positive attributes and provides a very high return on investment.

Experience and knowledge gained during the prime phase typically result in lower costs for extended mission operations, but there may be counteractive effects that can create upward pressure on operational costs. After the first two Senior Reviews, most missions have implemented all (or almost all) practical steps to reduce costs. Further budget cuts often then result in disproportionate cuts to project-funded science activities, increasing risks that science will be diminished or not performed at all.

This report consists of five chapters. Chapter 1 introduces the issues. Chapter 2 describes some of the valuable science discoveries that have been made during the extended phase of science missions. Chapter 3 discusses the Senior Review process and the requirement for conducting reviews every 2 years. Chapters 4 and 5 address the issues identified in the statement of task concerning balance and innovative approaches to reducing costs. The committee’s recommendations appear below and in their relevant chapters.

Recommendation: NASA’s Science Mission Directorate (SMD) policy documents should formally articulate the intent to maximize science return by operating spacecraft beyond their prime mission, provided that the spacecraft are capable of producing valuable science data and funding can be identified within the SMD budget. (Chapter 5)

Recommendation: NASA should strongly support a robust portfolio of extended-phase science missions. This support should include advance planning and sufficient funding to optimize the scientific return from continued operation of the missions. (Chapter 2)

Recommendation: If a Senior Review recommends termination of a mission due to funding limitations rather than limited science return, NASA should allow the team to re-propose with an innovative, possibly less scientifically ambitious, approach at reduced operational cost and increased risk. (Chapter 3)

Recommendation: NASA science divisions should be allowed to conduct reviews out of phase to allow for special circumstances and should have the added flexibility in organizing their reviews to take advantage of unique attributes of each division's approach to science. (Chapter 3)

Recommendation: Each of the divisions should ensure that their timelines allocate sufficient time for each stage of the Senior Review process, including a minimum of 6 to 8 weeks from distribution of proposals to the panels until the panel meets with the mission teams. The panels should have at least 4 weeks to review the proposals and to formulate questions for the mission teams, and the mission teams should be allocated at least 2 weeks to generate their responses to the panel questions. (Chapter 3)

Recommendation: NASA should conduct full Senior Reviews of science missions in extended operations on a 3-year cadence. This will require a change in authorizing language, and NASA should request such a change from Congress. The Earth Science Division conducts annual technical reviews. The other divisions should assess their current technical evaluation processes, which may already be sufficient, in order to ensure that the divisions are fully aware of the projected health of their spacecraft, while keeping these technical reviews moderate in scope and focused on changes since the preceding review. (Chapter 3)

Recommendation: In order to obtain best value for money, NASA should encourage extended mission proposals to propose any combination of new, ground-breaking, and/or continuity science objectives. (Chapter 3)

Recommendation: NASA's Science Mission Directorate should assemble Senior Review panels that

- Are comprised primarily of senior scientists knowledgeable about and experienced in mission operations so as to ensure that the operational context of the science being proposed and evaluated is considered in the review (individuals with operations and/or programmatic expertise may also be included as needed);
- Are assembled early to avoid or accommodate conflicts of interest, and ensure availability of appropriate expertise;
- Include some continuity of membership from the preceding Senior Review to reap advantage of corporate memory; and
- Include some early-career members to introduce new and important perspectives and enable them to gain experience for future Senior Reviews.

(Chapter 3)

Recommendation: NASA's Science Mission Directorate division directors should continue to communicate among themselves to identify and incorporate best practices across the divisions into the Senior Review proposal requirements and review processes and procedures. (Chapter 3)

Recommendation: In its guidelines to the proposal teams and the Senior Review panels, NASA should state its intention to solicit feedback from its proposal teams and review panels about the suitability of the proposal content and review process. After obtaining such feedback, NASA should respond and iterate as needed with stakeholders to improve the review process, where possible. (Chapter 3)

Recommendation: NASA should continue to provide resources required to promote a balanced portfolio, including a vibrant program of extended missions. (Chapter 4)

Recommendation: NASA should provide open communications and dissemination of information based on actual experience with extended missions so that all missions are aware of and able to draw on prior effective practices and procedures, applying them during development of ground systems and flight

procedures, as well as when formulating staffing and budgetary plans for the prime and extended-mission phases. (Chapter 5)

Recommendation: NASA should continue to encourage and support extended missions that target new approaches for science and/or for national needs, as well as extended missions that expand their original science objectives and build on discoveries from the prime phase mission. (Chapter 5)

Recommendation: NASA should continue to assess and accept increased risk for extended missions on a case-by-case basis. The headquarters division, center management, and the extended-mission project should discuss risk posture during technical reviews and as part of the extended mission and subsequent Senior Review proposal preparation process and should make all parties fully aware of all cost, risk, and science trade-offs. (Chapter 5)

Recommendation: NASA should continue anticipating that missions are likely to be extended and identify funding for extended missions in the longer-term budget projections. (Chapter 5)

Recommendation: Given the demonstrated science return from extended missions, NASA should continue to recognize their scientific importance and, subject to assessments and recommendations from the Senior Reviews, ensure that, after the first two Senior Reviews, both operations and science for high-performing missions are funded at roughly constant levels, including adjustments for inflation. (Chapter 5)

CONCLUSION

NASA's extended science missions provide excellent science return and, in some instances, also meet national interests and needs. Missions that have already been paid for and successfully launched can continue to provide very high return at a modest incremental cost. Although the committee has recommended a number of refinements, including a 3-year cadence for Senior Reviews, there is a strong consensus that NASA's approach to extended missions is fundamentally sound and merits continued support.

1

Introduction

At this moment, Voyager 1 and 2 are traveling away from the Sun, probing the outer edges of our solar system and analyzing the interaction of the solar wind and the interstellar medium nearly four decades after launch. The two Voyager spacecraft have contributed to our understanding of the giant planets of our solar system as well as the limits of the Sun's influence, but it is easy to forget that both Voyagers ended their primary mission phases soon after their encounters with Saturn, which for Voyager 2 occurred in summer 1981. More than 30 additional years of scientific discovery by the Voyagers have resulted from repeated extensions of the mission (Figure 1.1).

The Voyagers are not alone in functioning long after their planned prime mission. Many NASA science spacecraft—including but not limited to the Chandra X-Ray Observatory and the Kepler telescope; the *Opportunity* rover, the Lunar Reconnaissance Orbiter, and Cassini; the Aura, Aqua, and Terra Earth sciences spacecraft; the ACE and Wind spacecraft in interplanetary space between Sun and Earth, the THEMIS magnetospheric orbiter, and the SOHO and STEREO solar observatories—have provided incredible scientific value long after their primary missions.

These lengthy missions and their incredible scientific productivity are not simply due to happenstance or the unexpected longevity of some spacecraft: Extended missions are a mainstay of NASA's scientific endeavor, a major part of the agency's science portfolio, and the result not only of impressive engineering but also of careful management and effective planning.

NASA's Science Mission Directorate (SMD) operates several dozen spacecraft in Earth orbit and beyond. When these spacecraft were first launched, they entered what is known as the prime phase of their mission. During the prime phase, the spacecraft measurements are focused on achieving a specific set of mission objectives aimed at answering high-priority science questions. The objectives usually require measurements over one to several years and may be tied to the characteristics of the science target. For instance, 1 year at Mars lasts approximately 2 Earth years, so many Mars missions have prime phases lasting 2 Earth years. Spacecraft are designed to last through the proposed prime mission with a high level of certainty. They are tested to prescribed limits and include margins that ensure that a spacecraft has a high probability of achieving its design lifetime. These margins allow—but do not guarantee—the ability to use the spacecraft for well beyond the design lifetime.

After a mission has completed its prime phase, it can be considered for an extension, provided it is still operational and can make important scientific contributions. The decision to extend a mission is made via a deliberative process within SMD. Mission teams prepare a scientific and technical proposal that also contains relevant budgetary information. The proposals are reviewed by a peer advisory panel selected by the director (or their designee) of

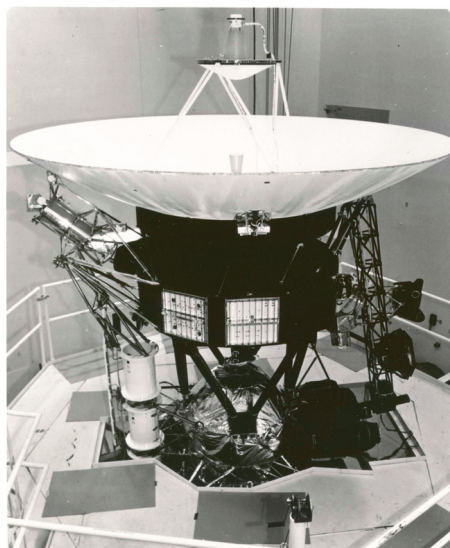


FIGURE 1.1 One of the Voyager spacecraft during final integration prior to launch in 1977. Voyager 2 has made numerous major scientific discoveries during three decades in extended mission phase. SOURCE: NASA/JPL; available at NASA, “Prototype Voyager,” release date May 14, 2013, <https://solarsystem.nasa.gov/galleries/prototype-voyager>.

SMD’s division for Astrophysics, Heliophysics, Earth Science, or Planetary Science (depending on which division supports the mission). A subsequent review by the division director takes into account various administrative considerations. A statute requires that such reviews (called Senior Reviews) take place every 2 years; however, there is no statutory definition of how such reviews must be conducted. Therefore, responsibility for defining and conducting each division’s Senior Review resides with the division of SMD in which it is held.

THE SCIENCE MISSION DIRECTORATE

SMD is tasked with helping to fulfill the goals of the national science agenda, as directed by the executive branch and Congress and advised by the nation’s scientific community. In doing so, SMD conducts scientific exploration missions that use spacecraft instruments to provide observations of Earth and other celestial bodies and phenomena.

SMD is allocated slightly less than one-third of NASA’s overall budget. In recent years SMD’s budget has been as follows:

- 2015 actual: \$5.2 billion out of \$18.0 billion total;
- 2016 enacted: \$5.6 billion out of \$19.3 billion total.

NASA currently has approximately 60 active space science missions with more than 20 additional missions currently under development—and missions can consist of multiple spacecraft. These spacecraft are sponsored by the Astrophysics, Heliophysics, Earth Science, and Planetary Science Divisions. Table 1.1 provides budget details for each of the four SMD divisions, along with data for the James Webb Space Telescope (JWST), which is separated from the Astrophysics Division for budgetary, management, and development purposes. Nonetheless, the science of JWST is largely astrophysical in nature, and it is treated as an Astrophysics Division mission in the remainder of this report. Table 1.2 shows the currently active extended missions in each division.

TABLE 1.1 NASA Science Mission Directorate (SMD) Division Budgets (in \$ million)

	2015 Actual	2016 Enacted
NASA Total	18,010.2	19,285.0
SMD	5,243.0	5,589.4
Earth Science	1,784.1	1,921.0
Planetary Science	1,446.7	1,631.0
Astrophysics	730.7	730.6
James Webb Space Telescope	645.4	620.0
Heliophysics	636.1	649.8

TABLE 1.2 The 45 NASA Missions in Extended Phase as of February 2016

Heliophysics	Earth Science	Planetary Science	Astrophysics
ACE	Aqua	Cassini	Chandra
AIM	Aura	LRO	Fermi
Geotail ^a	CALIPSO	Mars Express ^a	Hubble
Hinode ^a	CloudSat	Mars Odyssey	Kepler
IBEX	EO-1	MAVEN	NuSTAR
IRIS	GRACE (1/2)	MER <i>Opportunity</i>	Spitzer
RHESSI	LAGEOS (1/2)	MRO	Swift
SDO	Landsat 7	MSL <i>Curiosity</i>	XMM-Newton ^a
SOHO ^a	OSTM/Jason-2	NEOWISE	
STEREO (1/2)	QuikSCAT		
THEMIS	SORCE		
TIMED	Suomi NPP		
TWINS (A&B; 1/2)	Terra		
Voyager	Van Allen Probes		
Wind			

^a These missions are primarily foreign-led with some NASA participation.

NOTE: Numbers in parentheses indicate remaining spacecraft operating, compared to the original number. Acronyms are defined in Appendix F.

The Astrophysics Division focuses on understanding the universe beyond the solar system, seeking to catalog and understand astronomical phenomena such as black holes and exoplanets. Some missions are designed to observe the effects of dark matter, others to probe dark energy and to explore the origins of the cosmos. During 2016, there were approximately 10 active missions in the Astrophysics Division.

Heliophysics is the study of the Sun, the solar wind, and the physical domain dominated by solar activity, the heliosphere. The goals of the Heliophysics Division range from understanding the active processes within the interior of the Sun that drive the system, to measuring the space environments of Earth and other bodies within the solar system, stretching out to interstellar space. The Heliophysics Division during 2016 was responsible for approximately 16 active missions.

Earth science comprises the study of the diverse components that make up Earth as a planetary system, including the oceans, atmosphere, continents, ice sheets, and biosphere. Using observations on a global scale, the Earth Science Division (ESD) seeks to improve national capabilities to understand and predict climate, weather, and

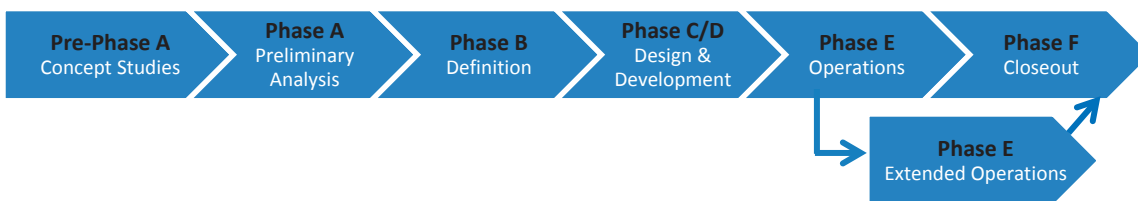


FIGURE 1.2 Phases of a NASA science mission.

natural hazards; manage natural resources; and collect the knowledge needed to develop environmental policy. During 2016, there were approximately 20 active missions in this division.

The Planetary Science Division is responsible for sending robotic spacecraft and landers to Earth's Moon, to the other planets and their moons, and to smaller celestial bodies, including asteroids and comets. These exploration activities are undertaken in order to better understand the origin and nature of the solar system and to provide a path forward for future human exploration. During 2016, there were approximately 14 active Planetary Science Division missions.

WHAT IS AN EXTENDED MISSION?

NASA missions progress through multiple phases (A-F), from early concept studies to end of life (Figure 1.2). Phase E is the operational phase of a mission. This can include transit to the science-gathering location (such as a Lagrange point for an astrophysical observatory, or a planet) and the science-gathering phase.

All missions have a prime phase during which they collect data and answer their top-level science questions. Spacecraft are designed and tested to specified lifetimes. Nevertheless, just as home appliances like dishwashers rarely stop working the day after the warranty expires, NASA spacecraft typically continue working after completing their prime phase. (This issue is further described in Chapter 4.) As a mission nears the end of its prime phase, the project team can request a mission extension through the relevant division's Senior Review process. Extended operation may be approved if a mission can collect data that will help to answer new science questions that were not anticipated when the mission was first formulated, or extend the existing data sets and improve understanding of the subjects being investigated. Table 1.2 lists SMD's current missions in extended operations.

The Senior Review process begins when SMD division issues a call for proposals, including guidelines for proposal content, several months before the desired due date. Proposing teams respond with written proposals that explain the accomplishments of the mission to date, the proposed observations that would be conducted during the mission extension and their scientific value, and the cost to support the observations for the period of time under consideration (typically the 2-year period until the next Senior Review). After submission and initial review of the written proposals, the Senior Review panel invites the proposal teams to give an oral presentation to the panel and answer questions about the proposed extended-mission activities. After a period that is usually on the order of a few weeks, the panel delivers to the relevant SMD division director a written report that contains the panel's assessment of the merit of each mission proposal under consideration in that division that year. Taking into consideration the panel's recommendation, as well as any programmatic or other factors, the director then decides which missions to continue, end, or reduce in scope. Additional details describing how the Senior Reviews vary between divisions are described in Chapter 3.

Most missions entered their extended mission phase after being recommended to do so by a Senior Review panel conducted within their division. There have been some exceptions. For instance, the NEOWISE mission, which is currently conducting a survey for near-Earth objects that could potentially impact Earth, was strategically directed to continue operations to satisfy agency requirements. It is not subject to the Senior Review process.

NASA's Associate Administrator for Space Science John Grunsfeld¹ regularly encountered what he referred to as “urban myths of extended missions.” These include the following: SMD spends most of its budget on extended missions for limited science return; NASA cannot build new missions because of the cost of extended missions; and NASA never terminates any missions. Dr. Grunsfeld stated that all of these claims are inaccurate and provided the committee with data that refuted them.

The first urban myth relates to the scientific productivity of extended missions. Dr. Grunsfeld explained to the committee that, despite spending only a modest percentage of the SMD budget on missions in extended phase, the scientific return from those missions has been substantial. Chapter 2 of this report is devoted to identifying a number of major scientific discoveries made by missions in their extended phase, indicating that extended phase missions make major scientific contributions.

WHAT DO NASA'S EXTENDED MISSIONS COST?

In addition to Dr. Grunsfeld's presentation, the committee heard from the four science division directors who presented further budget information about their directorates. They indicated that the amounts they spend on mission extensions vary. For example, in 2015 Earth Science Division (ESD) spent approximately 7 percent of its budget on extended missions and approximately 9 percent for 2016. The Astrophysics Division (ASD) spent approximately 17 percent of its budget in 2015 on extended missions, and 15.4 percent in 2016. In the Heliophysics Division (HD), 13 percent of the 2015 budget went to extended missions, and 12 percent in 2016. The Planetary Science division (PSD) spent 15 percent of its budget on extended missions in 2015, and 13 percent in 2016. Budget charts for fiscal year (FY) 2016 for all four NASA divisions are included in Appendix C.

NASA provided rather detailed information, year-by-year for FY2011-FY2015, showing the budget for each extended mission, the total for extended missions, and the total for all of SMD. Over the 5-year period, the total budget for extended missions ranged from \$544 million to \$591 million with the average over the 5 years at \$567 million. The average budget for SMD over the same 5-year period was \$5.03 billion. Thus, the extended missions accounted for 11.3 percent of the SMD funding from 2011 to 2015.

These numbers are the total listed under extended missions. However, there are additional funds expended on science from extended missions. In some cases, scientific research is supported through the mission line, but additional research may be supported under various research and analysis (R&A) or similar accounts in the four SMD divisions.

The split of research supported by mission lines and by R&A accounts varies from division to division and from year to year. Moreover, accounting is complicated by the fact that research may use data from the prime mission phase, from the extended phase, or from a mix of the two. Some of this research would be supported under R&A even if the relevant extended mission were to end, whereas some of it is tied to new observations acquired as an extended mission continues.

The committee heard that extended science mission budgets have fluctuated over time and will continue to do so based on many factors, including spacecraft health, the results of the Senior Reviews undertaken by the divisions, and other agency considerations. However, as discussed above, the overall SMD expenditure on extended science missions has averaged around 12 percent, which is significantly less than what is spent on missions in development, typically on the order of 50 percent (as calculated by combining the overall SMD development budget numbers for FY2016, which are shown graphically by division in Appendix C). The relatively small fraction spent on extended-phase missions compared to missions under development indicates that even if NASA were to end all extended missions in a division, the amount of funding this would free up for new missions would be of modest impact. The committee further addresses this issue in Chapter 4.

Another of the urban myths relates to the perception that SMD does not terminate missions that have outlived their utility. Then-Associate Administrator Grunsfeld explained to the committee that SMD has ended numerous space missions over the past two decades (see Table 1.3). In some cases, missions were terminated when the spacecraft could no longer be operated (e.g., the *Spirit* rover and the GRAIL lunar spacecraft), but the agency has also ended its support for some missions after finding that their science productivity no longer warranted support.

¹ Dr. John Grunsfeld was NASA's Associate Administrator for Space Science through April 2016.

TABLE 1.3 Examples of Science Missions Ended During Previous Two Decades

Mission	
IUE	Terminated 1996
ISEE-3/ICE	Ended 1997; recently rebooted by non-NASA group
Compton Gamma Ray Observatory	De-orbited June 2000, to avoid potential uncontrolled re-entry
EUVE	Decommissioned January 2001
SAMPEX	NASA funding ended June 2004, operated by Bowie State University thereafter until 2012 at no cost to NASA
CHIPS	NASA funding ended 2005; UCB operated until 2008
FAST	NASA funding ended 2005
ERBS	Terminated October 2005
Polar	Ended in 2007
Gravity Probe B	Funding ended 2008
TRACE	Terminated June 2010 after success of SDO
WMAP	Ended October 2010 after four extensions
GALEX	Terminated February 2011
WISE	Terminated in Astrophysics February 2011, restarted in Planetary Science in August 2013 for near-Earth object searching
RXTE	Terminated January 2012
QuikSCAT	Planned to be decommissioning in 2015, but continued following RapidScat issues

NOTE: Acronyms defined in Appendix F.

HOW DOES NASA DECIDE WHAT MISSIONS TO EXTEND?

A key aspect of the process for extending NASA science missions is the Senior Review. The requirement for this review is established in legislation as follows:

The Administrator shall carry out biennial reviews within each of the science divisions to assess the cost and benefits of extending the date of the termination of data collection for those missions that have exceeded their planned mission lifetime.²

The requirement was initially established in the 2005 NASA Authorization Act and repeated in the 2010 NASA Authorization Act. NASA ASD began conducting Senior Reviews of its missions in the early 1990s and established a 2-year cadence for such reviews. According to former congressional staffers who spoke to the committee, the Authorization Act language calling for biennial reviews was based in part on this previously established cadence and was in part somewhat of a guess, with one former staffer suggesting that, in Washington, D.C., “two is the average between one and infinity.”

NASA’s overall policies for extending science missions are outlined in the agency’s management plan. The 2013 *Science Mission Directorate Management Handbook* states that after a mission’s prime phase, entry into an extended phase “is possible if part of a compelling investigation that contributes to NASA’s goals” (NASA, 2013). This document also defines SMD’s implementation for the Senior Review process, which is codified, yet flexible for the needs of each division, and involves an evaluation of the productivity of the proposed extended mission by members of the scientific community.

NASA conducts Senior Reviews for astrophysics and planetary science missions in even-numbered years and

² National Aeronautics and Space Administration Authorization Act of 2005, P.L. 109-155, Section 304, “Assessment of Science Mission Extensions,” December 30, 2005.

for Earth science and heliophysics missions in odd-numbered years. The Senior Review processes for the four divisions are discussed in detail in Chapter 3.

The following chapters in this report review in greater detail the scientific return secured from extended missions, the process that is in place to ensure that extended missions are productive contributors to NASA's science goals, how the relatively modest costs associated with supporting extended missions compares to the support required for new mission development and the potential for science lost if extended missions are not supported, and the potential ways in which extended missions may realize cost savings relative to their prime phase.

REFERENCE

NASA. 2013. *Science Mission Directorate (SMD) Management Handbook*. Washington, D.C., October.

2

The Scientific Benefits of Mission Extensions

Many NASA missions over previous decades have operated into extended phases and produced significant scientific discoveries. Scientific research is often conducted using extensive data sets collected in both prime and extended mission phases. In the Earth science, heliophysics, and planetary science fields, it is often important to collect data over long periods of time to detect long-term trends; thus a discovery may be made long into extended phase that was only possible after the collection of a lengthy data set. There are also completely new discoveries, either from rare events, new observations of specific features, or new mission destinations or observing modes. Major results have been realized while missions were in extended phase.

This chapter highlights some of the discoveries made in extended mission phase, but certainly is not comprehensive. What this short overview demonstrates, however, is that all of the science disciplines in NASA's Science Mission Directorate (SMD) have experienced major benefits from the extended phase operations of spaceflight missions. This leads to the first major finding of this report.

Finding: NASA's extended science missions have made major contributions to scientific discovery over many decades.

ASTROPHYSICS DISCOVERIES DURING EXTENDED MISSIONS

The Astrophysics Science Division conducts a broad program of research in astronomy, astrophysics, and fundamental physics. Investigations address issues such as the nature of dark matter and dark energy, discovery of exoplanets and analysis of which planets could harbor life, and the nature of space, time, and matter at the edges of black holes. There were four "Great Observatories" consisting of the Hubble Space Telescope (HST), Compton Gamma-Ray Observatory, the Chandra X-Ray Observatory, and the Spitzer Space Telescope. Except for Compton (de-orbited in 1999), all of these are in extended mission phases (see also Box 2.1 for a discussion of HST). Examples of results from current extended missions are in Table 2.1.

The Chandra X-ray Observatory, which provides 10 times better spatial resolution (0.5 arcsec) than any other X-ray observatory to date or currently in development, was launched into a highly elliptical, geocentric orbit in 1999 and completed its prime mission in 2004. Since that time, it has been extended through the biennial Senior Review process and continues to be in good health. During its extended mission, Chandra has contributed important results over diverse areas of astrophysics, ranging from our solar system to cosmological studies. Chandra has provided

BOX 2.1**The Hubble Space Telescope Prime and Extended Missions**

Although the Hubble Space Telescope (HST) has been in orbit for more than 26 years, it has spent very little time in extended-mission phase due to repeated servicing and upgrading. Hubble was launched on April 24, 1990, as payload on the space shuttle *Discovery*. Hubble was designed with eight instrument bays. The original instruments included three fine guidance sensors used for pointing, the Wide Field Planetary Camera (WFPC) 1, the Faint Object Spectrograph (FOS), the Goddard High Resolution Spectrograph (GHRS), the Faint Object Camera (FOC), and the High Speed Photometer (HSP). Since the earliest plans, HST was designed to be serviceable via the space shuttle. In order to keep the observatory at the forefront of scientific ability, new instruments replaced the originals, and broken or outdated hardware was replaced over the course of five servicing missions from 1993 to 2009.

The first servicing mission (SM1) launched on December 2, 1993, and was focused primarily on repairing Hubble's optical system. To correct this problem, WFPC2 was designed with internal corrective optics and replaced WFPC1. Similarly, the Corrective Optics Space Telescope Axial Replacement (COSTAR) replaced HSP to serve as corrective optics for the FOS, GHRS, and FOC. Malfunctioning solar arrays were also replaced. With these new instruments installed, Hubble started a new prime mission phase.

On the second servicing mission (SM2) launched on February 11, 1997, the Space Telescope Imaging Spectrograph (STIS) replaced GHRS, and the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) replaced FOS. Both of these instruments contained internal corrective optics and therefore would not need to rely on COSTAR. During this mission, astronauts also replaced one Fine Guidance Sensor (FGS), installed a Solid State Recorder (SSR) in place of one of the original data recorders, and replaced one of the reaction wheel assemblies used for pointing. Hubble again started a prime mission phase.

The third (SM3A) and fourth (SM3B) servicing missions were originally supposed to be completed together, but when a third of Hubble's six gyroscopes broke down, NASA decided to split the mission into two parts. The telescope needs at least three gyroscopes for accurate pointing, so the first half of the servicing mission was moved up to a December 19, 1999, launch. This turned out to be excellent timing, as a fourth gyroscope broke down that November, necessitating that Hubble be put into a "safe mode" to protect it until it could be serviced. During SM3A, astronauts replaced all six gyroscopes, one FGS, and a broken radio transmitter, and installed a new central computer and a more advanced SSR.

During SM3B, launched March 1, 2002, the Advanced Camera for Surveys (ACS) replaced FOS, the last of the original instruments. Additionally, NICMOS was repaired during this mission, because its cooling system had exhausted its supply of nitrogen ice. Hubble's solar panels and another reaction wheel assembly were also replaced.

The fifth and final servicing mission (SM4) almost did not happen, because its initially planned 2004 launch was canceled in the aftermath of the 2003 *Columbia* space shuttle accident. After the mission was reinstated with an eventual May 2009 launch, NASA planned with an eye for the future. Two major instruments were replaced, with the Wide Field Camera (WFC) 3 replacing WFPC2 and the Cosmic Origins Spectrographs (COS) replacing the no longer needed COSTAR. In addition, repairs were made to STIS and ACS, which had gone offline in 2004 and 2007, respectively. To ensure the longevity of the telescope, astronauts replaced all six gyroscopes, all six of the original batteries, and another FGS, in addition to covering equipment bays with new insulating blankets. They also installed a backup Science Instrument Command and Data Handling Unit, because the original had malfunctioned and its backup had been activated. Planning for Hubble's eventual decommission, they also installed the Soft Capture Mechanism, allowing for a robotic mission to safely bring the telescope back through Earth's atmosphere.

Due to its unique serviceable design, Hubble entered a new phase of its prime mission after each servicing mission. In this way, the servicing missions "reset the clock," as updated technology and hardware repairs extended Hubble's lifetime as well as the time it spent in its prime phase. The final prime mission phase, post-SM4, began with the 2009 servicing mission and ended in 2014, when Hubble entered its extended-mission phase. With the retirement of the Space Shuttle Program in 2011, Hubble can no longer be serviced, but due to the efforts of SM4, NASA is hoping to keep it operational until at least 2020 to allow for at least 1 year of overlap with James Webb Space Telescope.

TABLE 2.1 Examples of Science Results Made Possible by Extended Missions in Astrophysics

Mission	Science Results
Chandra X-Ray Observatory	Discovery of the most recent known supernova explosion in our galaxy with an age of around 140 years, about 200 years younger than previous record-holder (Reynolds et al., 2008).
Fermi Gamma-ray Space Telescope	Discovery of a new class: classical novae that produce high-energy gamma rays, indicating acceleration of subatomic particles to cosmic-ray energies (Ackermann et al., 2015).
Hubble Space Telescope	The accelerated expansion of the universe due to dark energy is discovered by observations of Type Ia supernovae with HST and ground telescopes, celebrated by the 2011 Nobel Prize (Riess et al., 1998; Perlmutter et al., 1999).
Kepler	Great enhancement of the population of small, rocky planets orbiting Sun-like stars and stars with astroseismology periods.
NuSTAR (Nuclear Spectroscopic Telescope Array)	Best measurement of the spin rate of a supermassive black hole at the center of a galaxy (Walton et al., 2013).
Spitzer Space Telescope	Together with Hubble Space Telescope identified very distant galaxy GNz-11, finding that star formation proceeds much more rapidly than previously known in the early universe (Oesch et al, 2016).
Swift	Discovery of bright X-ray emission from a tidal disruption event where a star was torn apart when it orbited too close to a massive black hole (Bloom et al., 2011; Burrows et al., 2011).
XMM-Newton	Discovery of the first spinning neutron star in M31 (Esposito et al., 2016).

strong support for the existence of dark matter (Clowe et al., 2006), and it has recorded the long-term behavior of supermassive black holes, including Sagittarius A* at the center of the Milky Way (Ponti et al., 2015) (Figure 2.1).

The Spitzer Space Telescope was launched into an Earth-trailing heliocentric orbit in 2003. Upon completion of its prime mission in 2009, when its reserve of liquid helium cryogen was exhausted, Spitzer entered into the “warm” Spitzer extended mission phase. Although only two of its four original imaging arrays have remained useful (at wavelengths of 3.6 and 4.5 μm), Spitzer has successfully provided important observations of comets, near-Earth asteroids, brown dwarfs, transient objects, galaxy clusters, and the most distant galaxies (Werner et al., 2015).

One of the most important questions in astrophysics involves the details of star formation and galaxy growth in the early universe. On the basis of colors determined from Hubble and Spitzer (warm/extended mission) images in different wavebands, a galaxy named GNz-11 had an estimated distance and age suggesting it was one of the most distant and youngest observed to date. These Spitzer and Hubble images indicated that GNz-11 is about 25 times smaller than our Milky Way galaxy and about 100 times less massive. Nonetheless, GNz-11 forms stars at a rate about 20 times higher than the present rate of star formation in the Milky Way. Motivated by these prior Hubble and Spitzer data, spectroscopic observations made in 2015 with the Hubble Wide Field Camera 3 (during the Hubble extended mission) determined a precise redshift of 11.1 for this galaxy, meaning that it is being observed as it appeared just 400 million years after the Big Bang and about 200 million years earlier than the previous record holder (Oesch et al., 2016). This more precise distance determination tells us that star formation proceeds much more rapidly than previously known in the very early universe and promises many more such results from the upcoming James Webb Space Telescope (JWST) and Wide-Field Infrared Survey Telescope (WFIRST) missions.

Recent engineering modifications have enabled Spitzer to become an additional tool in the identification, confirmation, and classification of exoplanets. Moreover, Spitzer’s warm mission has become an essential tool for studying atmospheric properties of hot Jupiters and determining whether super-Earth-size planets have an atmosphere (see Figure 2.2). Thus, one of the lessons from Spitzer’s experience is that extended missions can be surprisingly useful and resilient, even to the people who developed them. There was widespread perception within the astrophysics community that the warm Spitzer phase would not be very productive, and yet it has resulted in numerous important scientific discoveries. There are many reasons for this, including the fact that new technologies on the ground, and new concepts, questions, and ideas generated by its mission team, can be applied to a spacecraft many years after the end of its prime phase.



FIGURE 2.1 Astronomers have observed the largest X-ray flare ever detected from the supermassive black hole at the center of the Milky Way galaxy. This event, detected by NASA's Chandra X-ray Observatory, raises questions about the behavior of this giant black hole and its surrounding environment. SOURCE: Chandra X-Ray Observatory, "NASA's Chandra Detects Record-Breaking Outburst from Milky Way's Black Hole," release date January 5, 2015, http://chandra.harvard.edu/press/15_releases/press_010515.html; courtesy of NASA/CXC/Amherst College/D. Haggard et al.

The Swift Gamma-Ray Burst Mission studies the most powerful explosions the universe has seen since the Big Bang. In its extended phase, Swift discovered the first jettied emission from a tidal disruption event (TDE). TDEs are a unique probe of dormant supermassive black holes in galaxies that are too distant for resolved kinematic studies. They occur when a star passes too close to a supermassive black hole and is ripped apart by the tidal forces. In an unexpected development, the TDE world was revolutionized in 2011 by Swift's discovery of the high-energy transient SwJ1644+57. While initially thought to be an exotic gamma-ray burst, SwJ1644+57 turned

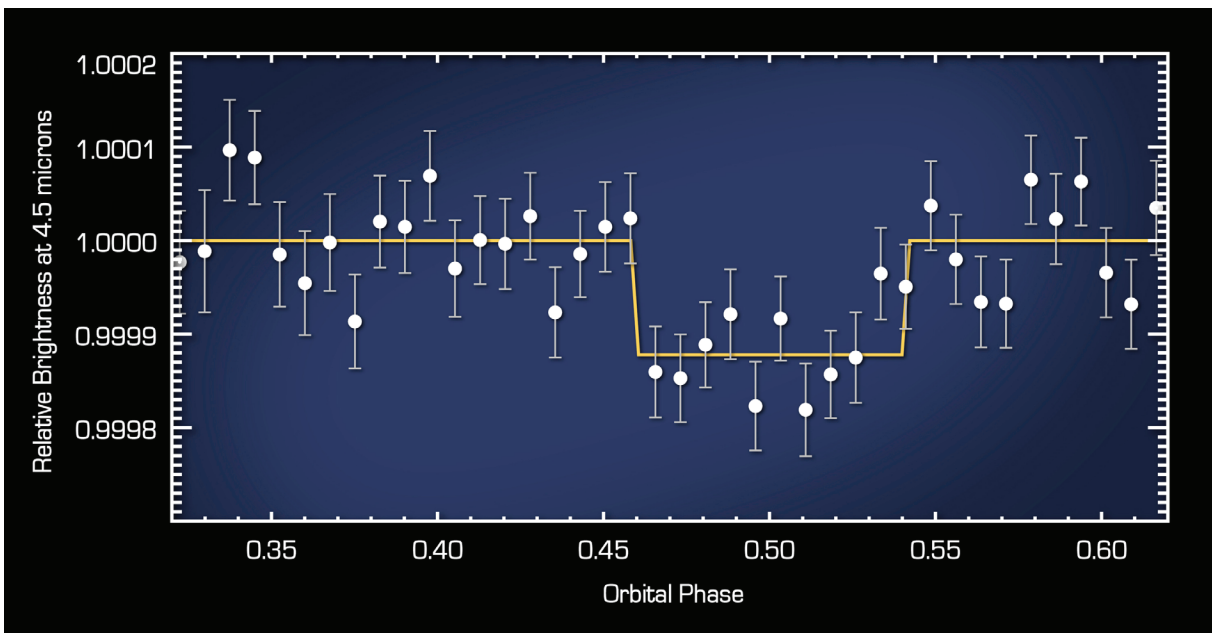


FIGURE 2.2 As measured by the Spitzer Space Telescope, the plot shows how the infrared light from the 55 Cancri system, both the star and planet, changed as the planet passed behind its star. When the planet disappeared, the total light dropped and then increased back to normal levels as the planet circled back into view. The drop indicated how much light came directly from the planet itself. This type of information is important for studying the temperatures and compositions of planetary atmospheres beyond our own. SOURCE: NASA, “Magician of a Planet Disappears to Reveal Itself,” last modified May 10, 2012, http://www.nasa.gov/mission_pages/spitzer/multimedia/pia15621.html; courtesy of NASA/JPL-Caltech/MIT.

out to be the birth of a relativistic jet triggered by the tidal disruption process. It was located at the center of an inactive galaxy nucleus, where a supermassive black hole is likely to exist. The initial bright flaring emission lasted for 1 day, followed by 1 year of fading afterglow. The formation of a relativistic outflow also powered a bright radio emission, visible for months after the onset of SwJ1644+57. Based on this Swift discovery, the new class of relativistic TDEs are predicted to be one of the most numerous class of extragalactic transients to be discovered by forthcoming wide-field radio surveys.

The Nuclear Spectroscopic Telescope Array (NuSTAR) provided the first orbiting telescopes to focus light in the high energy X-ray (6-79 keV) region of the electromagnetic spectrum to study highly energetic phenomena. In its extended mission, NuSTAR, working together with Chandra, for the first time witnessed a Type Ib supernova—the explosion of a massive star without a hydrogen envelope—metamorphose into a supernova with a shock wave interacting strongly with material previously ejected by the progenitor star (Margutti et al., 2016). The data for SN2014C (Figure 2.3) imply that the shell of material was ejected by the progenitor star 10 to 1,000 years before the explosion. This phenomenology challenges the current theories of massive stellar evolution and argues for a revision of the understanding of mass loss in evolved massive stars. In turn, such revisions would affect estimates of the stellar initial mass function in galaxies and of star formation through cosmic time, which rely on the predictions of stellar evolution models.

EARTH SCIENCE DISCOVERIES DURING EXTENDED MISSIONS

Earth is a complex, dynamic system and to fully understand it requires understanding Earth’s atmosphere, lithosphere, hydrosphere, cryosphere, and biosphere as a single interconnected system. Earth is changing on all

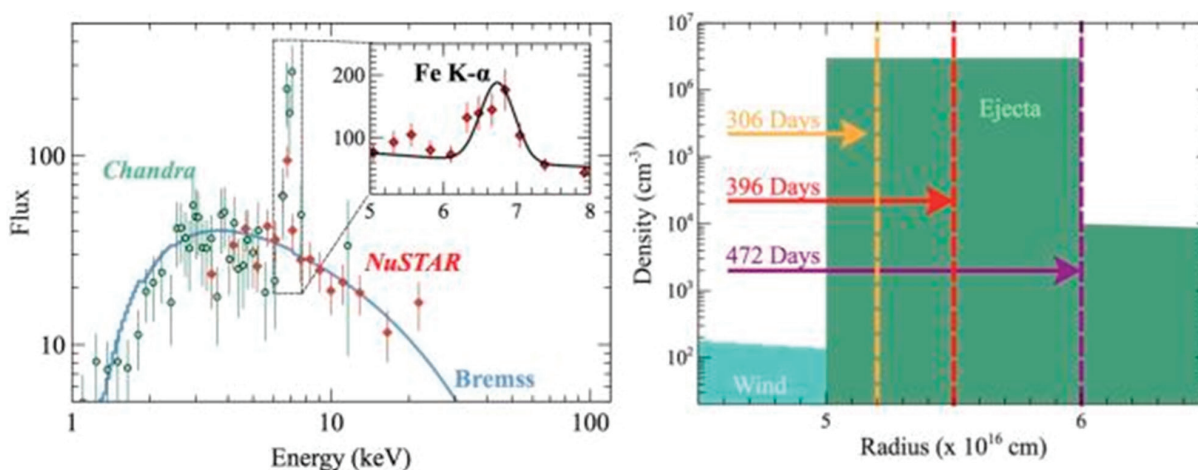


FIGURE 2.3 NuSTAR and the Chandra X-Ray Observatory track the emission from the outward propagating shock in SN2014C as it encounters a shell of material ejected from the progenitor star less than a thousand years before it exploded. *Left:* The broadband spectrum with Chandra and NuSTAR 396 days after the explosion. The simultaneous fit constrains both the temperature of the thermal emission and the density of the ejecta into which the shock is propagating. *Right:* Using the broadband data, the density profile can be reconstructed 306, 396, and 472 days after the explosion, revealing the density profile of the shell as the shock traverses it. SOURCE: Data from Margutti et al. (2016).

spatial and temporal scales. The purpose of NASA's Earth science program is to develop a sufficient understanding of Earth's system and its response to natural or human-induced changes to make accurate predictions of climate impacts under various scenarios. NASA Earth science missions are a mix of large directed (flagship) missions such as Terra and Aqua, plus smaller, competitively selected missions and instruments. Examples of major results from a sub-sample of extended missions are given in Table 2.2.

The Gravity Recovery and Climate Experiment (GRACE) is an Earth system science Pathfinder mission launched in 2002 and initially planned for 5 years. The Pathfinder Program provides periodic, competitively selected opportunities to accommodate new and emergent scientific priorities. GRACE goals included monthly measurements of Earth's gravity field with unprecedented accuracy, to help define Earth's geoid and help measure the dynamic ocean surface topography resulting from the general ocean circulation. The measurements contribute to understanding the temporal variations in global and regional sea level and are essential for separating the contributions of sea level rise due to thermal expansion from those of increasing seawater mass. This separation allows determination of the change in heat stored by the oceans. The monthly measurements also contribute to assessing ground water storage in aquifers, ocean mass change from melting of glaciers, measuring the change in mass distribution of polar ice and the episodic mass change associated with large earthquakes.

GRACE entered extended mission phase in 2008 and has been extended several times since then. Due to its unique measurements and well-designed spacecraft and instruments, this international partnership mission continues to play a vital role in assessing Earth's water resources. The long time series from the extended mission phase has enabled water resources to be monitored worldwide (e.g., Feng et al., 2013; Moiwo et al., 2013; Joodaki et al., 2014; Chen et al., 2011), and assessed relative to precipitation changes in El Niño years and La Niña years.¹

The demonstrated value of GRACE measurements for global water resource monitoring led to the decision to implement the GRACE Follow-On (GRACE-FO) mission, which is scheduled for launch in late 2017. To maintain the climate record, there is a strong desire within the Earth science community to continue extended operations of GRACE until GRACE-FO is launched and the overlapping data sets can be compared. If NASA does this,

¹ NASA, "GRACE Tellus: Gravity Recovery & Climate Experiment," <http://grace.jpl.nasa.gov/news/>, accessed June 8, 2016.

TABLE 2.2 Examples of Science Results Made Possible by Extended Missions in Earth Science

Mission	Science Results
Aqua	MODIS fractional snow cover, sea ice extent, and ice surface temperature products showed that the melting of the Greenland ice sheet in 2012 was the most extensive surface melting observed in the satellite era to that date (Hall et al., 2013).
Aura	Microwave Limb Sounder and Ozone Monitoring Instrument data revealed unprecedented ozone loss during the 2010-2011 Arctic winter (Manney et al., 2011).
CALIPSO	CALIPSO observations showed gradually increasing stratospheric aerosol loading from 2006-2011 due to a series of relatively moderate volcanic eruptions (Vernier et al., 2011) and resulting in a global cooling of about -0.07°C (Solomon et al., 2011), sufficient to offset a significant portion of the surface warming expected from increasing greenhouse gas concentrations over the past decade.
CloudSat	CloudSat data from 2008-2010 showed that trapping of heat by clouds is enhancing Greenland ice sheet meltwater runoff (Van Tricht et al., 2016).
EO-1	As a technology demonstration mission, EO-1 demonstrated over 12 years the practicality and stability of using ground-based calibration sites in support of sensor cross-comparisons and carbon flux measurements (Campbell et al., 2013).
GRACE	GRACE documented dramatic ice mass loss in Patagonia (Ivins et al., 2011), the Russian High Arctic (Moholdt et al., 2012), coastal Alaska (Sasgen et al., 2012), the Canadian Arctic (Gardner et al., 2011), and in the high mountains of central Asia (Jacob et al., 2012). GRACE data revealed groundwater depletion in the Colorado River basin from 2002-2014 during the recent drought in the western United States (Castle et al., 2014), as well as groundwater depletion in China (Feng et al., 2013; Moiwo et al., 2013), the Middle East (Joodaki et al., 2014), Turkey (Gokmen et al., 2013), the Aral Sea watershed (Zmijewski and Becker, 2014), Mexico (Castellazzi et al., 2014), and India (Chen et al., 2011; Chinnasamy et al., 2013).
Jason-1/Jason-2 (OSTM)	The Jason-1/Jason-2 (OSTM) observation record now stretches over 20 years, providing the most accurate and complete understanding of sea level change. The extended mission phases of Jason-1 and Jason-2 improved estimates of deep ocean topography, resolving many presently unknown seamounts and geologic features on the ocean bottom.
QuikSCAT	From 1999-2009, QuikSCAT provided ocean vector winds used by operational weather centers and the U.S. Navy. Since 2009, QuikSCAT provided a stable calibration of other spaceborne ocean wind vector measurements to enable a long-term, high-quality ocean wind vector database.
SORCE	SORCE observations have extended the record of solar irradiance to determine that warming over the past century is attributable mainly to increasing anthropogenic gases, with solar irradiance variability estimated to cause about 10 percent of the 0.74°C per century increase in global surface temperature (Lean and Rind, 2008). Furthermore, SORCE total solar irradiance data from the Total Irradiance Monitor instrument revealed a smaller solar irradiance than previously thought (Kopp and Lean, 2011).
Terra	MOPITT data between 2000-2003 and 2004-2008 show a clear decrease in carbon monoxide concentration worldwide (Worden et al., 2013) and over megacities (Pommier et al., 2013). MISR data show that human-caused fires limit rainfall in Africa, exacerbating dry conditions in the region (Tosca et al., 2015).

NOTE: CALIPSO, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation; EO-1, Earth Observing-One Mission; GRACE, Gravity Recovery and Climate Experiment; MISR, Multi-angle Imaging Spectroradiometer; MODIS, Moderate Resolution Imaging Spectroradiometer; MOPITT, Measurement of Pollution in the Troposphere; OSTM, Ocean Surface Topography Mission; QuikSCAT, Quick Scatterometer; SORCE, Solar Radiation and Climate Experiment.

then GRACE will have operated for over 15 years, only 5 of those in prime phase and the rest in extended phase. The GRACE experience demonstrates another typical value of Earth-science extended missions: providing cross-calibration of sensors. By enabling GRACE to continue operating until GRACE Follow-On is operational, scientists can remove any bias in the data caused by transferring from the current sensor to the next sensor, even though the two sensors theoretically have the same specification. Such cross-calibration has been important for other Earth science missions, such as missions for measuring solar irradiance (e.g., Acrimsat), sea-surface topography (e.g., Jason, OSTM), and ocean vector winds (e.g., QuikSCAT), and can be important for planetary missions.

Figure 2.4 shows the ground water storage percentage over the continental United States in September 2015 compared to the average historical results from 1948-2012, showing the severe drought in California and the Pacific Northwest.

Terra is a flagship EOS (Earth Observation System) mission launched in December 1999, whose prime mission ran through September 30, 2005. It has been extended through the Earth Science Senior Reviews in 2005, 2007, 2009, 2011, 2013, and 2015, and all five instruments are still operating nearly as well as at launch, with the exception of the 1999 failure of the shortwave-infrared instrument on ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer, a contribution from the Japanese Ministry of Economy, Trade, and Industry). There were more than 1,600 peer-reviewed science publications using Terra data in 2014 alone (NASA, 2015). Of the many science products produced over an increasingly long time period is the record of carbon monoxide (CO) concentration produced by the Canadian Space Agency-provided instrument Measurements of Pollution in the Troposphere (MOPITT), which has shown a steady decrease of CO concentration globally since Terra's 1999 launch. Due to its relatively long lifetime of several weeks in the troposphere, CO is used as a tracer of pollution transport in satellite or model studies and is an important precursor of ozone (O_3). Of particular note is the use of the shortwave and thermal infrared channels of MOPITT to increase the capability to assess CO concentration in the lower atmosphere, an algorithm enhancement developed well into the extended phase of Terra. Most megacities studied by MOPITT show a clear reduction in CO emission between 2000 and 2003 and 2004 and 2008, reaching -43 percent over Tehran, Iran, and -47 percent over Baghdad, Iraq (Pommier et al., 2013). Figure 2.5 shows a cross section of CO concentration upwind and downwind of Baghdad in 2000 to 2003 (blue line, prime mission)

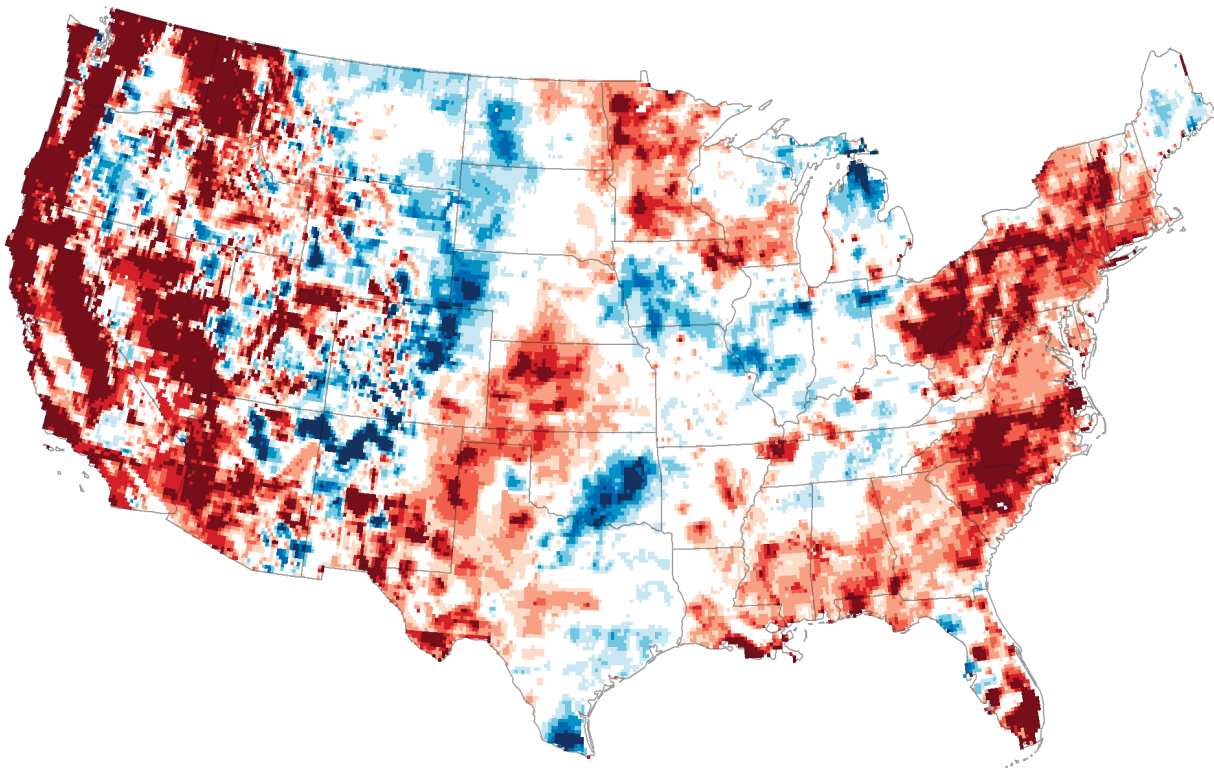


FIGURE 2.4 Ground water storage anomaly in the United States in mid-September 2015, compared to the average for the same time of year from 1948-2012, where the most recent values are derived from the GRACE satellite. SOURCE: K. Hansen, "The West Dries Up," NASA Earth Observatory, release date September 18, 2015, <http://earthobservatory.nasa.gov/IOTD/view.php?id=86632>.

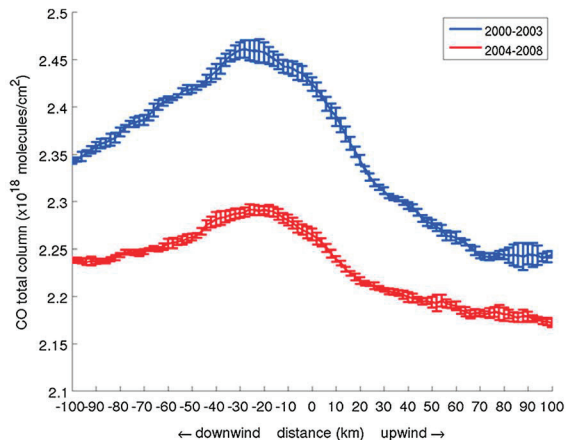


FIGURE 2.5 Measurements of Pollution in the Troposphere (MOPITT) carbon monoxide (CO) total column concentration (in 10^{18} molecules cm^{-2}) in an upwind-downwind direction over Baghdad, Iran, where the mean values were calculated from (blue) March 2000 to December 2003 and (red) January 2004 to December 2008. SOURCE: M. Pommier, C.A. McLinden, and M. Deeter, 2013, Relative changes in CO emissions over megacities based on observations from space, *Geophysical Research Letters* 40(14):3766-3771, ©2013 American Geophysical Union, all rights reserved.

and 2004 to 2008 (red line, extended mission). In addition to this focused study on various megacities around the world, MOPITT's long time series has enabled studies of the overall decrease of CO concentration worldwide, which shows an approximately 1 percent per year decrease in total column CO over the Northern Hemisphere from 2000 to 2011 (Worden et al., 2013), with a somewhat smaller but still decreasing trend in the Southern Hemisphere.

One of the lessons that Terra illustrates is that, although the spacecraft itself represents aging hardware, new technologies and techniques developed on the ground during an extended phase can be applied to the data. Thus, even a spacecraft that has been operating for many years and no longer represents the state of the art can be used in new and sophisticated ways.

HELIOPHYSICS DISCOVERIES DURING EXTENDED MISSIONS

Heliophysics is the study of the Sun, the heliosphere, and the interactions of the Sun and the solar wind with planetary environments. The heliosphere is a vast region of space carved out of the local interstellar medium by the solar wind, the magnetized plasma that flows outward at high speeds from its source in the solar corona. Heliophysics addresses fundamental properties of space plasmas. Using in situ spacecraft measurements of charged particles from low to high energies, the magnetic field, electromagnetic radiation, and energetic neutral atoms produced by charge exchange with energetic ions in regions remote from the observation point, studies in this area elucidate processes that apply to astrophysical systems throughout the universe. Research addresses the properties and the variability of the Sun and the solar wind, the interaction of the solar wind with planetary environments, and the outer heliosphere and its interaction with the interstellar medium, the latter a new frontier in the field. The interaction of the solar wind with planetary environments produces magnetospheres or analogous structures, and study of Earth's magnetosphere has profoundly contributed to our understanding of the complexities of magnetized plasmas.

The solar wind is confined within the heliosphere, a plasma bubble within the local interstellar medium, and the study of the outer heliosphere is a new frontier in the field. Heliophysics applies lessons of basic physics to the analysis and prediction of space weather, which is increasingly important to our technological civilization. Key objectives of heliophysics include unraveling of fundamental phenomena such as particle acceleration in turbulent plasmas and magnetic reconnection in space plasmas, goals that require multi-spacecraft measurements on scales

pertinent to exposing the details of this ubiquitous and critically important process. The science conducted by extended missions has been essential to advancing knowledge in all of the principal areas comprising heliophysics. Examples of major scientific results from a subsample are provided in Table 2.3 and the text that follows.

One outstanding example of discovery science emerging from data acquired during the extended phase of a mission is the first in situ exploration of the outer heliosphere. The evidence comes from the two Voyager spacecraft, initially approved for flybys of Jupiter and Saturn. Voyager 1 and 2 are perhaps the most remarkable spacecraft ever launched. (Voyager 1 flew by Jupiter in 1979 and Saturn in 1980. Voyager 2 flew by Jupiter in 1979, Saturn in 1981, Uranus in 1986, and Neptune in 1989.) Once past Neptune, the ongoing extended Voyager mission has provided unprecedented information about the outer boundaries of the region of interstellar space in which we live. The scientific benefits of the extended mission include the first observation of the termination shock (Stone et al., 2005), a front across which the solar wind slows markedly, and the first crossing of the outer boundary of the heliosphere and the first direct encounter with interstellar space (Stone et al., 2013; Krimigis et al., 2009) (see Figure 2.6). The dramatic results obtained at the outer boundary of the solar system are particularly remarkable in view of the small cost of extended operation. Even today, the in situ measurements of plasma and magnetic

TABLE 2.3 Examples of Science Results Made Possible by Extended Missions in Heliophysics

Mission	Science Results
ACE	Continuous observation of solar wind conditions for studies of energy, mass, and momentum flow through the geospace system (Gopalswamy et al., 2005). Long-term (over multiple solar cycles) observation of the solar wind is an essential part of the Heliophysics System Observatory (King and Papitashvili, 2005).
AIM	Long-distance relationships (“teleconnections”) were discovered between noctilucent clouds in one polar region and meteorological activity in the other (Holt et al., 2015).
ISEE-3	Launched in 1978, ISEE became ICE in 1982, and well into extended phase, it was retargeted to Comet Giacobini-Zinner, becoming the first spacecraft to traverse the plasma tail of a comet, where it measured particles, fields, and waves (Scarf et al., 1986).
STEREO	In its extended mission, STEREO obtained the first 360 degree images of the Sun. ^a
THEMIS/ARTEMIS	Conversion of magnetic energy in the magnetotail to particle energy in the inner magnetosphere was observed (Angelopoulos et al., 2013), particularly in conjunction with the Van Allen Probes (THEMIS). Retargeting two of the five spacecraft to circumlunar orbits (ARTEMIS) allowed for the first fully quantitative analysis of the structure and dynamical processes characteristic of the lunar wake (Wiehle et al., 2011).
TIMED	Dramatic cooling in the upper atmosphere was observed that correlated with the deep solar minimum in 2009 (Solomon et al., 2010).
Voyager 1 and 2, IBEX, Cassini	In situ measurements by Voyagers 1 and 2 of magnetized plasmas and energetic particles in the outermost regions of the heliosphere, combined with remote sensing energetic neutral atoms observations by IBEX and Cassini have led to development of new models of the heliosphere required to explain plasma properties of these strange plasma regions.
Wind	Direct observation of the electron diffusion region in collisionless reconnection (Øieroset et al., 2001).
HSO	HSO is not a single mission. It brings together the sum of spacecraft in both prime and extended phase. In particular, through the use of extended phase missions (including those not in this table), HSO has been able to document changes in the geospace environment over several solar cycles, especially the anomalously deep 2009 solar minimum (Russell et al., 2010), allowing for heliospheric wide observational studies (Gibson et al., 2009) and comparisons to models (Wiltberger et al., 2012) of entire Carrington rotations of the Sun.

^a NASA Science, “First Ever STEREO Images of the Entire Sun,” release date February 6, 2011, http://science.nasa.gov/science-news/science-at-nasa/2011/06feb_fullsun/.

NOTE: ACE, Advanced Composition Explorer; AIM, Aeronomy of Ice in the Mesosphere; ARTEMIS, Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon’s Interaction with the Sun; HSO, Heliophysics System Observatory; ICE, International Cometary Explorer; ISEE, International Earth-Sun Explorer; STEREO, Solar Terrestrial Relations Observatory; THEMIS, Time History of Events and Macroscale Interactions during Substorms; TIMED, Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics.

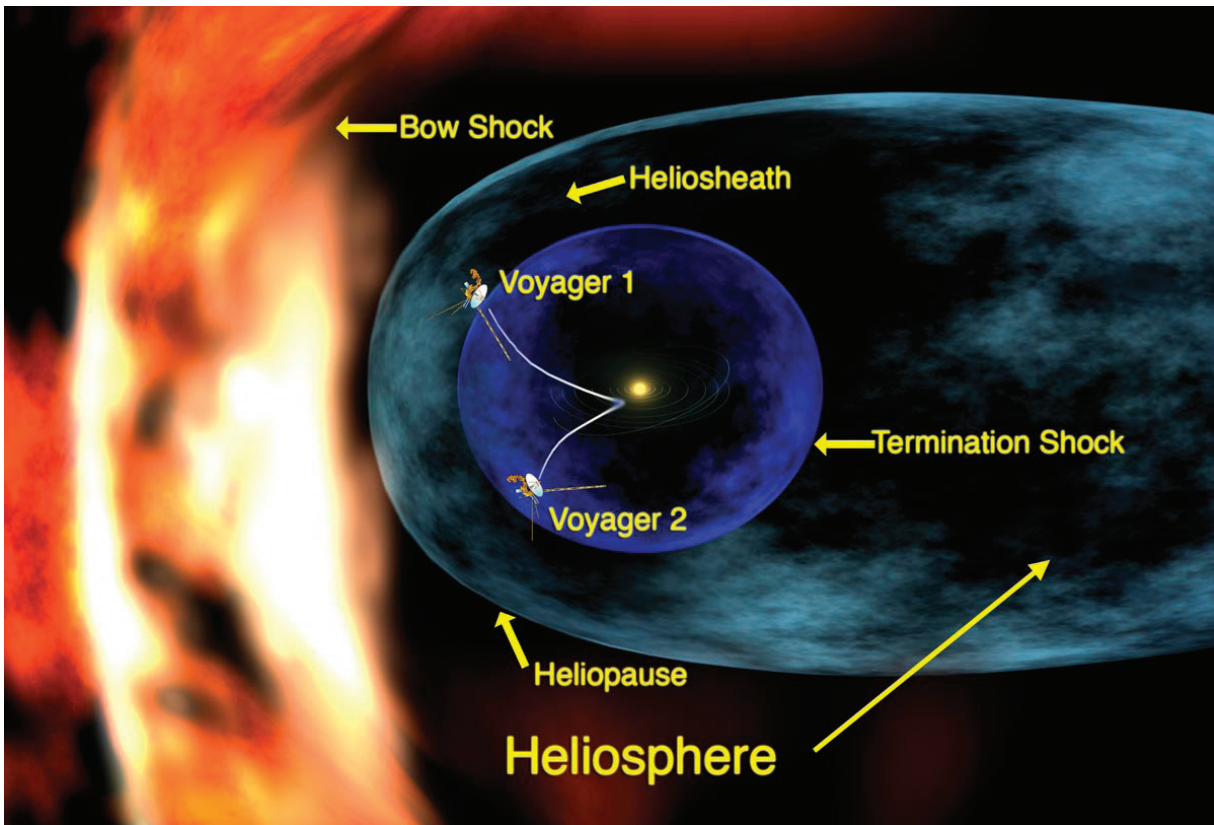


FIGURE 2.6 The Voyager interstellar mission is exploring the termination shock and heliopause for the first time. SOURCE: NASA, “What’s It Like Where Voyager Is?,” release date May 24, 2005, <http://www.nasa.gov/vision/universe/solarsystem/voyager-interstellar-terms.html>; courtesy of NASA/Walt Feimer.

field properties made by the two Voyager spacecraft and the remote sensing of the plasma and field properties by the Interstellar Boundary Explorer (IBEX) spacecraft in Earth orbit continue to provide information about the farthest reaches of the heliosphere; the new data challenge our scientific preconceptions and are generating new understanding.

From the large scale and the outer reaches of the solar system to the smallest scale in our own backyard, important scientific discoveries have been made and are continuing to be made using data from extended missions. A key example is the developing understanding of the process of magnetic reconnection. This dynamical phenomenon, ubiquitous in space plasmas, transfers energy from magnetic fields to plasmas and powers solar flares and magnetic storms. However, many details of the reconnection process are still poorly understood. There had been an ongoing argument whether resistive or collisionless processes were at the heart of reconnection in Earth’s magnetosphere. The question was hard to answer because space is big, and the electron diffusion region where the critical processes take place is very small. But in 2001, NASA’s Wind spacecraft, well into its extended mission, was in the right place at the right time to capture crucial evidence that collisionless reconnection was occurring (Øieroset et al., 2001). Data from the ongoing THEMIS (Time History of Events and Macroscale Interactions during Substorms) extended mission have been illuminating in considerable detail the fundamental mechanisms through which energy released in magnetic reconnection is converted into plasma energy that powers the aurora and helps create the Van Allen radiation belts (Angelopoulos et al., 2013).

Tracking energy flows through the magnetospheric system is central to our understanding of space weather. We live in the neighborhood of a variable star, and understanding its variations is fundamental to understanding our space climate. In the past decade, something has been happening with the Sun. In 2009, Earth experienced the deepest prolonged solar minimum of the space age with almost no sunspot activity (e.g., Russell et al., 2010). Fortunately, the Wind and ACE (Advanced Composition Explorer) extended missions were operating and were able to monitor the state of the Sun and the solar wind. The deep solar minimum was felt throughout the system; for example, data from the TIMED (Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics) extended mission revealed a link between the anomalously low solar extreme ultraviolet irradiance and the thermospheric density (Solomon et al., 2010). This type of correlated response highlights the need for the constellation of spacecraft that comprise the Heliophysics System Observatory (HSO) to provide a long-term monitoring of Earth's space environment (see Figure 2.7).

Additional questions addressable through heliophysics observatories include the following: How will the Sun evolve over the next solar cycle or two? Will it enter into a new extended minimum in solar magnetic activity

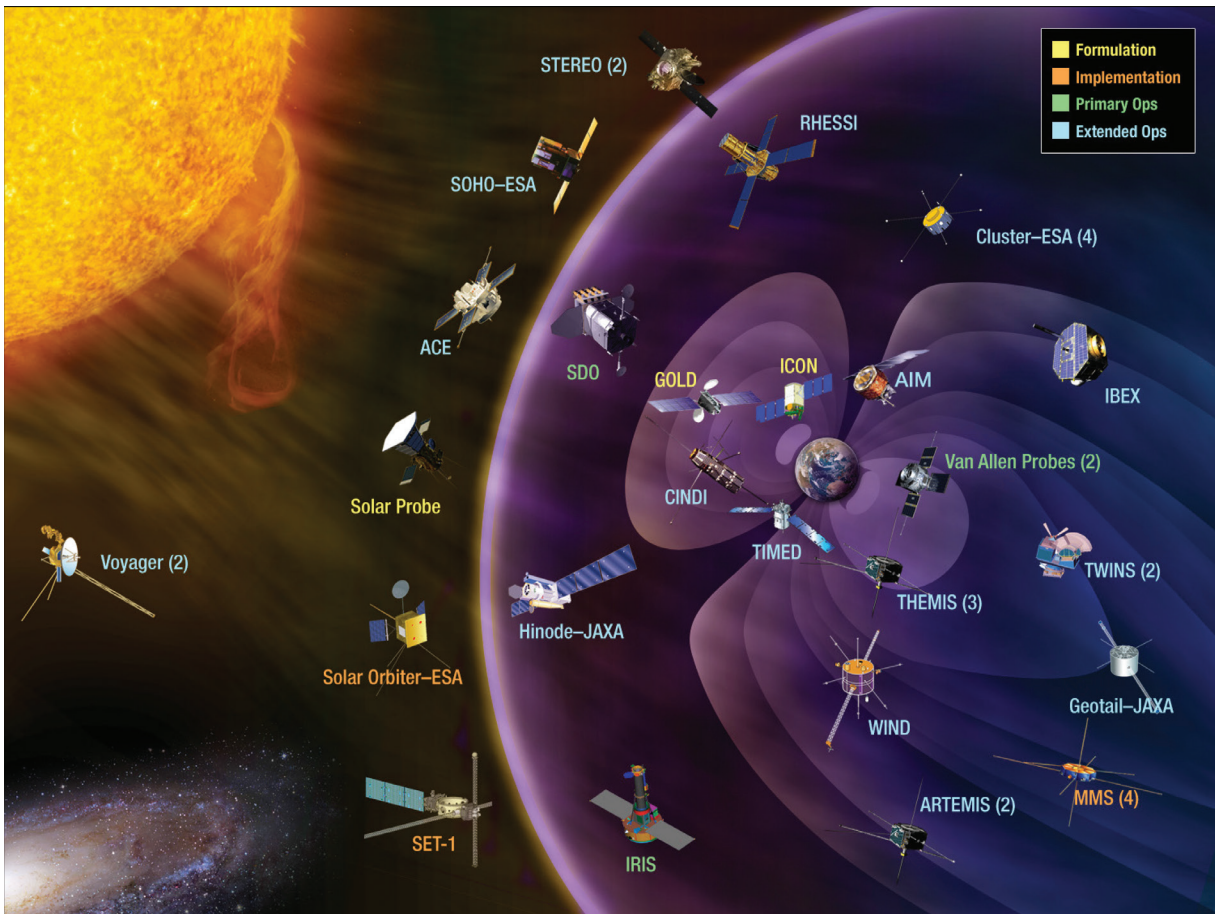


FIGURE 2.7 The Heliophysics System Observatory, dominated by extended missions, provides the widespread coverage needed to understand solar physics. NOTE: Acronyms are defined in Appendix F. SOURCE: NASA, “Heliophysics System Observatory (HSO),” last modified March 2, 2015, <http://www.nasa.gov/content/goddard/heliophysics-system-observatory-hso/#.V3FY8vkrJki>.

like that of the Dalton minimum of the 19th century or even the Maunder minimum of the 17th century?² What will be the effect on space weather, or even on terrestrial climate? Only a continuous monitoring of all of the components of the system can help to answer these questions. Fortunately, the armada of spacecraft that comprise the HSO are already operating and most are still functioning well. Given that it would never be possible to launch all of the elements of the HSO simultaneously as new missions, it is essential that existing spacecraft be operated as long as they are functioning effectively because they are needed to provide the required long-term records that can reveal temporal changes of key elements of the heliosphere.

PLANETARY SCIENCE DISCOVERIES DURING EXTENDED MISSIONS

The strategic goal of NASA's Planetary Science Division (PSD) is to advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space. Planetary science differs from the other science disciplines in a key way: it commonly takes significant time and energy for a spacecraft to reach its operating location and begin collecting data. For planetary science missions, a number of major science results have been possible only because of extended missions (see Table 2.4 for examples from some current extended missions). This section focuses on three examples to demonstrate the value of extended missions: recent extended mission discoveries about Mars, about ocean worlds, and near-Earth objects. In the first two cases, these discoveries have been critically important to shaping future exploration to achieve the highest priorities of NASA PSD. In the latter case, a relatively recent discovery revealed that Earth may have previously unknown companions in its orbit.

During the 2014 Planetary Science Senior Review, both the Lunar Reconnaissance Orbiter and the *Opportunity* rover were rated highly for their continued scientific contributions. However, they were both zeroed out for funding in the President's fiscal year (FY) 2015 and FY2016 budgets. The scientific discoveries made by both missions during their extended phase are addressed in Appendix B of this report.

NASA's Mars Exploration Program has benefited from missions lasting well beyond their primary missions, including the Mars Global Surveyor (MGS), Mars Odyssey, Mars Reconnaissance Orbiter (MRO), and the Mars Exploration Rovers (MER) *Spirit* and *Opportunity*. Each of these missions has spent far more time in extended phases than in the prime missions. For example, *Spirit* did not arrive at the Columbia Hills until well into its extended mission, where it achieved its most important results, describing a habitable ancient hydrothermal environment (Squyres et al., 2008; Ruff et al., 2011). This region is now one of the top candidate landing sites for the Mars 2020 rover, designated to cache samples for future return to Earth.

MRO was launched in 2005, achieving orbit around Mars in 2006. After completing its 4-year prime mission, MRO then entered into the extended mission phase in 2010, in which it continues to be operated. During the extended mission, the MRO science team first observed recurring slope lineae (RSL) on the surface of Mars (see Figure 2.8)—dark streaks that grow and fade with the seasons (McEwen et al., 2011). In the extended missions, these features were systematically monitored to understand their temperature behavior, consistent with briny water, and geographic distribution (McEwen et al., 2014). Spectral data collected during the extended missions enabled the detection of hydrated salts at some of these locations, confirming a role for briny water (Ojha et al., 2015). The RSL and other discoveries are of key importance for understanding potential present-day habitability, "Special Regions" for planetary protection plans, and resources for future humans on Mars, leading to the major science focus of the next recommended orbiter (MEPAG, 2015).

The outer planet moons with confirmed subsurface oceans are the Saturnian moons Titan and Enceladus and the icy Galilean satellites of Jupiter. Europa is the most interesting case because water is in contact with tidally heated silicates. An ocean in Europa was only suspected following three close encounters during the Galileo prime mission (Pappalardo et al., 1999). It was not until eight successful encounters in the extended missions that new

² The Dalton minimum was a period of low sunspot count, representing low solar activity, named after the English chemist, physicist, and meteorologist John Dalton, lasting from about 1790 to 1830. The Maunder minimum is the name used for the period starting in about 1645 and continuing to about 1715 when sunspots became exceedingly rare, named after the solar astronomer Annie Russell Maunder (1868-1947) and E. Walter Maunder (1851-1928).

TABLE 2.4 Examples of Major Science Results Made Possible by Extended Missions in Planetary Sciences

Mission	Science Results
Cassini	Global subsurface oceans were discovered in Titan (Lorenz et al., 2008; Iess et al., 2012) and in Enceladus (Thomas et al., 2016).
LRO	Hundreds of new impact events (Speyerer et al., 2016) as well as recent or active tectonics (Watters et al., 2015) were detected, and polar ice was quantified (Hayne et al., 2015; Patterson et al., 2016).
MERs <i>Spirit</i> and <i>Opportunity</i>	A habitable hydrothermal environment was discovered by the <i>Spirit</i> rover (Squyres et al., 2008; Ruff et al., 2011). The <i>Opportunity</i> rover, along with MRO, mapped hydrated magnesium and calcium sulfate minerals that formed from rising ground waters (Arvidson et al., 2015).
Mars Odyssey	Extensive chloride-bearing deposits were discovered, likely ancient playas (Osterloo et al., 2008).
MRO	Recurring slope lineae were discovered (McEwen et al., 2011) and their association with hydrated salts was studied (Ojha et al., 2015).
Mars Science Laboratory	The <i>Curiosity</i> rover arrived at the base of Mt. Sharp and discovered evidence for a long-lived lake (Grotzinger et al., 2015). Evidence of refractory organic material on Mars was discovered (Eigenbrode et al., 2015).
NEOWISE	Earth's Trojan asteroid was discovered (Connors et al., 2014).
Voyager 2	The first exploration of ice giant systems was completed of Uranus (Stone, 1987) and Neptune and Triton (Stone and Miner, 1989).

NOTE: LRO, Lunar Reconnaissance Orbiter; MER, Mars Exploration Rovers, MRO, Mars Reconnaissance Orbiter, NEOWISE, Near-Earth Object Wide-field Infrared Survey Explorer.

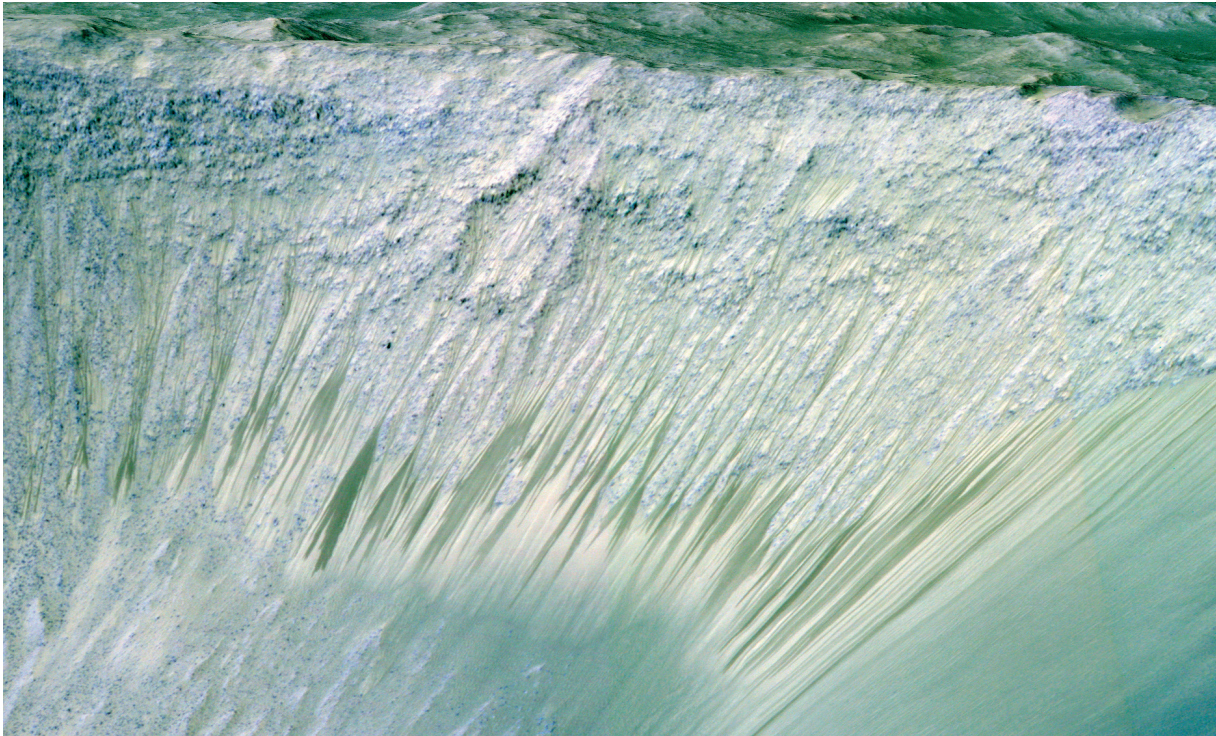


FIGURE 2.8 Dark narrow streaks, called “recurring slope lineae,” emanate from the bedrock layers of Garni Crater on Mars, in this oblique view constructed from observations by the High Resolution Imaging Science Experiment (HiRISE) camera on NASA’s Mars Reconnaissance Orbiter. Image width ~1 km. The scale varies from top to bottom because it is an oblique view. SOURCE: HiRISE image ESP_031059_1685, <http://hirise.lpl.arizona.edu/>; courtesy of NASA/JPL/University of Arizona.

geophysical (Kivelson et al., 2000) and other results (Pappalardo et al., 2009) were considered definitive evidence for an ocean. This changed the focus of future Europa exploration from confirmation of an ocean to *habitability* of that ocean. The multiple flyby mission to study Europa's habitability is now in Phase A development, and a Europa lander is also being studied.³

Cassini-Huygens is a flagship mission originally launched in 1997 that, after 7 years in transit, reached Saturn in 2004 to begin its 4-year prime mission of exploring the local system and landing the Huygens probe on the surface of Saturn's largest moon, Titan. Upon completing the prime mission, the orbiter was extended in 2008 for the 2-year Cassini Equinox Mission, including a series of close approaches to the icy moon, Enceladus. Having previously discovered active cryo-volcanism near the southern pole of this moon, Cassini was able to engage its suite of remote sensing and fields and particle experiments to determine the trace constituents within the plumes, as well as the conditions near the surface fractures where the jets emanate. These observations provided strong additional evidence for the existence of a liquid water reservoir beneath the surface of Enceladus (e.g., Waite et al., 2009; Figure 2.9) and for hydrothermal activity in the deep subsurface (Hsu et al., 2015). Cassini was extended again in 2010 for the Cassini Solstice Mission in order to study seasonal-temporal changes within the Saturn system, with an additional 12 encounters with Enceladus and 56 of Titan. In the Cassini prime mission, a subsurface ocean (perhaps not global) was only suspected in Enceladus, and confirmation came from the extended mission with many more encounters (Jess et al., 2014; Thomas et al., 2016) (see Figure 2.10). For Titan, surface hydrocarbon lakes or seas were known, but confirmation of a deep global water ocean was a key extended mission result (Jess et al., 2012). Based on these extended mission results, Congress has recommended, and NASA is acting on, creating a new Ocean Worlds program with a series of future missions.

Earth is now known to share its orbit with a Trojan asteroid that librates around its L4 Lagrange point, joining Venus, Mars, Jupiter, Neptune, and Uranus among the list of planets known to host such co-orbital objects. The first and only known Earth Trojan, 2010 TK₇, was discovered by the Wide-field Infrared Survey Explorer (WISE) (Wright et al., 2010) satellite and its enhancement for solar system science, known as NEOWISE (Mainzer et al., 2011). WISE, launched in December 2009, surveyed the full sky in four infrared wavelength bands (3.4, 4.6, 12, and 22 μm) until the frozen hydrogen cooling the telescope was depleted in September 2010. The survey continued as NEOWISE for an additional 4 months used the two shortest wavelength detectors. The spacecraft was placed into hibernation in February 2011 after completing its search of the inner solar system. NEOWISE was brought out of hibernation (now supported by PSD) to learn more about the population of near-Earth objects and comets that could pose an impact hazard to Earth. NEOWISE observations resumed in December 2013. Shortly after the survey start, NEOWISE discovered its first potentially hazardous near-Earth asteroid, 2013 YP139. Earth Trojan 2010 TK₇ was discovered on October 1, 2010, approximately a day after the cryogen was fully depleted and the survey was originally scheduled to stop. Numerical integrations have shown that 2010 TK₇ is likely to remain a Trojan asteroid for thousands of years (Connors et al., 2011, 2014; Figure 2.11). Subsequent fits to the data yielded diameter and albedo estimates for the object, indicating that it is several hundred meters across (Mainzer et al., 2012). It is possible that 2010 TK₇ represents the first of a population of Earth Trojans, some of which may be primordial. The decision to operate the WISE spacecraft beyond its original lifetime has provided a first glimpse into this unique and rare population of small bodies.

What the planetary science extension examples demonstrate is that sometimes new scientific discoveries are only possible after a spacecraft moves into a new orbit or to a new location that could not be achieved during the prime mission, such as Cassini making multiple orbits around Saturn enabling it to make more and better planned observations of Enceladus, or a Mars rover reaching a new location far from its landing site. In addition, as in the earlier example of Earth science missions, sometimes data collected later in a mission (such as repeated observations of the time-varying RSL on Mars) enables fuller interpretation of earlier data. Finally, as NEOWISE demonstrates, surprising discoveries, like Earth's Trojan asteroid, can be made at any time, including long after a prime mission has ended.

³ NASA, "Mission to Europa," <https://www.nasa.gov/europa>, last updated January 26, 2016.

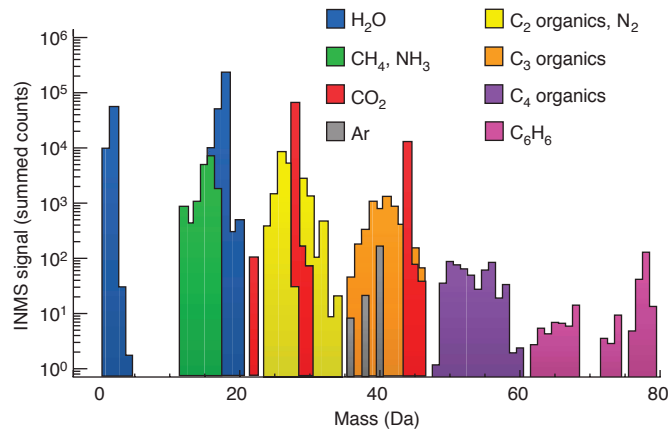


FIGURE 2.9 Measurements of constituent gases and particles within the center of the Enceladus plumes, as observed by Cassini's Ion and Neutral Mass Spectrometer during the October 9, 2008, encounter, its closest approach of the entire mission at only 27 km (16 miles). SOURCE: Reprinted by permission from Macmillan Publishers Ltd: Nature, J.H. Waite, Jr., W.S. Lewis, B.A. Magee, J.I. Lunine, W.B. McKinnon et al., Liquid water on Enceladus from observations of ammonia and 40Ar in the plume, *Nature* 460:487-490, copyright 2009.

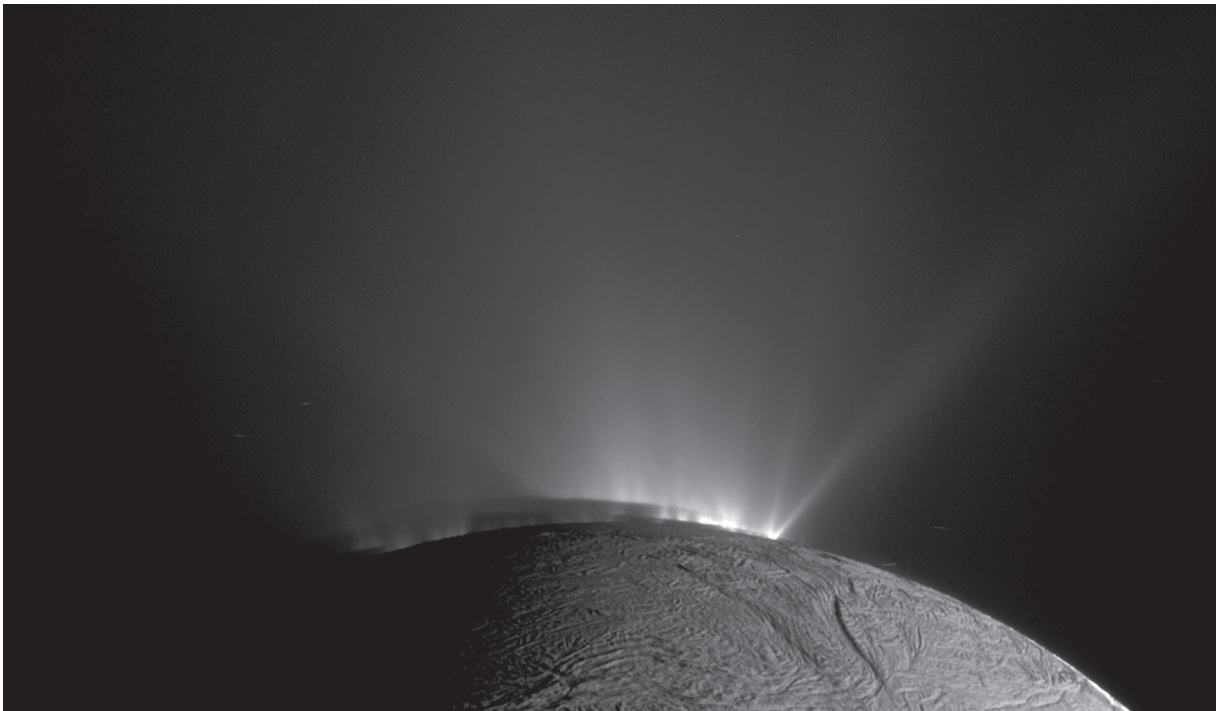


FIGURE 2.10 The erupting jets and curtains of water on Enceladus. SOURCE: NASA Jet Propulsion Laboratory, "Encroaching Shadow," accessed June 27, 2016, <http://www.jpl.nasa.gov/spaceimages/details.php?id=PIA17184>; courtesy of NASA/JPL-Caltech/Space Science Institute.

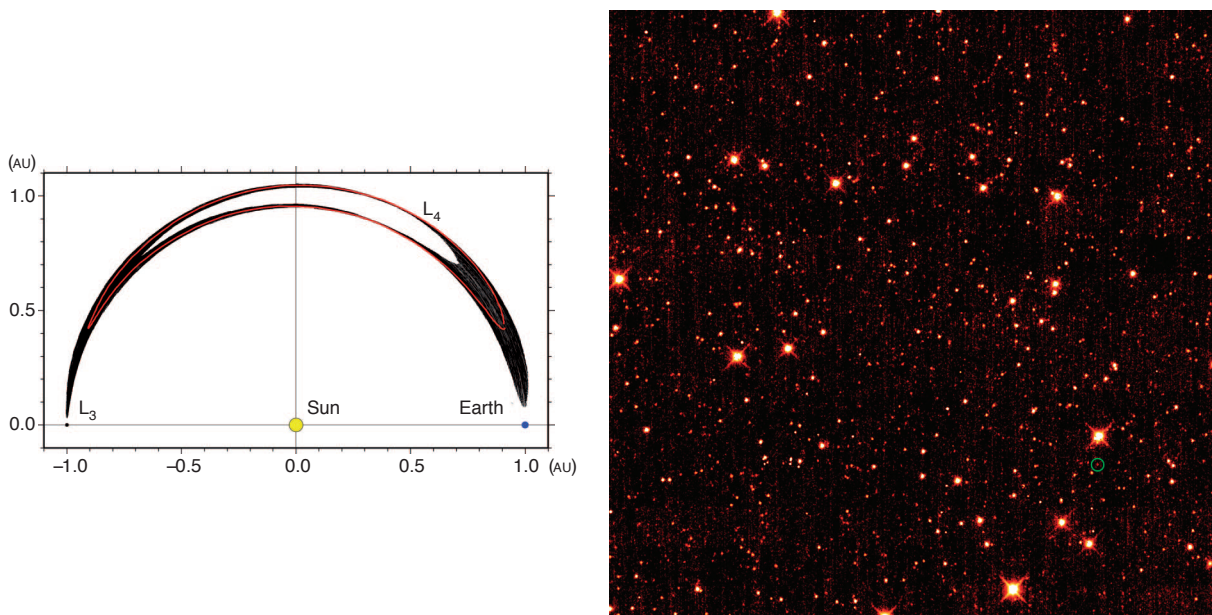


FIGURE 2.11 *Left:* Earth's only known Trojan asteroid, 2010 TK₇, was discovered because the Wide-field Infrared Survey Explorer (WISE) satellite observes near 90° solar elongation (blue dashed line) and thus detected the object as it reached an extreme point in its libration. *Right:* Thermal fits to the infrared discovery data reveal the object to be several hundred meters across with a moderately low albedo. SOURCE: *Left:* Reprinted by permission from Macmillan Publishers Ltd: Nature, M. Connors, P. Wiegert, and C. Veillet, 2011, Earth's Trojan asteroid, *Nature* 475(7357):481-483, copyright 2011. *Right:* NASA, "A Glimmer in the Eye of WISE," last modified July 27, 2011, http://www.nasa.gov/mission_pages/WISE/multimedia/gallery/neowise/pia14405.html; courtesy of NASA/JPL-Caltech/UCLA.

CONCLUSIONS

Extended missions in all four divisions of NASA's Science Mission Directorate have made major scientific contributions at low cost relative to the initial investments for the prime missions.

Finding: Extended science missions are valuable assets in NASA's portfolio because they provide excellent science at low incremental cost.

In numerous cases, the long-baseline data is critical to recognizing changes over time, especially in understanding the dynamic Earth system, the large and dynamic heliosphere, and for active planetary bodies such as Mars. Long-baseline data are also essential to discovery of rare events, such as supernova explosions and X-ray flares and relativistic jets from supermassive black holes.

Finding: Continuity, long-baseline data sets, and statistically significant observations of infrequent events require continuity of measurement over years or decades and are best provided through missions in extended phase.

In multiple cases, extended missions are able to accomplish surprising new results, either from a new orbit or observation profile or from new data analysis techniques. Examples include the Voyager spacecraft exploring the outer heliosphere, new Cassini orbits advancing understanding of the ocean and erupting jets of Enceladus, and development of a new algorithm to track carbon monoxide using Terra.

Finding: Extended missions may accomplish surprising new results via new destinations, observation types, or data analysis methods.

NASA extended mission science results have been sufficiently compelling to change the future exploration priorities of NASA and the decadal surveys. Examples include GRACE leading to GRACE-Follow On, Mars discoveries leading to new landing sites and future orbiter science priorities, and discovery of subsurface oceans leading to new missions such as the Europa multiple flyby mission and a new Ocean Worlds program.

Finding: NASA's extended missions are an important part of both achieving science objectives of the decadal surveys (see Appendix D) and determining priorities or approaches for future exploration.

Recommendation: NASA should strongly support a robust portfolio of extended-phase science missions. This support should include advance planning and sufficient funding to optimize the scientific return from continued operation of the missions.

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3

Review of Extended Missions by NASA

NASA ensures that its fleet of extended science missions provides good value and remains in balance with other science-motivated pursuits by periodically reviewing operating missions. Extended missions generally provide excellent, cost-effective science value by leveraging existing assets. Although the resource levels required to operate extended missions are generally much lower than those required for developing comparable new prime missions, the required investment levels are substantial enough that careful stewardship is warranted.

NASA reviews its extended missions biannually in accordance with Public Law 109-155 (passed in 2005 and renewed in 2010 as part of the NASA Authorization Act). Because that law does not prescribe implementation details, NASA has designed and implemented a review process in each of the Science Mission Directorate (SMD) divisions. The review process was described to the committee through presentations by the SMD associate administrator and each of the SMD division directors. The committee received further information in the form of archival documents and data. The overall approach to the reviews is based on peer-review principles commonly used to assess scientific merit. The reviews are called Senior Reviews, and each of the four SMD divisions conducts its own Senior Review using its own processes and criteria. Many aspects of the reviews are shared across the divisions, but each division implements processes and criteria tailored to its own characteristics and needs. The present-day Senior Reviews are derived from those that began in the 1990s within what are now called the Astrophysics Division and the Heliophysics Division. The Planetary Science Division also began conducting Senior Reviews in the 1990s, and the Earth Sciences Division has been conducting them since 2005. All SMD divisions therefore have extensive experience with conducting Senior Reviews.

NASA uses the Senior Reviews as key guidance for managing extended missions. The reviews are the primary gauges of the scientific value of each mission, and the findings resulting from these reviews play a central role in NASA's decision-making and resource allocation planning. Guidance from the Senior Reviews is used, along with other significant factors that are taken into account, for any NASA activity, including "the budget, programmatic considerations, agency or national policy, and international partnerships."¹

Finding: The Senior Review is a valuable peer-review process for assessing the utility, scientific value, and interagency applications of spacecraft missions that continue to operate beyond their prime mission.

¹ Clarke, S., NASA Science Mission Directorate. 2016. "Heliophysics Division," presentation to the Academies' Committee on NASA Science Mission Extensions, February 1, Washington, D.C.

This chapter describes NASA's present implementation of Senior Reviews. It discusses elements that are common to the four SMD divisions and highlights aspects that differ among the divisions. It presents perspectives on the process gleaned from presentations by and conversations with a cross section of stakeholders. The chapter discusses evolution of the Senior Review process through incorporation of experiences from previous reviews, and it presents a summary history of the missions that have been reviewed since 2005. This chapter also compares NASA's process to that practiced by the European Space Agency (ESA) for reviewing its extended missions.

SMD-WIDE CHARACTERISTICS OF SENIOR REVIEWS

The Senior Review process is based on a proposal-driven paradigm. It begins with a division director issuing a call for proposals to the teams that operate missions under the management of that division. The call is timed such that the results can be used as input to NASA's annual budgeting process. The call contains instructions for proposal preparation and submission and explains how the proposal will be reviewed by a Senior Review panel convened for this purpose. It delineates the criteria to be used by the panel in its assessment. It explains that a budget guideline for the amount of funding available for each mission has been developed by NASA within the Planning, Programming, Budgeting, and Execution (PPBE) process and specifies a period of performance. It contains the schedule for submission, typically about 4 months after the release of the call, and discusses how each team is to make an oral presentation to the panel. The call also contains links to supporting documents. Proposals are typically 30 pages in length, plus appendices, although the guidelines have varied from division to division and review to review over the years.

Senior Reviews are nominally conducted on a biannual basis, with Astrophysics and Planetary Science reviews occurring in even-numbered years and Earth Science and Heliophysics reviews occurring in odd-numbered years. Although the reviews happen on a regular basis, science missions are subject to different events and timelines, which can affect how recommendations are implemented or when individual reviews take place. For example, a launch failure of a new mission might occur after a Senior Review recommended termination of an earlier mission, thus requiring the earlier mission to be extended to avoid a gap in data continuity. Another possibility is that a spacecraft may be due to run out of fuel a few months after a scheduled review, and it would make little sense to hold a new review for only a short life extension. Perhaps most importantly, mission teams spend up to 6 months preparing for a Senior Review, and if the review and a major mission event are scheduled to occur around the same time, this could jeopardize the mission's success by diverting the team members' attention when they should be focused on mission operations. Specific examples of missions that were reviewed off-cadence are given later in this chapter.

Within each division, a panel of experts evaluates the division's extended-mission portfolio. Strategic or directed missions like NEOWISE (Near-Earth Object Wide-field Infrared Survey Explorer), principal investigator-led missions, and foreign partner-led missions to which SMD contributes, like Mars Express, are commonly, but not always, considered together. After its deliberations have concluded, the Senior Review panel issues a report containing its findings to the division director. A typical report contains an executive summary, an overview, and a digest of findings for each mission. Grades for the overall scientific merit of each mission are given. Occasionally, areas of special concern for some missions are called out and explained. The division uses this report as a basis for managing its portfolio of extended missions, including the following:

1. Prioritizing the operating missions and projects;
2. Defining an implementation approach to achieve division strategic objectives;
3. Providing programmatic direction to the missions and projects for years 1 and 2 following the review; and
4. Issuing initial funding guidelines for years 3 and 4 following the review.

DIVISION-SPECIFIC CHARACTERISTICS OF SENIOR REVIEWS

Each SMD division tailors its Senior Reviews to take into account special conditions and aspects of the division and the way it performs its overall undertaking. Thus, there are differences in the reviews across the divi-

sions. This section describes the division-specific aspects of the Senior Reviews and explains the rationales for these differences.

Astrophysics

Unlike the other divisions, the Astrophysics Division does not review all missions in the same manner. It has a different process for the Hubble Space Telescope and Chandra X-Ray Observatory than for the other astrophysics missions. These missions, as members of the Great Observatories, are treated as general-purpose facilities capable of addressing wide areas of astrophysics research and therefore are not tied to specific scientific goals. Thus, the Hubble and Chandra reviews are incremental or “delta” reviews that focus on changes since the previous review, with an emphasis on mission efficiency.

Reduced funding guidelines provided to extended missions and to the Senior Review panels in recent years has become a key concern. For example, in its 2014 Senior Review,² Spitzer was ranked highly enough to be fully funded, yet the projected budget for the set of extended missions would not accommodate that. Two lower-ranked missions would not add up to the required cut, so one option recommended by the Senior Review committee was to zero out Spitzer. In response, the Astrophysics Division provided some additional funding and allowed the Spitzer team to propose for an extension with reduced operations and higher risk. The reduced mission was approved and has delivered excellent science at lower cost. For the 2016 Astrophysics Senior Review, the guideline budgets were again insufficient to fully fund all of the missions under review. Following recommendations from the review panel to continue funding all of the missions, the Astrophysics Division reworked its constrained budgets to enable ongoing operation for all of the proposed missions. Some missions, however, are required to find further operating efficiencies to deal with reduced funding, and one mission is allocated a modest over-guide budget to augment its guest observer program.

Finding: In recent Senior Review cycles, the Astrophysics Division has adopted effective options for dealing with budget constraints and the likelihood that Senior Review panels will recommend supporting extended missions at a level above the nominal total guideline. The extent to which future cycles will be able to rely on needed budget flexibility within the divisions, as well as the ability of the missions to find further savings, albeit with increased risk, is less clear, as is the question as to whether similar approaches are applicable in other SMD divisions.

Recommendation: If a Senior Review recommends termination of a mission due to funding limitations rather than limited science return, NASA should allow the team to re-propose with an innovative, possibly less scientifically ambitious, approach at reduced operational cost and increased risk.

Earth Sciences

Earth Science Division (ESD) Senior Reviews³ begin with an assumption that a mission will be continued if its unique contributions are still rated highly and if the health of the instruments and spacecraft are still very good. An additional consideration for long-term Earth Science missions is the NASA policy requirement (NASA NPR 8715.6A) that maneuverable spacecraft that are terminating their operational phases at altitudes of less than 2,000 km above Earth shall have fuel and capability to reduce their remaining orbital lifetime to 25 years.

The Earth Science Senior Reviews explicitly acknowledge the importance of long-term data sets and the overall value of data continuity for Earth science research. This importance leads to a different risk posture for Earth Science missions in comparison to other SMD missions. The other divisions explicitly tolerate higher risk in

² The Astrophysics Division Senior Reviews are available at NASA Science, “Astrophysics: Documents,” <http://science.nasa.gov/astrophysics/documents/>.

³ The Earth Science Division Senior Reviews are available at NASA Science, “Earth: Missions: Operating,” <http://science.nasa.gov/earth-science/missions/operating/>.

extended missions than they do for prime missions, with the idea that costs can be reduced by accepting higher risk levels. Because of national interests and needs, Earth Science has more stringent requirements for data continuity and cannot accept additional risk for extended missions as a way to reduce costs.

The Earth Science Division explicitly takes into account national operational objectives in its Senior Review process. The 2005 National Research Council report *Extending the Effective Lifetimes of Earth Observing Research Missions* recognized that Earth science missions “have unique considerations, such as future operational utility and interagency partnerships, that distinguish them from space science missions” (NRC, 2005, p. 1), and the same report contained a recommendation that NASA consider the operational use of NASA Earth science missions in the mission-extension process. As a result, a National Needs Panel has been included in ESD Senior Reviews since 2007 (being more recently renamed the National Interests Panel). The findings of the National Interests Panel provide a secondary evaluation criterion; the primary evaluation criterion is the scientific merit of the mission. The National Interests Panel determines the value of the data sets for applied and operational uses that serve national interests—including operational uses, public services, business and economic uses, military operations, government management, policy making, and nongovernmental organizations’ uses. The organizations that were represented during the 2015 Senior Review are as follows:

- National Oceanic and Atmospheric Administration National Weather Service,
- National Oceanic and Atmospheric Administration National Ocean Service,
- Federal Aviation Administration,
- U.S. Department of Agriculture,
- Naval Research Laboratory,
- U.S. Army Corps of Engineers,
- Environmental Protection Agency,
- U.S. Geological Survey,
- Department of Homeland Security Federal Emergency Management Agency,
- Centers for Disease Control and Prevention,
- Alliance for Earth Observations,
- International Association of Wildland Fire,
- Conservation International,
- National States Geographic Information Council,
- U.S. Geospatial Intelligence Foundation, and
- Urban and Regional Information Systems Association.

ESD also supplements the Senior Review with an annual Operations Review. This review evaluates spacecraft and instrument health, mission operations functionality, anomalies, new or monitored risks, and science data product production for all division missions.

Finding: NASA Earth Science missions have potential or realized nonresearch utility. Evaluating the applied and operational use of NASA Earth Science missions is a secondary factor in Senior Review evaluation and extension decisions. Recognizing and promoting the contribution of NASA Earth Science data sets to applied and operational uses by public and private organizations (nonresearch purposes) increases the benefits from public investment in these missions.

The committee notes that the above finding can also apply to some heliophysics missions as well.

Heliophysics

The Heliophysics Division recognizes the interconnectedness of its discipline by explicitly considering the contributions each mission makes to the Heliophysics System Observatory (HSO). The HSO consists of all operating Heliophysics missions, and its purpose is to investigate the behavior of the entire interconnected heliophysics

domain through simultaneous multipoint sampling throughout that domain. The Senior Review panel evaluates the contributions of each mission to the HSO and reflects these evaluations through a separate set of scores reported alongside the scores of overall scientific merit.

Heliophysics extended mission proposals include a 10-page Mission Archive Plan as an appendix. This appendix describes the data products of the mission and how they will be archived for use by the research community. (Similar data archiving plans are required for the other divisions' extended mission proposals as well.)

Like the missions of the Earth Science Division, the missions of the Heliophysics Division collect data that are used by other agencies. The Senior Review includes a mechanism to include input from these agencies. Because data from some current missions are being used by the National Oceanic and Atmospheric Administration (NOAA), the 2015 Senior Review panel included a scientist from NOAA's Space Weather Prediction Center.⁴

Planetary Science

The Planetary Science Division incorporates flexibility into its regimen of mission review with occasional mission-specific adjustments to review timing due to the special constraints of planetary missions, such as target body encounters and critical mission events that require the undivided attention of the team members who would also be charged to write the Senior Review proposal. Flexibility has also been employed to recognize other aspects of planetary missions. For example, a 3-year proposal was requested from Cassini in the 2014 Senior Review in recognition that the mission's "Grand Finale" scenario would require slightly more than the nominal 2-year extension period, but the mission would then be terminated due to lack of fuel and the need to dispose of the spacecraft for reasons of planetary protection. Therefore, Cassini was not reviewed in the 2016 Senior Review.⁵ The Planetary Science Division also convenes out-of-sequence reviews as needed for missions that enter into extended operations off-cycle.

The Planetary Science Senior Review panels are sometimes split into separate subpanels by subject matter. In 2014, the Mars Exploration Program missions under review were considered by a separate group of reviewers from the other missions, and this separation was retained in 2016. The division indicated that separate review panels are used primarily because the Mars missions are parts of an integrated program, where the value of each mission is not independent of the other. The non-Mars Exploration Program missions are viewed as independent from one another.

STAKEHOLDERS

As part of its assessment process, the committee heard from various Senior Review stakeholders, including the NASA SMD associate administrator and the four division directors, panel chairs from the most recent Senior Reviews in each division, and principal investigators or science team leads for at least one large and one small mission currently in extended phase in each of the divisions. These presenters represent the immediate stakeholders of the Senior Review process—that is, the NASA Headquarters program executives, the review panels, and the mission teams. Each of the stakeholders has their own interests and perspectives on various aspects of the Senior Review process and on the overall value of Senior Reviews.

NASA Headquarters

The Senior Reviews are essential for NASA assessment of the scientific return and costs of missions in extended phases. In some cases, it is obvious that a mission has reached the end of its scientific productivity, but in most cases missions remain healthy with continued scientific return. In a cost-constrained environment, infor-

⁴ The Heliophysics Division Senior Reviews are available at NASA Science, "Heliophysics: Missions: Senior Review Reports," <http://science.nasa.gov/heliophysics/senior-review/>.

⁵ "Report for Planetary Mission Senior Review 2016," letter from J. Douglas McCuiston to James Green, Planetary Science Division Director, NASA Headquarters, June 17, 2016, <http://solarsystem.nasa.gov/missions/2016seniorreview>.

mation is needed on the absolute worthiness of the missions and the relative importance of their future scientific promise. Implementation and cost information from the mission teams also is important for planning future budgets.

Review Teams

The review panels represent the community in assessing the NASA portfolio of missions in extended phase. There are trade-offs between the cost and benefit of operating current missions and applying the funding to other areas of NASA science, and the SMD divisions utilize the reports from the Senior Review panels to refine initial allocations of funding among the extended missions as well as for deciding whether to allocate additional funding from elsewhere in the science portfolios. There is significant work involved for the panel members, who must carefully assess each mission and prepare the final report. Recent panel chairs indicated that they believed that a minimum period of 6 to 8 weeks between receipt of proposals and the panel meeting with the mission teams was required to effectively review and assess the proposals. They recommended that the panels have at least four weeks to read the proposals and to formulate questions for the mission teams. The committee considered the substantial workload on the community in formulating its assessments below. The panel members serve without compensation. The community and NASA Headquarters owe a huge debt of gratitude to the review panels for this essential work.

Mission Teams

For the mission teams, the preparation of Senior Review proposals and presentations requires a tremendous amount of work. Some of the work may be needed in any case for future planning, but substantial extra effort is needed to prepare formal proposals for the Senior Review. According to many of the mission team members who met with the committee, it typically requires up to 6 months of every 2-year period to prepare for and present at a Senior Review, which diverts mission teams from producing scientific results with their spacecraft during that period. Representatives from mission teams reported that there are commonly a large number of questions from the panel with very limited time for the mission teams to prepare responses. They suggested that the review panels should provide the questions to the proposers a minimum of 2 weeks before the panel meets with the teams. It is clear that this process presents a workload on the mission teams that could reasonably be called burdensome and therefore represents an important consideration for the committee.

In summary, the reviews are a huge amount of work for all stakeholders. NASA invests considerable resources on the reviews. A substantial amount of effort goes into choosing panels without conflicts of interest and in preparing the call for proposals. The mission teams spend a significant fraction of their time and effort preparing proposals, answering questions, and presenting to the Senior Review panels. The review panels devote a significant amount of time to reading and accurately reviewing the proposals.

Finding: Flexibility in scheduling the Senior Reviews—for example, the ability to change the timing of individual reviews to avoid mission-critical events—is valuable for NASA's science divisions.

Recommendation: NASA science divisions should be allowed to conduct reviews out of phase to allow for special circumstances and should have the added flexibility in organizing their reviews to take advantage of unique attributes of each division's approach to science.

Finding: At times, the Senior Review process becomes too compressed, and insufficient time is allocated for some of the stages that are essential for an effective Senior Review.

Recommendation: Each of the divisions should ensure that their timelines allocate sufficient time for each stage of the Senior Review process, including a minimum of 6 to 8 weeks from distribution of proposals to the panels until the panel meets with the mission teams. The panels should have at least 4 weeks to review the proposals and to formulate questions for the mission teams, and the mission teams should be allocated at least 2 weeks to generate their responses to the panel questions.

The committee recognizes that some of these recommendations have already been in practice for some divisions (such as the length of time allocated to a panel to review the proposals) and believes that they should be adopted in general for all Senior Reviews regardless of the division. These minimums are essential for obtaining the best quality recommendations from the review panels, and considering that NASA holds Senior Reviews on a regular cadence, the agency can plan for the reviews well in advance.

Finding: Regular reviews of operating missions are essential. However, the current 2-year cadence creates an excessive burden on NASA, mission teams, and the Senior Review panels. A 3-year cadence would ease this burden, while enabling timely assessment of the quality of the data returned from these missions and their potential for continued productivity. The committee judged that a 4- or 5-year cadence might be too long, given potential science developments and also changes in a mission's health or overall capabilities.

The committee recognizes that because the 2-year cadence is established in congressional budget authorization language, NASA alone cannot change to a 3-year cadence. The committee believes that NASA will have to work with Congress to seek a change in the requirement for Senior Reviews, but that the advantages of such a change are significant and can save money and effort while continuing to maximize scientific return from the space agency's extensive fleet of science missions.

Recommendation: NASA should conduct full Senior Reviews of science missions in extended operations on a 3-year cadence. This will require a change in authorizing language, and NASA should request such a change from Congress. The Earth Science Division conducts annual technical reviews. The other divisions should assess their current technical evaluation processes, which may already be sufficient, in order to ensure that the divisions are fully aware of the projected health of their spacecraft, while keeping these technical reviews moderate in scope and focused on changes since the preceding review.

As the recommendation indicates, an important component of this revised 3-year cadence is conducting regular assessments of the health of the spacecraft and instruments. This is necessary so that both the agency and proposers are aware of any potential issues that might result in shorter useful lifetimes and can plan accordingly. NASA's science divisions already have provisions for doing this. These assessments do not need to be extensive, and their primary focus can be assessing changes since the last review.

The committee heard from the division director of the Earth Science Division that continuity of scientific measurements is a priority, because climate and other studies benefit most from similar measurements over time. Mission budgets are normally only sufficient to cover the processing, validation, and distribution of the approved standard data products. Innovative uses of current missions and the development of new data products can be, and often are, proposed through the ROSES (Research Opportunities in Space and Earth Sciences) investigation solicitations.

Conversely, in the other divisions, many mission teams believe that they must emphasize "new science," over continuity measurements in their proposals, to be competitive. A careful reading of recent Senior Review proposal guidelines documents (Heliophysics 2015, Astrophysics 2014 and 2016, and Planetary Science 2014 and 2016) shows that new science is not required for a mission's extension, although the potential for (or enabling of) new science may be evaluated. However, due to the emphasis on demonstrating that the primary science goals must help achieve NASA's Science Plan or decadal survey objectives, in combination with the idea that the objectives of the prime phase of the mission have already been satisfied before proceeding into extended phase, it is easy to see how such a de facto requirement could be inferred by both the mission teams and the review panels evaluating the proposed activities. This de facto requirement is then underscored by the competitive environment of the Senior Review process. For example, in the case of the Planetary Science Division, language stating that a criterion of the evaluation is the "potential for groundbreaking science" has been widely interpreted by recent Senior Review panels and proposing mission teams as a requirement for new science and a diminution of continuity science.

Finding: In some divisions, there is greater prioritization of new or ground-breaking science, whereas in other divisions continuity of observations may be emphasized.

Recommendation: In order to obtain best value for money, NASA should encourage extended mission proposals to propose any combination of new, ground-breaking, and/or continuity science objectives.

INCORPORATION OF LESSONS LEARNED INTO SENIOR REVIEWS

Based on inputs from across the divisions, lessons learned include the following:

- *Maximizing the number and experience of returning panel members facilitated the work of the Senior Review panels.* The goal of ESD is to recruit panel members for a two-review commitment, with half of the panel returning from the prior review and half of them new. Other divisions have carry-over members, but the numbers are not specifically called out. Inclusion of some early-career panelists is also desirable in that it promotes opportunities for presentation of new perspectives as part of the review process.
- *The process for developing questions for the mission teams' oral presentations to the panel still needs improvement in some divisions.* Although having a few standard questions can facilitate discussion between the panel and the missions, there also need to be mission-specific questions to fill in possible blanks and to provide essential clarifications without overloading the mission team or the review panel.
- *The budget evaluation process has been improved over the years.* More detail is now requested in the proposal and more support from NASA's SMD/Resources Management Division Assessment and Evaluation Group in recent Senior Reviews greatly improved the use of the proposal budget information in decision making.
- In some instances, better coordination is needed with the PPBE (NASA's annual budget planning) decision process and the PPBE submittal schedule.

Recommendation: NASA SMD should assemble Senior Review panels that

- **Are comprised primarily of senior scientists knowledgeable about and experienced in mission operations so as to ensure that the operational context of the science being proposed and evaluated is considered in the review (individuals with operations and/or programmatic expertise may also be included as needed);**
- **Are assembled early to avoid or accommodate conflicts of interest and ensure availability of appropriate expertise;**
- **Include some continuity of membership from the preceding Senior Review to take advantage of corporate memory; and**
- **Include some early-career members to introduce new and important perspectives and enable them to gain experience for future Senior Reviews.**

Because continuity from one Senior Review to the next is valuable, introducing early-career members into the Senior Review process provides a way to ensure that future reviews will have a pool of scientists experienced in the process.

SUMMARY HISTORY OF MISSIONS REVIEWED BY THE SENIOR REVIEWS

The Senior Review process has been used by SMD to review a total of 73 science missions since 2005. Most missions have been reviewed several times in this interval, with proposals for a total of some 290 mission-years evaluated. Tables 3.1 through 3.4 present a history of these reviews for each division. The process has generally worked as it was conceived, and recommendations to terminate missions that were returning useful data have been infrequent. Exceptions for Astrophysics are GALEX and WISE in 2010 and Spitzer in 2014. Three missions were recommended for termination in Earth Sciences: ACRIMSAT in 2007 and 2009, ICESat in 2009, and EO-1 in

2009, 2013, and 2015.⁶ In Planetary Science, no missions were recommended for termination in the 2014 Senior Review. However, both the Lunar Reconnaissance Orbiter and *Opportunity* were eliminated from funding in the President's fiscal year (FY) 2015 and FY2016 budget proposals. Congress later added money to continue these missions. The results of the four divisions' Senior Reviews since 2005 are presented in Tables 3.1, 3.2, 3.3, and 3.4.

There also have been circumstances that have caused the NASA extended mission fleet to be operated in a manner that deviated from the recommendations of the Senior Reviews. Other than budgetary shortfalls, significant deviations have been necessary for a variety of reasons. An example is ACRIMSAT, which was extended after the failure of the Glory launch in 2011 to provide a backup for total solar irradiance measurements performed by SORCE. Similarly, an out-of-sequence Senior Review was convened to continue QuikSCAT when the performance of the RapidScat instrument on the International Space Station became unpredictable. These experiences underscore the value of allowing SMD to have flexibility in interpreting the Senior Review recommendations.

One thing that is apparent in Table 3.4 is that the Planetary Science Division has held a number of reviews in between the normal 2-year Senior Review cycle, such as Cassini in 2007 and 2009 and MESSENGER in 2011 and 2013. These off-year reviews were prompted by individual mission needs, indicating that a certain degree of flexibility on the cadence for Senior Reviews has been necessitated by mission operations.

EXTENSION OF EUROPEAN SPACE AGENCY SCIENCE MISSIONS

NASA is not the only agency that operates long-lasting science missions. ESA also operates a number of Earth science, heliophysics, astrophysics, and planetary science spacecraft. Like NASA, ESA has also developed a process for reviewing missions after their prime phase has been completed. ESA makes a commitment for the first 2 years of extended phase, but after that conducts Senior Reviews for the missions to extend them for 2 years at a time.

For ESA missions in which there is a NASA contribution (e.g., Rosetta), ESA approaches the international partners, such as NASA, and verifies the status of their commitment before the Senior Review. That information is then presented to the ESA Senior Review.

ESA conducts its Senior Reviews on a 2-year cadence, like NASA. According to an ESA representative who spoke to the committee, this is a compromise. This rolling process provides a sufficient continuity for managers to plan and provides checkpoints to ensure that there are sufficient reviews to change course if the mission is no longer compelling. The representative stated that some people have called for yearly reviews of ESA programs.

According to the ESA representative, there is no pressure for immediate balance across science disciplines when Senior Reviews are conducted. However, he stated that there is an understanding that the goal is a long-term balance. ESA ranks science first and foremost; the same is true for mission proposals (not just extensions).

According to the ESA representative, scientific proposals have a page limit (approximately 12 pages) that is significantly shorter than NASA's requirements (which have varied from 20 to 50 pages). According to the ESA representative, this short length is not an excessive burden for the scientific community, but he also stated that the mission operations people would prefer longer proposals so as to provide more details of their plans and capabilities. Proposers for extended missions are asked to make an oral presentation to the peer review committee. The committee discussed the issue of page length for proposals with NASA proposal teams and determined that the NASA requirement is more appropriate for NASA missions. Some teams noted that shorter page requirements do not necessarily save preparation time because teams spend more time and effort deliberating on what should be included and excluded, and excluding important data may limit a review panel's ability to understand the proposal.

⁶ EO-1 was recommended for termination in 2009. However, the Senior Review specifically allowed for further consideration of the mission in the 2011 Senior Review. Utilization of EO-1's instruments increased significantly after 2009 and by 2011 the spacecraft was increasingly used for disaster monitoring. The 2011 Senior Review recommended a continued mission, although it also called for improvements in data utilization. The 2013 Senior Review recommended an additional 2-year extension but did not recommend that the mission be allowed to propose to the 2015 Senior Review. The EO-1 team responded by indicating that there was still a demand for EO-1 data and they were allowed to propose to the 2015 Senior Review. The 2015 Senior Review recommended an additional year of operation but that EO-1 begin the termination phase by October 2016, which is the current plan.

TABLE 3.1 Astrophysics Division Senior Reviews by Year and Missions Reviewed

Mission	2006	2008	2010	2012	2014	2016
Chandra		●	●	●	●	●
Fermi				●	●	●
FUSE	●					
GALEX	●	●	●			
Gravity Probe B		●				
Hubble				●	●	●
INTEGRAL	●	●	●			
Kepler				●	●	●
Max WISE					●	
NuSTAR					●	●
Planck			●	●	●	
RXTE	●	●	●			
Spitzer		●	●	●	●	●
Suzaku	●	●	●	●	●	
Swift	●	●	●	●	●	●
WISE			●			
WMAP	●	●	●			
XMM-Newton	●	●	●	●	●	●

NOTE: Acronyms defined in Appendix F.

TABLE 3.2 Earth Science Division Senior Reviews by Year and Missions Reviewed

Mission	2005	2007	2009	2011	2013	2015
ACRIMSAT	●	●	●		●	
Aqua		●	●	●	●	●
Aquarius						●
Aura			●	●	●	●
CALIPSO		●	●	●	●	●
Cloudsat		●	●	●	●	●
ERBE	●					
EO-1		●	●	●	●	●
GPS Science	●					
GRACE	●	●	●	●	●	●
ICESat	●	●	●			
Jason-1	●	●	●	●	●	
OSTM				●	●	●
QuikSCAT	●	●	●	●	●	●
SAGE	●					
SORCE	●	●	●	●	●	●
Terra	●	●	●	●	●	●
TOMS	●					
TRMM	●	●	●	●	●	
UARS	●					

NOTE: Acronyms defined in Appendix F.

TABLE 3.3 Heliophysics Division Senior Reviews by Year and Missions Reviewed

	2005	2008	2010	2013	2015
ACE	●	●	●	●	●
AIM		●	●	●	●
CINDI			●	●	●
Cluster	●	●	●	●	
FAST	●	●			
Geotail	●	●			
Hinode			●	●	●
IBEX				●	●
IMAGE	●				
IRIS					●
Polar	●				
RHESSI	●	●	●	●	●
SDO					●
SOHO	●	●	●	●	
STEREO		●	●	●	●
THEMIS		●	●	●	●
TIMED	●	●	●	●	●
TRACE	●				
TWINS			●	●	●
Ulysses	●				
Van Allen Probes					●
Voyager	●	●	●	●	●
Wind	●	●	●	●	●

NOTE: Acronyms defined in Appendix F.

TABLE 3.4 Planetary Science Division Senior Reviews by Year and Missions Reviewed

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2016
Cassini		●		●			●		●	
Curiosity									●	●
Dawn										●
Deep Impact							●			
GRAIL							●			
LRO							●		●	
MAVEN										●
MER	●		●		●		●		●	●
Mars Global Surveyor	●									
Mars Express	●		●		●		●		●	●
MRO			●		●		●		●	●
MESSENGER						●		●		
Odyssey	●		●		●		●		●	●
Phoenix			●							
New Horizons										●
Stardust-NExT			●							

NOTE: Acronyms defined in Appendix F.

During the last ESA Senior Review process, 10 missions were put up for extended missions. Eight of these were approved for extension. The two that were not extended were reaching the end of their technical lifetimes and could not be extended.

CONCLUSION

The committee did not identify major problems with NASA's overall approach to Senior Reviews, although it did conclude that the agency needs to provide more time for its review teams in order to ensure that they can devote appropriate time to conduct quality reviews. The committee also concluded that NASA's divisions also communicate with each other about review processes best practices and believes that this is a valuable practice.

As the divisions have performed more Senior Reviews, the details of the process have become more stable from cycle to cycle. Stability includes consistency of information requested, proposal format, timing for the various stages of the review, and so on. Maintaining best practices through regular interactions and feedback between NASA Headquarters, the mission teams, and review panels will help to ensure that this consistency is maintained while also providing opportunities for incremental improvements in the process.

Finding: As the divisions have performed more Senior Reviews, the details of the process have become more stable from cycle to cycle. Stability includes consistency of information requested, proposal format, timing for the various stages of the review, and so on.

Recommendation: NASA's Science Mission Directorate division directors should continue to communicate among themselves to identify and incorporate best practices across the divisions into the Senior Review proposal requirements and review processes and procedures.

Recommendation: In its guidelines to the proposal teams and the Senior Review panels, NASA should state its intention to solicit feedback from its proposal teams and review panels about the suitability of the proposal content and review process. After obtaining such feedback, NASA should respond and iterate as needed with stakeholders to improve the review process, where possible.

REFERENCE

NRC (National Research Council). 2005. *Extending the Effective Lifetimes of Earth Observing Research Missions*. The National Academies Press, Washington, D.C.

4

The Balance of New Missions Versus Extended Missions

The committee's task includes addressing the proper balance between new and extended missions. NASA's Science Mission Directorate (SMD) is currently operating approximately 60 science missions, of which approximately three-fourths are in their extended mission phase and one-fourth in their prime phase. This complementary arrangement has proved effective in enabling all four mission divisions to achieve scientific goals that could not have been reached with either primary or extended missions alone.

An example of a scientific goal that could only have been reached with both prime and extended missions concerns the magnetized plasmas that fill near-Earth space and produce long-range interactions that can be understood only by taking measurements at widely distributed observing points and continuing to monitor them over decades. By extending missions beyond their prime lifetime and adding additional spacecraft every few years, NASA's Heliophysics Division has created what is referred to as the Heliophysics System Observatory (HSO), a network of spacecraft that monitors the entire heliosphere with a special emphasis on a volume of space with a radius 200 times that of Earth's orbit. In 2016, the HSO, which includes the STEREO (Solar Terrestrial Relations Observatory) spacecraft in the same orbit as Earth and the two Voyager spacecraft more than 100 astronomical units from the Sun, comprised 18 missions (28 spacecraft). Only one mission, the four-spacecraft Magnetospheric Multiscale mission, is in prime phase (see Figure 4.1). Thus, extended missions are an essential component of the ensemble of HSO spacecraft that is monitoring the interconnected system of the solar wind and Earth as well as the outer boundary of the heliosphere. The importance of the HSO is acknowledged in the first research recommendation of the 2013 heliophysics decadal survey (NRC, 2013), which calls for continued support of the complement of spacecraft it comprises.

Other divisions have equally compelling reasons to extend the operation of missions beyond their prime phases. For example, the Cassini mission of the Planetary Science Division has gathered extensive data on Saturn's small moon, Enceladus, during its extended phases. Only during the extended operations were the properties of the vapor plumes of this small moon established, and in addition, it was shown that Enceladus likely harbors a global-scale ocean beneath its icy surface. Data collected during the mission's extensions also revealed that the puzzling periodicities of electromagnetic phenomena at Saturn vary in frequency with season. By operating missions into their extended phases, missions in the Earth Sciences Division have monitored the retreat of the Antarctic ice shelf and established the temporal variation of atmospheric gases and other key elements of the coupled atmosphere-ocean system. Astrophysics has also benefitted from missions in their extended phase, including new discoveries made by the Kepler, Spitzer, and Chandra observatories.

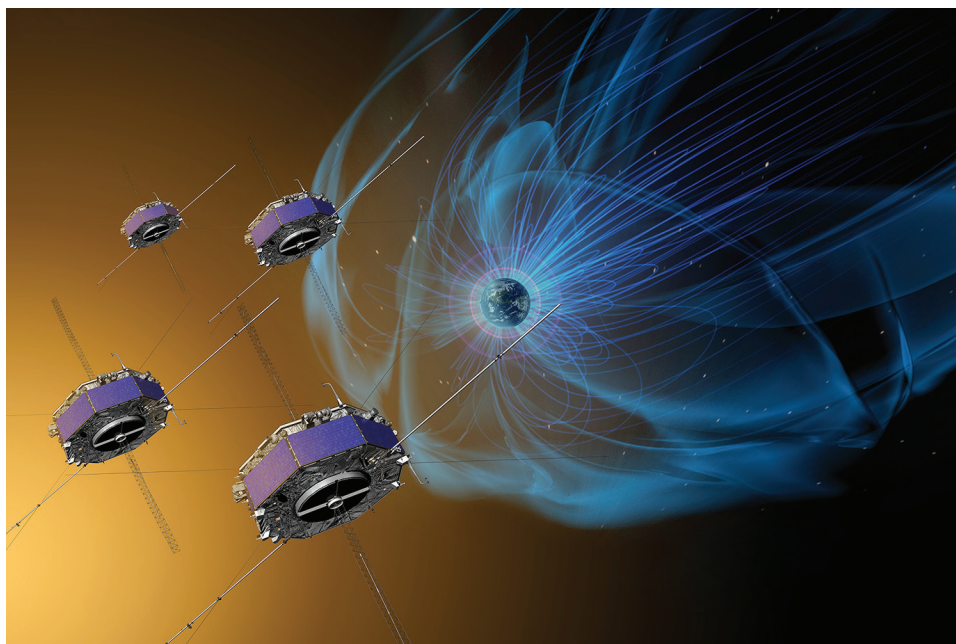


FIGURE 4.1 The Magnetospheric Multiscale (MMS) Mission is the only heliophysics mission currently in prime phase, emphasizing just how much the Heliophysics Science Division relies upon extended missions for most of its data. SOURCE: NASA, “NASA’s MMS Celebrates a Year in Space,” release date March 14, 2016, <http://www.nasa.gov/feature/goddard/2016/nasas-mms-celebrates-a-year-in-space/>.

Extended missions require resources, which naturally raises the question of how much SMD resources should be allocated for this purpose and whether typical expenditures are the proper amount. The most recent budget figures indicate that SMD is spending approximately 12 percent of its budget on extended missions. NASA officials stated to the committee that, although the fraction of funding going to operating missions in extended phase has fluctuated over time, it has, on average, remained close to the present 12 percent. As demonstrated in Chapter 2 of this report, major scientific discoveries have been made by NASA missions in extended phase. This record of scientific productivity leads the committee to conclude that continuing most NASA missions into extended phase is justified.

Missions in prime or extended phase also utilize communications support including the DSN (Deep Space Network) and NEN (Near Earth Network), which may be stressed by the number of spacecraft requiring their services. As such, the total number of missions and their locations in the sky impact the support infrastructure (although the impact cannot be quantified without a detailed evaluation of mission-specific needs).

Typically for space science missions in different divisions, maintaining balance among small, medium, and large missions, and including a diversity of targets, have been identified as important goals. “Lack of balance” has been generally understood by the scientific community to mean too much emphasis on either a single bandwidth or target (e.g., measurements in a specific range of frequencies or measurements at a particular planet) or support of one costly space mission at the expense of all others. The committee is unaware of any published evaluation of what constitutes the “proper” balance between new and extended phase missions, other than the 2005 National Research Council report *Extending the Effective Lifetimes of Earth Observing Research Missions* (NRC, 2005). The various decadal surveys consistently have stressed the importance of missions in extended phase, but they have not specifically addressed the balance between extended phase missions and new ones, or even sought to define a desirable balance (see Appendix D).

Extended missions provide a suitable training ground for students and early-career scientists. For graduate students, the predictability of data sources and operations, particularly with respect to the timeline for completing

thesis research, is invaluable and far preferable to delaying graduation or completing a changed project if a prime mission's launch is delayed or, in a worst case, lost. For other early- or mid-career scientists, the experiences gained in an environment conducive to learning on the job provide valuable payback to the enterprise in the form of much more experienced personnel to perform in the pressure cooker of mission formulation and development. Thus, a robust portfolio of extended missions helps to provide the workforce for future new missions.

The committee considered the issue of appropriate balance between prime and extended phase missions, initially seeking to identify how much NASA currently spends on prime and extended missions in each division. A key question the committee considered was the approximate buying power of the funds that support mission extensions—in other words, if a division canceled all of its extended missions and spent all of that money on new missions, how many new missions could it buy? More specifically, the data show that if the Astrophysics Division canceled and turned off all of its missions currently in extended phase—Hubble, Chandra, Spitzer, NuSTAR, and so on—it could purchase less than one MIDEX (Medium-Class Explorer) mission per year, or approximately one additional flagship mission every decade. Of course, this would come at tremendous cost in scientific productivity—ending data return from eight operating missions in return for adding perhaps two new medium-sized missions every 3 years.

The calculation for the Earth Science Division indicated greater adverse impact: ending all Earth science missions in extended phase—such as Aura, Terra, Aqua—could release funding for approximately one new Earth Systems Science Pathfinder mission every 2-plus years, or one new flagship class mission every 12 years. For the Heliophysics Division, the effects were also disproportionate: ending all current extended missions could provide funds for approximately one new MIDEX mission every 4 to 5 years, or two new Small Explorers (SMEX) every 3 years, or a new flagship class mission every 19 years. The scientific loss to heliophysics, however, would be tremendous. The Heliophysics System Observatory, which relies upon multiple observations at multiple locations, would simply collapse.

The results for the Planetary Sciences Division are similar: canceling all operating extended phase missions—*Curiosity*, *Opportunity*, Lunar Reconnaissance Orbiter, Mars Reconnaissance Orbiter, MAVEN, Cassini, and even New Horizons, which will finish its prime phase soon—would result in approximately one new Discovery mission every 2-plus years, or one new flagship class mission every decade (see Table 4.1).

TABLE 4.1 Approximate Buying Power Resulting from Cancelling All Extended Phase Science Missions per Division

Division	Total Budget for Fiscal Year 2016 (\$millions) ^a	Approximate Savings (\$millions) If All Extended Missions Are Eliminated	Equivalent Number of New Small Science Missions per Year ^b	Equivalent Number of New Large Science Missions per Year ^c
Astrophysics	768 (+JWST: 620)	214	~ 0.6 MIDEX	~ 1/10 flagship mission
Earth Science	1,921	180	~ 0.4 ESS Pathfinder ^d	~1/12 flagship mission
Heliophysics	640	78	~ 0.2 MIDEX ~ 0.4 SMEX	~1/19 flagship mission ^e
Planetary Science	1,628	216	~ 0.4 Discovery missions	~ 1/10 flagship mission

NOTE: The table does not account for the normal spending profile for a mission that is not evenly distributed over each year.

^a NASA, "NRC Extended Missions Follow up questions, SMD Responses," submitted to the committee, April 5, 2016.

^b The committee assumed launch costs of approximately \$150 million. A MIDEX mission costs from approximately \$330-\$350 million total, including launch costs, and a Discovery mission costs approximately \$575 million total, including launch costs. (<http://explorers.gsfc.nasa.gov/missions.html> and http://discovery.nasa.gov/p_mission.cfm, accessed May 5, 2016).

^c This assumes that a typical flagship mission costs \$2 billion and launch costs are approximately \$250 million, for \$2.250 billion total.

^d For Earth Science, the committee took the cost of the most recent Earth Systems Science Pathfinder mission, the Orbiting Carbon Observatory 2, which cost approximately \$470 million, including launch (http://www.jpl.nasa.gov/news/press_kits/oco2-launch-press-kit.pdf, accessed May 26, 2016).

^e For heliophysics, the committee took the current \$1.5 billion estimated cost (including launch) for the Solar Probe Plus mission.

Of course, it would be possible to cancel some but not *all* extended-phase science missions in a division. Criticism of continuing to fund extended science missions (see Chapter 1) is usually formulated as a proposal to spend an undefined “less” on extended missions and to devote the money saved to new mission development. But what Table 4.1 demonstrates is that even drastic cuts to the extended missions budgets would result in very few new science missions. Another way to look at this trade-off is that, because each of the divisions spends approximately 50 percent of its budget on new development and approximately 12 percent on extended missions, ending all extended missions in a division would increase the respective development budget by approximately 25 percent. Thus, even the drastic action of ending all extended missions has a relatively limited effect on both development spending and the number of new missions.

The cost to science of ending all extended science missions, however, would be catastrophic. In some cases, it could create gaps during which no new data are being returned from any mission for a division. Such breaks could destroy some scientific disciplines, particularly Earth science and heliophysics, which require understanding their subjects via multiple observations made by multiple spacecraft over many years. For planetary science, ending extended missions at Mars would not just impact science but could mean shutting off spacecraft that provide data relay for other spacecraft, thus eliminating infrastructure needed to support both prime and extended missions (see Figure 4.2). Astrophysics benefits by using multiple observatories—many in their extended phase—to take data at different wavelengths simultaneously to understand how many astrophysical systems work. Ending missions that have many productive years left would also be tremendously wasteful—the equivalent of throwing away a functioning appliance at the end of its warranty. Finally, eliminating all extended missions would contradict the recommendations in the divisions’ decadal surveys.

Of course, ending many or all extended missions is an extreme example, but it demonstrates the limitations of what can be accomplished even by making major changes to the current balance of spending on extended missions. Although the committee could not establish a clear definition of balance, it was able to conclude that substantial changes in the current balance between new and extended missions would be highly deleterious in terms of scientific return.

Finding: NASA’s extended science missions constitute approximately three-fourths of the missions in flight, but cost a relatively small percentage of the overall SMD budget, on average 12 percent over the last 5 years.

Finding: Eliminating all of the extended missions would

- Increase the funds available for new development only by approximately 25 percent;
- Make it difficult or impossible to achieve many objectives of decadal survey science; and
- Adversely and significantly impact SMD’s overall science return.

Finding: The current balance between prime and extended missions is reasonable.

Recommendation: NASA should continue to provide resources required to promote a balanced portfolio, including a vibrant program of extended missions.

CONCLUSION

Although the committee did not develop a formal definition or recipe for the ideal balance between prime and extended missions, it found the present mix to be excellent and identified no basis for substantially altering the current balance based upon either scientific or monetary considerations.

REFERENCES

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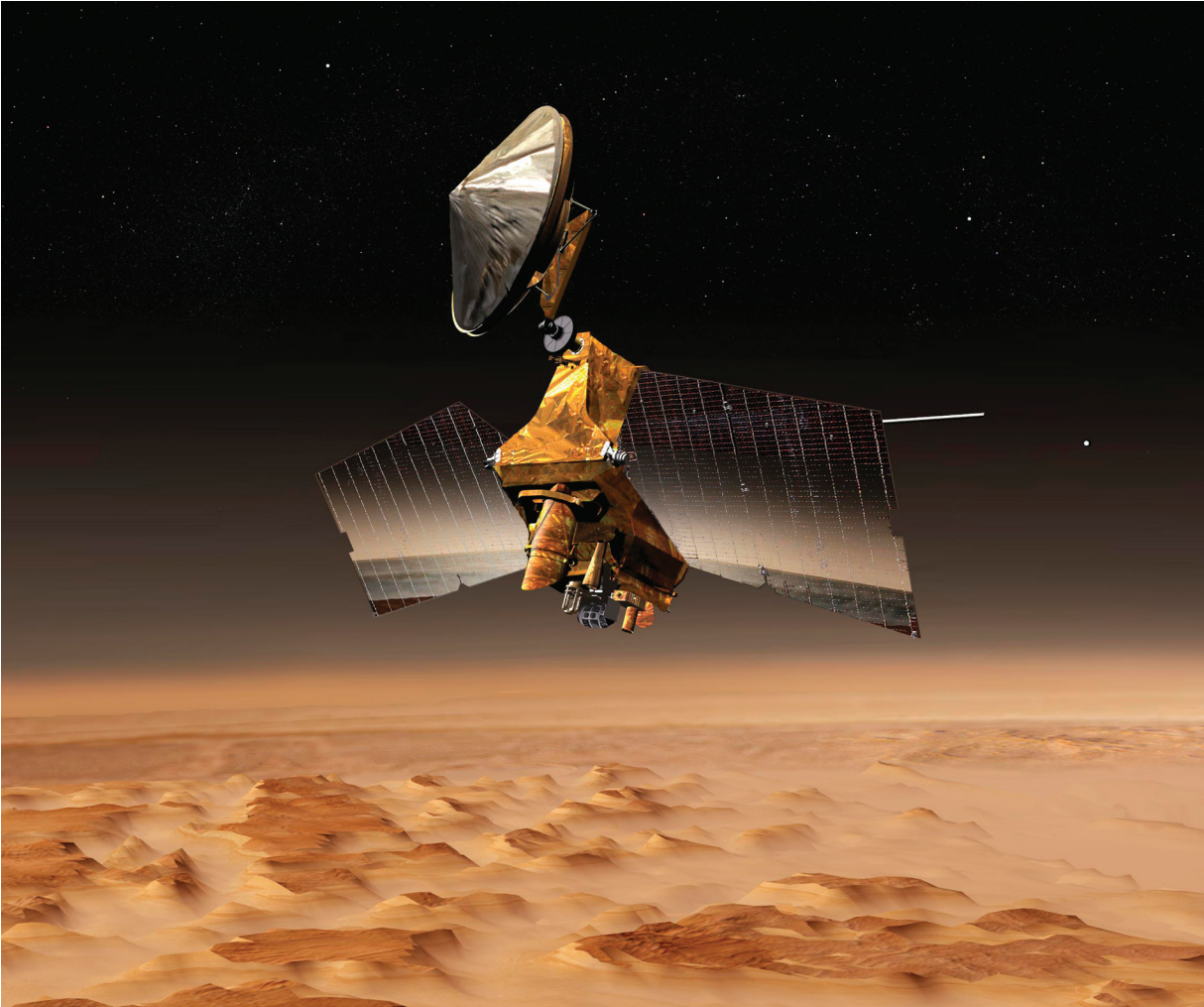


FIGURE 4.2 The Mars Reconnaissance Orbiter not only performs extended mission science at Mars but also serves as a relay spacecraft for the *Opportunity* and *Curiosity* rover missions. Ending operating Mars orbiters would eliminate vital infrastructure supporting other missions in both prime and extended phase. SOURCE: NASA, Image PIA04916, December 10, 2003; courtesy of NASA/JPL-Caltech.

5

Innovative Cost Reductions for Extended Missions

The committee's charge included identifying possible innovative ways to reduce costs for extended missions. During the course of this study, the committee heard several presentations addressing cost reduction approaches for extended missions and discussed specific case studies in the search for overarching principles that might be applied to other missions. The committee evaluated approaches to cost savings within the context of increased risk and potential impacts on science return.

COLOCATING OPERATIONS

One method for increasing efficiency for space science missions is collocating multiple mission operations at a given location, which is an approach that NASA already takes for many of its missions. For example, NASA's Goddard Space Flight Center (GSFC), the California Institute of Technology's (Caltech's) Jet Propulsion Laboratory (JPL), and the Johns Hopkins Applied Physics Laboratory (APL) each operate multiple missions using their on-site operations centers. In some cases, these missions are concentrated by type—for example, Earth science missions at GSFC and planetary missions at JPL. However, GSFC also operates the Lunar Reconnaissance Orbiter as well as a number of astrophysics missions, JPL operates some Earth science and astrophysics missions, and APL operates Earth science, heliophysics, and planetary missions. The committee notes that there is no inherent reason that all similar missions have to be handled by the same operations center.

Although collocating multiple missions operations at a single location is likely to produce added efficiencies due to some level of commonality in spacecraft operations, the Science Mission Directorate's (SMD's) current portfolio includes competed science missions and principal investigator (PI) teams that provide NASA with different opportunities to draw on scientific expertise that is spread throughout the United States. Added operations efficiencies and scientific synergies may result from collocating science operations and mission operations close to, or at, the host institution for the science team, as exemplified by the Chandra X-ray Center located in Cambridge, Massachusetts, and the Infrared Processing and Analysis Center at Caltech.

Finding: Collocating mission operations centers may provide added efficiency (and cost savings) in some cases. The location and responsibilities of the science team and the potential advantages of collocating the science and mission operations teams are also important factors, so flexibility and trade studies are required when deciding how to organize and where to site science and operations centers.

INNOVATIVE APPROACHES

The committee also was briefed on the innovative approaches adopted to continue operations during the extended phase of several missions, including the Galaxy Evolution Explorer (GALEX), the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX), and the Mars Exploration Rover *Opportunity*. The level of NASA support varied for the later stages of these missions, as discussed below, and this factor should be kept in mind when assessing the effectiveness of the approaches.

The GALEX mission provided important ultraviolet astronomy observational capabilities (see Figure 5.1). It transitioned from prime to extended phase in 2007 and was highly recommended in the 2004, 2006, and 2008 Astrophysics Senior Reviews. However, the 2010 Senior Review recommended only 2 more years of operations, followed by close-out. That review also opposed a suggested move of the operations to Caltech, saying that the move would introduce unnecessary risk and would provide no cost savings, given the limited remaining time they were recommending for operating the mission. Subsequently, NASA decided to terminate the mission after just 1 year. The mission PI and the science team negotiated with NASA to transfer operations and ownership of the satellite to Caltech, but several issues arose, including the question of liability associated with possible collisions on-orbit and eventual Earth re-entry. Ultimately, this issue was surmounted by a NASA decision to “loan” the telescope to Caltech, with NASA retaining ownership. However, no NASA funding was provided, so the GALEX team and Caltech endeavored to raise just over \$1 million for a bare-bones operation of the satellite for approximately 1 year. Several universities and telescope consortia purchased observing time, JPL funded efforts to complete the galactic plane portion of an all-sky survey, and the PI team raised modest amounts of additional private funding.



FIGURE 5.1 The Galaxy Evolution Explorer (GALEX) spacecraft during construction. SOURCE: GALEX Technical Documentation, “Chapter 1. Instrument Overview,” accessed June 27, 2016, <http://www.galex.caltech.edu/researcher/techdoc-ch1.html>; courtesy of JPL/Caltech and the GALEX science team.

Employment of student operators on a part-time basis also reduced costs somewhat. Although these efforts successfully extended the mission, there was no immediate funding or time for science research. According to the PI, the team was exhausted after 1 year, and the satellite was “returned” to NASA and decommissioned. The PI informed the committee that he would not recommend this option to future missions. An unanswered question is the extent to which this approach might have been less taxing on the team, with the possibility of operating in this mode for longer than 1 year, had NASA at least provided partial funding support.

Continuing GALEX operations after the end of NASA funding involved a rather rushed effort with some complicated issues. It is possible that, with more advance notice and careful planning, taking advantage of lessons learned, this kind of effort could be less stressful and more successful in some future situations.

There could be an important ancillary benefit to efforts to transition older missions to a NASA-university/consortia partnership: increasingly, the development of space hardware and missions is concentrated at NASA centers. Encouraging universities to become involved in extended-phase missions may be one way of rekindling a broader involvement in space hardware and space science. However, this may only be applicable to smaller missions with more focused scientific objectives. Observatories as large and complex as the Hubble Space Telescope and the Chandra X-Ray Observatory cannot easily be transitioned in this way; given the breadth of science that they continue to enable even in their extended phase, it is important that operations do not change drastically.

SAMPEX was NASA's first Small Explorer mission. Launched in 1992, SAMPEX was designed as a 1-year mission, with a goal of 3 years, to study space weather through measurements of particles and cosmic rays in near-Earth space as a function of solar activity. The mission was extended to cover a full solar cycle, and NASA support ended in 2004. However, data continued to be acquired for another 8 years, with the Aerospace Corporation funding the downloading and Bowie State University operating the spacecraft (starting in 1997) as an educational tool for its students. A GSFC scientist obtained a NASA grant to process the 2004–2012 data and to provide access to the data for the science community. SAMPEX continued to provide valuable science data until it re-entered Earth's atmosphere in late 2012, just over 20 years after it was launched. Without question, SAMPEX exceeded expectations, thanks in large part to the confluence of factors listed above that enabled the last 8 years of the mission. However, it does not seem realistic to plan future extended missions based on highly uncertain support relying on corporate funding commitments, university interest for educational purposes, or grants that must be competitively secured.

The Mars Exploration Rover has operated on the surface of Mars for more than 12 years (see Figure 5.2). Given that *Opportunity's* prime phase was 90 martian days, the duration of the extended phase has exceeded the prime by almost 50-fold. The project has been under continuous pressure during this time to reduce the cost of extended operations without adding risk of loss of mission. The project responded to this new reality by adopting a number of innovative cost-saving measures, most of which were not foreseen at the start of operations, partly due to the very short anticipated prime mission duration. These innovations drew heavily from the actual experience of having operated the spacecraft through the prime mission period. Notable among these cost-saving measures were the use of cloud computing in lieu of purchasing and maintaining hardware systems, the use of information technology automation to handle many routine operational tasks, the cross-training of team members to allow individuals to cover more than one job as extended mission work lessened, and the elimination of deputy positions as team members gained job skills experience and became cross-trained. Overall, this approach was very successful, with increases in efficiency and associated cost reductions implemented “on the fly,” according to one of the mission's managers.

Unlike the two cases discussed above, NASA did provide continuous, albeit reduced, funding for *Opportunity's* extended mission. As noted in Chapter 2, the President's FY 2015 and FY2016 budget request zeroed out the funding for *Opportunity* as well as the Lunar Reconnaissance Orbiter, even though both were highly rated in the Planetary Science Division's 2014 Senior Review. (See Appendix B for sampling of scientific contributions during the extended phases of both missions.) Congress subsequently decided to continue the funding for both *Opportunity* and LRO.

Subject to recommendations from the Senior Review process, NASA SMD generally expects to extend the mission operations beyond the original prime mission period, provided the spacecraft is returning valuable science data and the cost for extending the operations fits within the program budget. Given that extended operations are

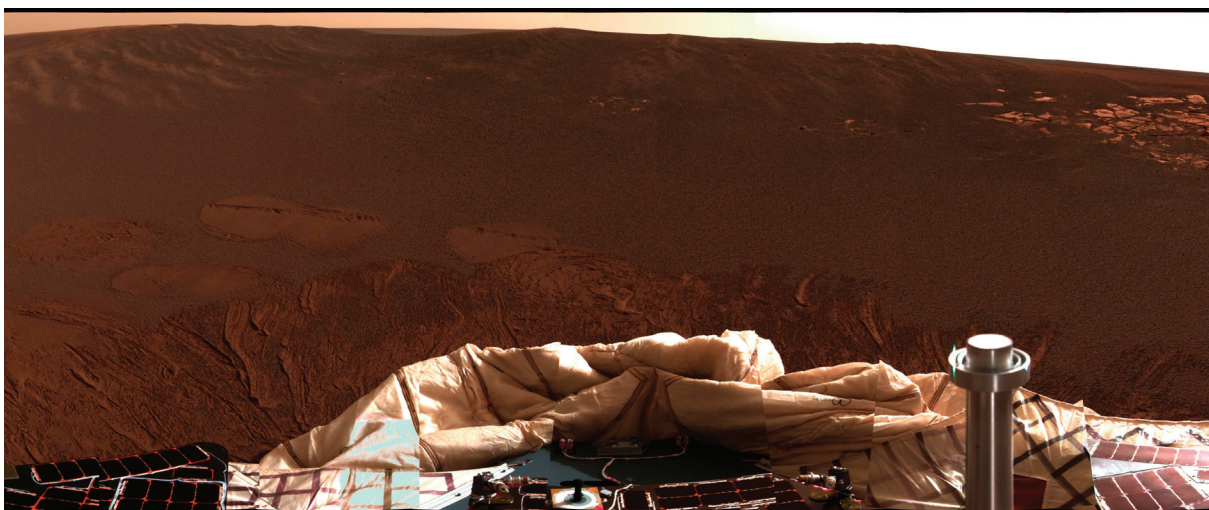


FIGURE 5.2 First color image taken by the *Opportunity* rover soon after touchdown in 2004. The rover was expected to last only 90 days but has operated for more than 12 years. SOURCE: NASA Jet Propulsion Laboratory, “Panoramas: Opportunity,” release date January 26, 2004, <http://mars.nasa.gov/mer/gallery/panoramas/opportunity/2004.html>; courtesy of NASA/JPL/Cornell.

a likely eventuality, planning of the ground system and operations approaches from the early phases of the program can include an awareness (without driving costs) of the potential for a mission extension that is likely to be implemented with reduced budgets, reduced and changing staff, aging hardware, and, possibly, new objectives. Such early steps may provide benefits for later reducing the cost of extended mission operations and limiting the increase in risk.

The committee was briefed on a number of different approaches but did not identify any new over-arching cost-saving principles to apply across the board—every mission has unique circumstances. Using the information presented, the committee was able to extract a number of best practices including the following:

- Allow for the possibility of extended operations without driving costs as projects plan and develop their ground operations and flight procedures for the prime mission.
- Consider the implications of possibly transitioning from prime mission operations into extended missions when recruiting and assigning the operations team for the prime mission.
- Plan for and then cross-train mission and science operations staff to more effectively enable reductions in workforce and staff at reduced risk as a mission transitions to extended phase.
- Perform appropriate trade studies for purchase versus “rental” of computer hardware and data storage (e.g., use of cloud capabilities) for operations and data processing, while addressing factors such as information technology security and upgrade requirements.

Finding: Many extended missions have adopted innovative planning and operations approaches that translate to good practices (e.g., early awareness of potential for extended mission while developing ground system and flight procedures; generating staffing plans and preparing for reduced budgets during the extended phase) that may be applicable to other missions. Each mission has unique features, so no single approach will be optimal for all.

Recommendation: NASA should provide open communications and dissemination of information based on actual experience with extended missions so that all missions are aware of and able to draw on prior

effective practices and procedures, applying them during development of ground systems and flight procedures, as well as when formulating staffing and budgetary plans for the prime and extended-mission phases.

The committee determined that communication about Senior Review processes among SMD divisions is relatively good and encourages the divisions to continue this communication about other aspects of extended-mission operations. There are many possible ways that NASA could ensure open communications and dissemination of information, including websites, conferences, and even contractual communications. As the committee has noted, the best time to begin preparations for extended missions is when a mission is still in its formulation phase, a time when decisions can have significant impacts many years after the prime mission has ended.

REPURPOSING EXTENDED MISSIONS TO CREATE NEW SCIENCE MISSIONS

Upon completion of a prime mission and during the transition to an extended phase, opportunities may arise to consider a major redirection of the project. One example is the Deep Impact mission that was launched in 2005 to study the interior of comet Tempel 1. On July 4, 2005, the spacecraft's impactor collided with the comet, producing effects that were observed by the main spacecraft. Shortly afterwards, Deep Impact's prime mission ended, even though the spacecraft was still healthy. NASA then sought proposals for an extended mission and eventually selected and merged two proposals that included both original and new members of the Deep Impact team. The extended mission was named EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation).

The EPOXI mission recycled the Deep Impact spacecraft to visit a second comet, Hartley 2. The November 4, 2010, flyby of Hartley 2 marked only the fifth time a comet had been visited by a spacecraft. The EPOXI mission flyby revealed that the rocky ends of comet Hartley 2 spew out tons of golf-ball to basketball-size fluffy ice particles, whereas the smooth middle area is more like what was observed on comet Tempel 1, with water evaporating below the surface and percolating out through the dust. Repurposing the Deep Impact spacecraft enabled NASA to take advantage of new ideas and a wider array of expertise that would have otherwise required NASA to initiate and fund the development of a whole new mission.

Another example is the WISE (Wide-field Infrared Survey Explorer) mission, launched in December 2009. WISE surveyed the full sky in four infrared wavelength bands until the hydrogen cooling the telescope was depleted in September 2010. The survey continued as NEOWISE (Near-Earth Object WISE) for an additional 4 months using the two shortest wavelength detectors to detect previously known and new minor planets and to study asteroids throughout the solar system. NEOWISE enabled the discovery of the first known Earth Trojan asteroid. The spacecraft was placed into hibernation in February 2011, after completing its search of the inner solar system.

In response to increasing scientific interest and growing geopolitical concern about the possibility of near-Earth objects (NEOs) impacting Earth and the consequential impacts to human life and damage to the environment and economy, NASA's Planetary Science Division reactivated the mission (as a directed mission of national priority and no longer subject to the Senior Review process) in December 2013, with the primary goal of learning more about the population of NEOs and comets that could pose an impact hazard to Earth. During its first 3 years of operations, NEOWISE characterized many NEOs and obtained accurate measurements of their diameters and albedos (how much light an object reflects). NEOWISE is equally sensitive to both light-colored asteroids and the optically dark objects that are difficult for ground-based observers to discover and characterize.

As of mid-April 2016, NEOWISE was approximately 73 percent of the way through its fifth coverage of the entire sky. The repurposing of this mission after its prime phase has provided a very cost-effective means of addressing questions of great scientific interest and in this case of great importance to our planet's, and our own, well-being.

A third example is provided by the Heliophysics THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission. In this instance, a multi-spacecraft mission was partially repurposed to obtain new science. Originally composed of five spacecraft to study magnetospheric substorms, the THEMIS mission proposed that two spacecraft be diverted to lunar orbit. The new mission, called ARTEMIS, has provided important observations of the lunar wake (Wiehle et al., 2011), while the remaining three spacecraft constitute a revised

THEMIS extended mission that continues to provide crucial observations of energy conversion processes in Earth's magnetotail (Angelopoulos et al., 2013).

Finding: Repurposing of extended missions, such as Deep Impact to EPOXI, WISE to NEOWISE, and THEMIS to ARTEMIS and THEMIS, is an extremely cost-effective approach for addressing new science opportunities and national interests.

Recommendation: NASA should continue to encourage and support extended missions that target new approaches for science and/or for national needs, as well as extended missions that expand their original science objectives and build on discoveries from the prime phase mission.

RISK ASSESSMENT AND ACCEPTANCE

NASA mission and science operations budgets typically decrease significantly when a mission enters extended phase, which is normally expected and usually justifiable. After that, costs may reduce further as a consequence of additional performance improvements over time and learning-curve effects. However, after several years of extended operations, most missions have implemented all steps that safely can be taken to reduce cost. Further funding cuts increase risk, including a real loss of unique science or possible degradation or loss of a spacecraft. Based on the mission team presentations to the committee, there is a perception among proposal teams that NASA at times may not fully recognize the changed risk posture when reducing funding for mission extensions, instead assuming that funds for extended missions can be continually cut without ramifications. To be fair, NASA is at times under intense budget pressures, and agency officials may believe they have no choice other than to apply such cuts. Moreover, given the national interest needs met by Earth science missions, there is much less risk acceptance for extended missions by the Earth Science Division than the other divisions. Increased risk can take various forms. One example is that missions in extended phase may go for longer periods between communications sessions with ground control. This could mean that a problem on the spacecraft could go undetected and pose a threat to loss of an instrument or the spacecraft. Decisions by NASA and mission proposers to accept such risks have long been made for extended missions, but not everyone involved may be aware of the risks.

Finding: Some divisions permit missions entering into or already in extended phase to accept increased risk, which is an inevitable consequence for aging spacecraft and science instruments and, at least for some divisions, an acceptable option in the context of reduced budgets.

Recommendation: NASA should continue to assess and accept increased risk for extended missions on a case-by-case basis. The headquarters division, center management, and the extended-mission project should discuss risk posture during technical reviews and as part of the extended mission and subsequent Senior Review proposal preparation process, and all parties should be made fully aware of all cost, risk, and science trade-offs.

THE NEED FOR SUPPORT IN RESPONSE TO SPACECRAFT ANOMALIES

In some instances, mission operations costs may also rise over time due to changes in mission profile; the need to respond to anomalies that are commonly but not always age-related, such as deteriorating performance of flight systems; as well as inflation. For example, the complete loss of one radio receiver on Voyager 1 and the loss of frequency tracking capability on the remaining redundant unit required intense and costly operational workarounds, as did the failure of the high-gain antenna on Galileo during its prime mission phase. Historically, barring such extenuating operational cost drivers, extended missions often experience additional cuts to their budgets at subsequent Senior Reviews, which along with inflation, often result in disproportionate cuts to project-funded science activities. This is because mission management normally prefers to limit increased risk and, therefore, attempts to minimize cuts to the operations budgets. In turn, mission science teams then seek support from research and

analysis programs. However, those programs are also under increasing funding pressure, which means that all-too-frequently science is diminished or sometimes not performed at all.

Finding: Experience and knowledge gained during the prime phase frequently result in lower costs for extended mission operations, but occasionally there may be counteracting effects that can create upward pressure on operational costs.

Finding: After the first few years of extended operations, most missions have implemented all (or almost all) practical steps to reduce costs. Further budget cuts often then result in disproportionate cuts to project-funded science activities, increasing risks that science will be diminished or not performed at all.

Recommendation: Given the demonstrated science return from extended missions, NASA should continue to recognize their scientific importance and, subject to assessments and recommendations from the Senior Reviews, ensure that, after the first two Senior Reviews, both operations and science for high-performing missions are funded at roughly constant levels, including adjustments for inflation.

CONTROL OF COSTS AND RISKS RELATED TO THE INTRODUCTION OF NEW PROCEDURES

In concert with the assessment of past experiences and evaluation of innovative ideas for reducing costs and increasing the science cost-effectiveness of extended missions, the committee discussed the question of increased risk associated with such approaches. It usually costs money upfront to develop new procedures that could eventually reduce costs, but the upfront funding usually is not available during the extended phase of a mission, unless it is diverted from science or essential operations activity. Keeping procedures as simple as possible in the prime mission, which projects should do to the extent possible, may be the best way to control costs and limit risks in extended missions. Increased risk from any new procedure is unavoidable but may be acceptable in some cases. For example, if the alternative is to terminate a mission, then substantially increased risk may be acceptable. Also, risk to the science data is less critical than risk of catastrophic failure of the mission. As is commonly done by project management, all such risks are best identified, described, and carefully evaluated in order to avoid making decisions that could keep a spacecraft operating but drain it of scientific productivity.

Finding: Investment in the development of standard procedures and templates, with complexity as limited as possible, for use during the prime phase may be the best way to control operations costs and limit the risks from introducing new procedures specifically developed for extended operations.

DETERMINING THE LIFETIME COST OF SCIENCE MISSIONS

NASA's present approach is to develop prime mission hardware specifications (e.g., lifetime) such that there will be a high level of confidence in the mission's ability to meet prime mission requirements. This approach is both understandable and appropriate and has served the agency well. Furthermore, it implies that there is a distinct probability that most missions will survive in good enough shape to propose an extension. Even so, NASA defers formal requests for extended mission operations funding until the approach of the prime mission completion along with achievement of the stated science objectives. This practice probably traces back to the early days of spacecraft development when there was lower confidence that spacecraft and science instrument operations would even reach, let alone exceed, desired mission lifetimes. Some critics have noted that this approach produces life-cycle cost estimates for missions that are lower than they would be if budgets for extended mission operations were included from the start. Moreover, deferring formal requests for mission extensions may encourage some skeptics to question the merits of such extensions. On the other hand, NASA's 5-year budget projections for the SMD do carry funding for extending missions on a division-by-division basis (sometimes by individual missions and sometimes as an aggregate number), so the planned expenditures are included in NASA's budget projections.

The committee debated this question and concluded that the current NASA approach is very reasonable. Spacecraft and science instruments are designed and tested for specific lifetimes with corresponding requirements (and associated costs) for component and subsystem reliability. The lifetime design requirements also include margins, which increase the probability that the mission will meet its design lifetime, but do not guarantee how much longer it will continue working beyond its prime phase. After the design lifetime is reached, nobody expects the spacecraft or instruments to immediately stop working, just as nobody expects a household appliance to break the day after its warranty expires, but there is an understanding that degradation in function may occur. The committee also discussed the merits for NASA to further describe this philosophy in its own policy documents as a means to better communicate both internally and externally its intent to extend the operations of missions as long as they continue to return useful data and the resources needed to do so fit within their overarching budget constraints.

In addition, the prime phase of a mission is not only defined by the hardware lifetimes but by the science goals that are to be achieved during that time. If NASA were to define a longer lifetime for a mission from the outset, development, integration, and testing costs would increase, while NASA and the science team might also have to expand the science goals corresponding to a longer prime mission. One of the benefits of an approach that keeps the prime phase separate from the extended phase is that it enables NASA and the science teams to apply knowledge gained during the prime mission to develop expanded, or even totally new, goals for the extended mission. This insight and the new goals cannot be predicted far in advance, so the current approach is a good method of tapping into new knowledge and applying it to an already flying mission.

Finding: NASA's current approach to establishing requirements and designs for prime phase and budgeting for extended missions has many positive attributes and provides a very high return on investment.

Recommendation: NASA should continue anticipating that missions are likely to be extended and identify funding for extended missions in the longer-term budget projections.

Recommendation: NASA's Science Mission Directorate (SMD) policy documents should formally articulate the intent to maximize science return by operating spacecraft beyond their prime mission, provided that the spacecraft are capable of producing valuable science data and funding can be identified within the SMD budget.

CONCLUSION

The committee is very supportive of the current NASA approach to mission design, which provides a high probability of achieving prime mission objectives while also allowing a reasonable likelihood that an extended phase with high science return will be achievable. As stated earlier, extended missions enable new science, provide for data continuity, and enable long baseline studies—all at very modest incremental cost. The committee has identified a number of good/best practices for missions to adopt in order to limit increased risk and prepare to operate extended missions under likely reduced budgets. Various cost-saving approaches were presented to the committee, and a number of positive attributes were identified, although no global solutions were found, given the distinct aspects of the various missions. The committee is supportive of the acceptance of increased risk during the extended phase of most missions while noting that the national interests or needs aspects of Earth science missions (and possibly some Heliophysics missions as well) establish different risk acceptance levels. The committee also notes the importance of considering operations trades along with science impacts when budget reductions are required and notes the importance of providing roughly constant funding for highly performing missions after the first two Senior Reviews.

Appendixes

A

Statement of Task

The NRC will appoint an ad hoc committee to conduct an assessment of the scientific value of extended missions in the overall program of NASA's Science Mission Directorate (SMD). The committee's report will provide recommended guidelines for future NASA decision-making about such mission extensions. In conducting this study, the committee could address the following questions:

1. Historically, what have been the scientific benefits of mission extensions? How important are these benefits (for example, benefits that might only accrue during the extended mission phase but not earlier)?
2. What is the current SMD Senior Review process for extending missions—for example, how are reviews chartered and conducted, by whom, and using what criteria? What should be division dependent and what should be uniform across the Directorate?
3. The NASA Authorization Act of 2005 requires biennial Senior Reviews for each mission extension. Is this biennial time period optimal for all divisions? Would a longer or shorter time period between reviews be advantageous in some cases?
4. Does the balance currently struck between starting new missions and extending operating missions provide the best science return within NASA's budget? That is, how much of an acceleration of new mission initiation could realistically be achieved by reallocating resources from mission extensions to new programs, compared to the corresponding scientific loss from terminated or diminished mission extensions?
5. Are there innovative cost reduction approaches that could increase the science cost-effectiveness of extended missions? Are there any general principles that might be applied across the board or to all of the missions for an individual science theme or a particular class? Are there alternative mission management approaches (e.g., transfer to an outside technical or educational institution for training or other purposes) that could reduce mission costs during extended operations and continue to serve SMD's science objectives?

B

Scientific Discoveries of the Lunar Reconnaissance Orbiter and *Opportunity* Rover During Extended Phase

LUNAR RECONNAISSANCE ORBITER

The Lunar Reconnaissance Orbiter (LRO) has been orbiting the Moon for nearly 7 years. Originally in a quasi-circular 50 km orbit, after 18 months of operation LRO was moved to a $\sim 30 \text{ km} \times \sim 180 \text{ km}$ orbit to conserve fuel; all extended mission observations have been from the fuel-saving elliptical orbit. LRO includes seven science experiments; all remain healthy, except that the Miniature Radar Frequency (Mini-RF) transmitter ceased to function in December 2010 but still produces useful measurements as a receiver in a bi-static configuration (Earth-based assets transmit). An important legacy of the LRO mission is the vast amount of data made available to the scientific community, which is expected to be $>900 \text{ TB}$ by the end of 2018. This legacy data set will be used for decades of lunar exploration and science.

A few of the key LRO science results from the extended mission are summarized below. More than 220 new resolved impact craters were discovered as of March 2016 (Figure B.1), having diameters of 1.4 to 43 m. The number of new craters shows that the size frequency distribution is steeper than expected based on models commonly used to date surfaces. In addition to the craters themselves, $>45,000$ albedo marks (splotches) are observed that provide information regarding secondary cratering processes (Robinson et al., 2015).

The high-resolution LROC images also revealed numerous small-scale tectonic features with pristine morphologies, indicating that they are likely still forming, most likely due to cooling of the interior. The orientation of these scarps is not random but rather consistent with a pattern expected from stresses introduced from solid body tides with Earth (Watters et al., 2015). The Lunar Orbiter Laser Altimeter (LOLA) detected enhanced reflectivity @1064 nm in permanently shadowed regions at both the north and south poles (Lucey et al., 2014). These data, together with other data such as from the Lyman Alpha Mapping Project (LAMP) and temperatures measured by Lunar Diviner Radiometer (Hayne et al., 2015), collectively suggest that a micron-thick layer of water ice is present in these regions. The polar hydrogen distribution at both the north and south poles is asymmetric and mirrored, suggesting that true polar wander has occurred (Siegler et al., 2016). Although most volcanism on the Moon appears to have ended 2 to 3 Gyr ago, observations by LROC suggest late stage activity persisted until $<100 \text{ Myr}$ (Braden et al., 2014). The abundance of rocks in ejecta blankets is well correlated with the age of the crater from $\sim 100 \text{ kyr}$ to $\sim 1.5 \text{ Gyr}$ (Ghent et al., 2014), establishing a new “lithochronology” technique. The Mini-RF instrument is operated in concert with the Arecibo Observatory to collect bistatic radar data of the lunar nearside from 2012 to 2015; the response for the floor of the south-polar permanent shadowed region in Cabeus crater is consistent with the presence of blocky, near-surface deposits of water ice (Patterson et al., 2016).

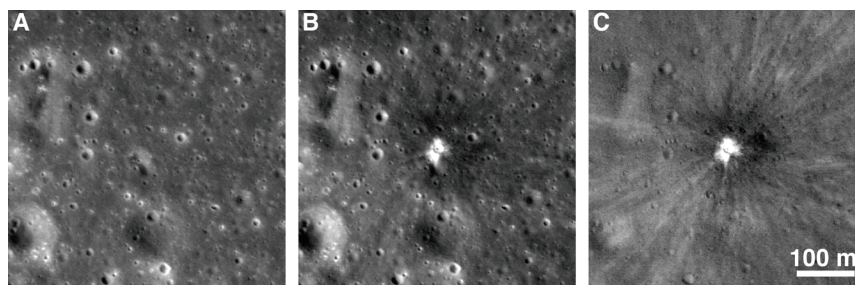


FIGURE B.1 An 18 m diameter crater that formed on the Moon on March 17, 2013, and was observed by Earth-based monitors. Before and after images acquired by the LROC NAC enabled scientists to locate the newly formed impact crater and study secondary surface changes. (A) Before image acquired by the LROC NAC (right before the crater formed). (B) After image acquired by the LROC NAC of the same area as image A (right after the crater formed). (C) Ratio of the after image divided by the before image. SOURCE: M.S. Robinson, A.K. Boyd, B.W. Denevi, S.J. Lawrence, A.S. McEwen, D.E. Moser, R.Z. Povilaitis, R.W. Stelling, R.M. Suggs, S.D. Thompson, and R.V. Wagner, 2015, New crater on the Moon and a swarm of secondaries, *Icarus* 252:229-235, doi:10.1016/j.icarus.2015.01.019.

MARS EXPLORATION ROVER *OPPORTUNITY*

The Mars Exploration Rover (MER) *Opportunity* landed on the Meridiani Planum plains of Mars in January 2004. After completing its initial 90-sol (92.5-day) mission, *Opportunity* entered the extended-mission phase and has remained operational for more than 12 years—more than 4,500 sols. *Opportunity* continues a legacy of U.S. in situ exploration of Mars that was initiated with the 1997 Mars Pathfinder mission. The rover initially traversed the Eagle Crater to look for signs of habitability, but then continued traversing tens of thousands of meters further to survey the Endurance crater, Victoria crater, Endeavour crater, and beyond (Figure B.2). Microscopic Imager (MI) glitches, flash memory data loss, and an “arthritic” robotic arm have not yet become mission-inhibiting challenges. Its instruments are all fully operational; the rover continues to survey the planet using cameras, spectrometers, and magnets, although its Rock Abrasion Tool is no longer operational. *Opportunity*’s ongoing observations continue to be a valuable source of insight into the ancient Mars environment. This section will summarize the key findings made by *Opportunity* since it began its extended-mission phase.

It is important to establish that the extended mission was vital toward characterizing past environments. The Burns Formation, named after Roger Burns, is a designation for a region-wide group of rocks exposed by impact-related crater formation or fracturing and explored by *Opportunity*. The observations from the Burns Formation in the Endurance crater helped support early observations of the formation in the Eagle crater, which together confirmed the past presence of water on Mars (Squyres and Knoll, 2005; Grotzinger et al., 2005).

Grotzinger et al. (2005) divided the Burns Formation into an upper, middle, and lower unit by similar depositional features and characterized eolian dune, eolian sand sheet, and damp to wet interdune environment types (called facies associations) in the Eagle and Endurance craters. All three units were composed of sandstone (Grotzinger et al., 2005). It was found that tepee-like or salt-ridge irregularities on a scoured sandstone facies suggested a regularly oscillating water table that sometimes reached the surface to create an ephemerally damp environment (Grotzinger et al., 2005). Miniature Thermal Emission Spectrometer (Mini-TES) data detected evaporite and sulfate minerals, suggesting that the grains deposited in the Burns Formation dunes were transported from an evaporite basin containing water that interacted with basalt (Grotzinger et al., 2005; McLennan et al., 2005). Bromine, which is found in very soluble minerals, was also detected in Meridiani Planum soils, suggesting activity by liquid water (Yen et al., 2005). Meanwhile, the unambiguous presence of jarosite—a sulfate mineral group—as an evaporite mineral suggested that Mars liquid water had a low pH because jarosite precipitates only from acidic solutions (McLennan et al., 2005; Squyres and Knoll, 2005). Additionally, hematite spherules about 4 mm in diameter, informally named “blueberries,” were theorized to be formed by a concretion process from the

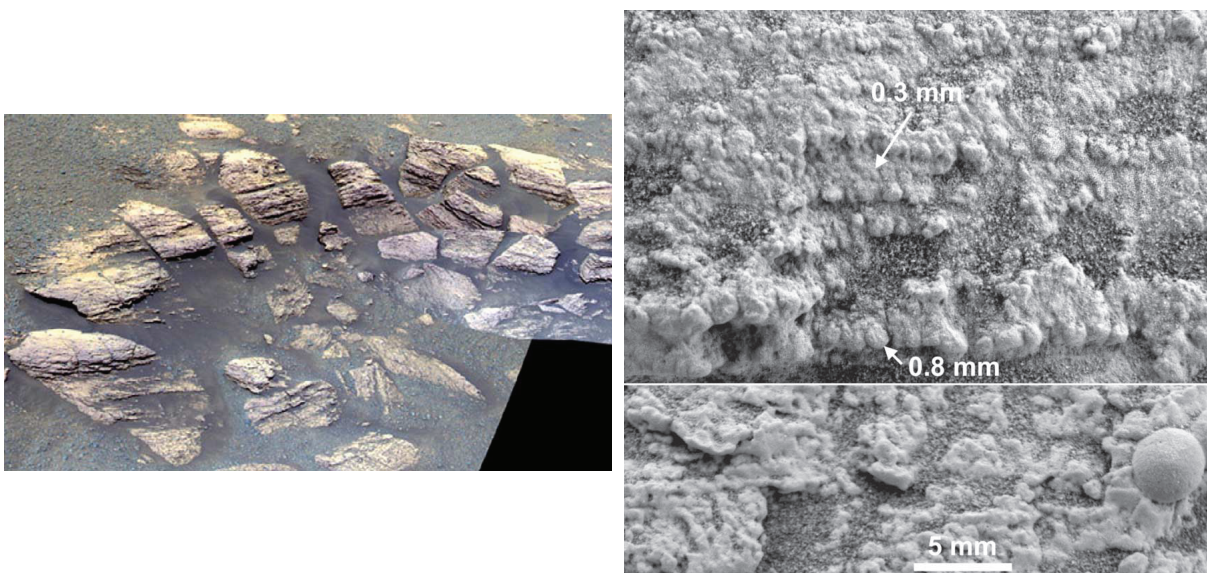


FIGURE B.2 *Left:* Pancam image of sedimentary rocks exposed in blocks along the wall of Eagle Crater. The bedding, cross-lamination, and hematite concretion “blueberries” are visible. *Right:* Microscopic Imager image of sandstone grains and highly spherical hematite concretions. SOURCE: *Left:* Reprinted from S.W. Squyres and A.H. Knoll, Sedimentary rocks at Meridiani Planum: Origin, diagenesis, and implications for life on Mars, *Earth and Planetary Science Letters* 240:1-10, 2005, Copyright 2005, with permission from Elsevier. *Right:* Reprinted from J.P. Grotzinger, R.E. Arvidson, J.F. Bell, W. Calvin, B.C. Clark, D.A. Fike, M. Golombek, et al., Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars, *Earth and Planetary Science Letters* 240:11-72, 2005, Copyright 2005, with permission from Elsevier.

breakdown of jarosite by groundwater or by oxidation of ferrous sulfates (McLennan et al., 2005). Therefore, grain formation on the Meridiani Planum of Mars was discovered to be once driven by acidic liquid water.

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C

NASA Science Mission Directorate Budgets by Division for Fiscal Year 2016

Data for Figures C.1 through C.4 were provided by NASA to the committee. They demonstrate the individual budgetary breakdowns for each division. They are primarily included here to enable comparison of the size of development budgets versus extended science operations budgets in each division. Because the divisions manage and calculate their budgets in slightly different ways, it is not possible to make detailed budget category comparisons between the divisions.

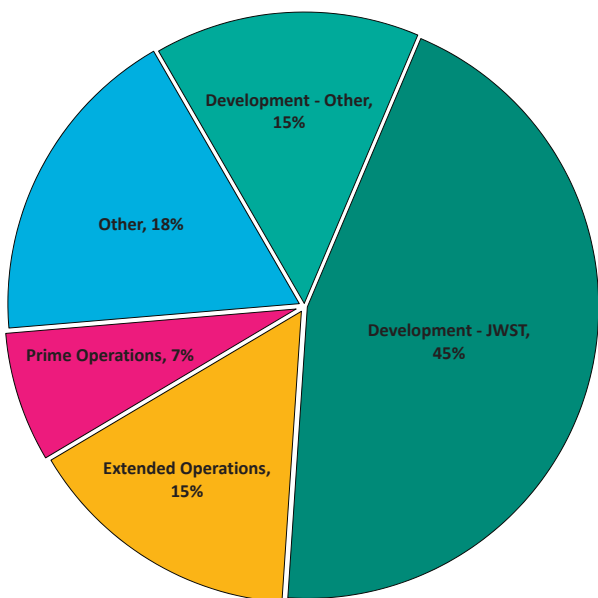


FIGURE C.1 Astrophysics Sciences Division fiscal year 2016 budget.

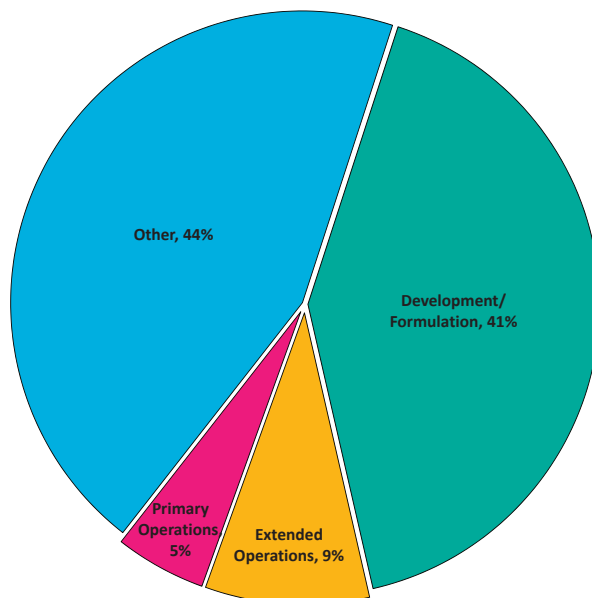


FIGURE C.2 Earth Sciences Division fiscal year 2016 budget.

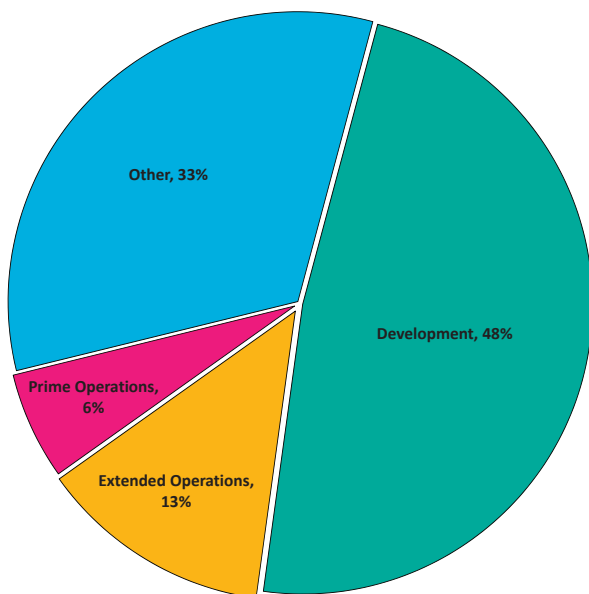


FIGURE C.3 Planetary Sciences Division fiscal year 2016 budget.

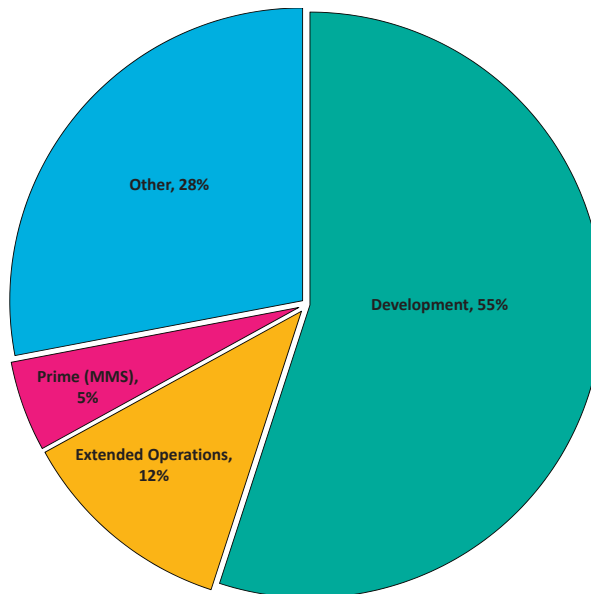


FIGURE C.4 Heliophysics Sciences Division fiscal year 2016 budget.

D

Extended Mission and Senior Review References in Decadal Surveys

Extended missions have been mentioned in a number of decadal survey reports. However, their value has rarely been explicitly highlighted in these reports.

2010 ASTRONOMY AND ASTROPHYSICS DECADAL SURVEY

National Research Council, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., 2010.

Page 16, *Wide-Field Infrared Survey Telescope (WFIRST)*

A 1.5-meter wide-field-of-view near-infrared-imaging and low-resolution-spectroscopy telescope, WFIRST will settle fundamental questions about the nature of dark energy, the discovery of which was one of the greatest achievements of U.S. telescopes in recent years. It will employ three distinct techniques—measurements of weak gravitational lensing, supernova distances, and baryon acoustic oscillations—to determine the effect of dark energy on the evolution of the universe. An equally important outcome will be to open up a new frontier of exoplanet studies by monitoring a large sample of stars in the central bulge of the Milky Way for changes in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters. It will also, in guest investigator mode, survey our galaxy and other nearby galaxies to answer key questions about their formation and structure, and the data it obtains will provide fundamental constraints on how galaxies grow. The telescope exploits the important work done by the joint [Department of Energy] DOE/NASA design team on the Joint Dark Energy Mission—specifically the JDEM-Omega concept—and expands its scientific reach. WFIRST is based on mature technologies with technical risk that is medium low and has medium cost and schedule risk. The independent cost appraisal is \$1.6 billion, not including the guest investigator program. As a telescope capable of imaging a large area of the sky, WFIRST will complement the targeted infrared observations of the James Webb Space Telescope. The small field of view of JWST would render it incapable of carrying out the prime WFIRST program of dark energy and exoplanet studies, even if it were used exclusively for this task. The recommended schedule has a launch date of 2020 with a 5-year baseline mission. An extended 10-year mission could improve the statistical results and further broaden the science program. The European Space Agency (ESA) is considering an M-class proposal, called Euclid, with related goals. Collaboration on a combined mission with the United States playing a leading role should be considered so long as the committee's recommended science program is preserved and overall cost savings result.

Page 167

NASA holds regular senior reviews to decide which missions to terminate, and it is anticipated that every one of its currently orbiting space telescopes, including Hubble (which needs an expensive de-orbiting mission), will cease operations before the end of the decade. SOFIA [Stratospheric Observatory for Infrared Astronomy], which has operations costs of \$70 million per year, will be subject to a senior review after 5 years of operations. Thus, with the possible exception of JWST and SOFIA, none of the missions operating or started today are expected to be operational at the end of the decade.

Page 174, *National Aeronautics and Space Administration*

In the course of formulating recommendations that include large, medium, and small missions, as well as targeted augmentations to some of the core supporting activities, the committee considered broader issues of balance between a range of elements across the NASA program: between larger and smaller missions; between NASA-led and international-partner-led missions; between university-led and NASA-center-led missions; between mission-enabling and mission-supporting activities (technology development, suborbital program, theory, ground-based observing) and the missions themselves; between mission construction/operation and data archiving and analysis; and between extended mission support for operating missions versus funding of new missions. During its deliberations the committee attended to the general principle of balance in developing its recommended prioritization of projects within the NASA Astrophysics Division program during the coming decade.

Page 207, *Priority 1 (Large, Space). Wide-Field Infrared Survey Telescope (WFIRST)*

In a 5-year baseline mission, its observations would emphasize the planet census and dark energy measurements, while accommodating a competed general investigator program for additional surveys that would exploit WFIRST's unique capabilities using the same observation modes. The powerful astronomical survey data collected during all of the large-area surveys would be utilized to address a broader range of science through a funded investigator program. An extended mission, subject to the usual senior review process, could both improve the statistical results for the main science drivers and broaden the general investigator program.

Page 225, *Priority 1 (Large, Ground). Large Synoptic Survey Telescope (LSST)*

The technical risk of LSST as determined by the survey's cost appraisal and technical evaluation (CATE) process was rated as medium low. The committee did identify additional risk with establishing data management and archiving software environments adequate to achieving the science goals and engaging the astronomical community. The appraised construction cost is \$465 million with a time to completion of 112 months. The committee recommends that LSST be started as soon as possible, with, as proposed by the project, two-thirds of the construction costs borne by NSF [National Science Foundation] through its MREFC [Major Research Equipment and Facilities Construction] line and a quarter by DOE using Major Item of Equipment (MIE) funds. The estimated operations cost is \$42 million per year over its 10-year lifetime, of which roughly \$28 million is proposed to be borne by the U.S. agencies—the committee recommends two-thirds of the federal share of operations costs be borne by NSF and one-third by DOE. It is recommended that any extended mission should only happen following a successful senior review. By its very nature LSST will stimulate a large number of follow-up studies, especially of a spectroscopic character. The planning and administration of an optimized plan for follow-up studies within the public-private optical-infrared system could be carried out by the National Optical Astronomy Observatory.

2011 PLANETARY SCIENCE DECADEAL SURVEY

National Research Council, *Vision and Voyages for Planetary Science in the Decade 2013- 2022*, The National Academies Press, Washington, D.C., 2011.

Page 12, *NASA ACTIVITIES*

Continue missions currently in flight, subject to approval obtained through the appropriate senior review process. 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.

Page 14, *Recommended Program of Missions*

Within the category of small missions are three elements of particular interest: the Discovery program, extended missions for ongoing projects, and Missions of Opportunity.

Mission extensions can be significant and highly productive, and may also enhance missions that undergo changes in scope because of unpredictable events. In some cases, particularly the “re-purposing” of operating spacecraft, fundamentally new science can be enabled. These mission extensions, which require their own funding arrangements, can be treated as independent, small-class missions. The committee supports NASA's current senior review process for deciding the scientific merits of a proposed mission extension. The committee recommends that early planning be done to provide adequate funding of mission extensions, particularly for flagship missions and missions with international partners.

Pages 27 and 67, *International Cooperation*

1. Scientific support through peer review that affirms the scientific integrity, value, requirements, and benefits of a cooperative mission;
2. A historical foundation built on an existing international community, partnership, and shared scientific experiences;
3. Shared objectives that incorporate the interests of scientists, engineers, and managers in common and communicated goals;
4. Clearly defined responsibilities and roles for cooperative partners, including scientists, engineers, and mission managers;
5. An agreed-upon process for data calibration, validation, access, and distribution;
6. A sense of partnership recognizing the unique contributions of each participant;
7. Beneficial characteristics of cooperation; and
8. Recognition of the importance of reviews for cooperative activities in the conceptual, developmental, active, or extended mission phases—particularly for foreseen and upcoming large missions.

Page 35, *Non-Mars Mission Priorities in 2003, Small*

The 2003 decadal survey identified two small-class initiatives. They were, in priority order:

1. *Discovery program.* The 2003 survey recommended that the Discovery line of innovative, principal-investigator-led missions should continue and that a new one should be launched approximately every 18 months (Figure 1.3). This mission line has continued, but the flight rate has not matched the 2003 decadal survey's expectations.
2. *Cassini extended mission.* The 2003 decadal survey recommended that the Cassini Saturn orbiter mission be extended beyond its 4-year nominal lifetime. Operation of this highly successful and scientifically productive spacecraft (Figures 1.4 and 1.5) now extends through 2017.

Page 103, *Chiron Orbiter*

Given the growing number of known Centaurs and KBOs, the committee concluded that it is scientifically desirable that missions directed to the outer solar system take advantage of opportunities to fly by such objects (at ranges less than 10,000 km) en route to their ultimate targets. During the next decade there will be a growing desire to investigate some large trans-Neptune objects beyond the orbit of Pluto. The New Horizons mission already en route to Pluto (Figure 4.4) has the potential to fly by a small KBO. This extended mission opportunity will be a first chance for a close-up view of this class of object and should not be missed if a suitable target is available.

Page 123, *Constrain Ancient Climates on Venus and Search for Clues into Early Terrestrial Planet Environments So As to Understand the Initial Conditions and Long-Term Fate of Earth's Climate*

Data from the ASPERA [Analyzer of Space Plasmas and Energetic Atoms] instrument on Venus Express suggest provisionally that hydrogen escape rates are an order of magnitude slower than previously assumed, implying that the hydrogen in Venus's atmosphere has an average residence time of some 1 billion years. This result, if confirmed by further observations during an extended Venus Express mission, has important implications for the history of water and the current rate of outgassing on Venus. Another significant discovery is that Venus's atmosphere is losing unexpectedly large quantities of oxygen to deep space by way of nonthermal processes. This finding calls into question the long-standing assumption that a massive escape of hydrogen from Venus's atmosphere must have left the atmosphere and surface highly oxidized.

Page 257, *UNDERLYING PROGRAMMATIC REQUIREMENTS*

The individual flight projects for the coming decade must be considered within the context of the broader program of planetary exploration. The goal is to develop a fully integrated strategy of flight projects, technology development, and supporting research that maximizes the value of scientific knowledge gained over the decade. All of the recommendations in this chapter are made under the assumption that the following basic programmatic requirements are fully funded:

- Continue missions currently in flight, subject to approval obtained through the appropriate senior review process. These missions include the Cassini mission to the Saturn system, several ongoing Mars missions, the New Horizons mission to Pluto, ongoing Discovery missions, and others. 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.

Page 264, *Extended Missions for Ongoing Projects*

Mission extensions can be significant and highly productive, and may also enhance missions that undergo changes in scope because of unpredictable events or opportunities. The Cassini and Mars Exploration Rover extensions are examples of the former, and the “re-purposing” of missions such as Stardust (NExT) and Deep Impact (EPOXI) are examples of the latter. In some cases, particularly the re-purposing of operating spacecraft, fundamentally new science can be enabled. These mission extensions, which require their own funding arrangements, can be treated as independent, small-class missions. The committee supports NASA's current senior review process for deciding the scientific merits of a proposed mission extension. The committee recommends that early planning be done to provide adequate funding of mission extensions, particularly for flagship missions and missions with international partners.

2007 EARTH SCIENCE DECADAL SURVEY

National Research Council, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, The National Academies Press, Washington, D.C., 2007.

Page xiv

A related issue concerns the process for extension of a NASA-developed Earth science mission that has accomplished its initial objectives or exceeded its design life. NASA decisions on extension of operations for astronomy, space science, and planetary exploration are based on an analysis of the incremental cost versus anticipated science benefits. Historically, NASA has viewed extended-phase operations for Earth science missions as operational and therefore the purview of NOAA [National Oceanic and Atmospheric Administration]. However, the compelling need for measurements in support of human health and safety and for documenting, forecasting, and mitigating changes on Earth creates a continuum between science and applications—illustrating again the need for multiple agencies to be intimately involved in the development of Earth science and applications from space.

Page 13

The elimination from NPOESS [National Polar-orbiting Operational Environmental Satellite System] of requirements for climate research-related measurements is only the most recent example of the nation's failure to sustain critical measurements. The committee notes that despite NASA's involvement in climate research and its extensive development of measurement technology to make climate-quality measurements, the agency has no requirement for extended measurement missions, except for ozone measurements, which are explicitly mandated by Congress. The committee endorses the recommendation of a 2006 National Research Council report that stated, “NASA/SMD [Science Mission Directorate] should develop a science strategy for obtaining long-term, continuous, stable observations of the Earth system that are distinct from observations to meet requirements by NOAA in support of numerical weather prediction.”

2013 HELIOPHYSICS DECADEAL SURVEY

National Research Council, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C., 2013.

Page 240, *Heliophysics Systems Observatory*

In the area of comparative magnetospheres, Juno will enter its prime mission phase when it arrives at Jupiter in 2016, while Cassini at Saturn is approved for a final mission extension to 2017, and MESSENGER [Mercury Surface, Space Environment, Geochemistry, and Ranging] will complete its prime mission early in the decade. Past and current missions continue to provide deep insights into general solar wind magnetosphere interactions. For example, Ganymede's Alfvén wings have led to modern theories of Earth's own polar cap potential saturation mechanism; Saturn's explosive energy releases have much in common with substorm injections at Earth; and Jupiter's interchange motions enabling convection under Io's mass loading have led to similar theories pertaining to inward penetration of fast reconnection flows. As is the case for Earth-orbiting satellites, extended missions for planetary missions that continue to return valuable science data are strongly encouraged.

Page 307, *L5 Mission Concept*

Two science phases are envisioned: drift to L5 at about 38° per year with continuous collection of science data and orbit around L5, 45°-90° from the Sun-Earth line. A long extended mission is possible.

Page 313, *Heliophysics Systems Observatory [HSO] and MO&DA [Mission Operations and Data Analysis] Support*

Resource allocation among extended HSO missions is determined through the senior-review process, which evaluates future scientific priorities for each mission. The present 5-year budget requests show flat or declining HSO funding. In addition to supporting existing HSO missions, the budget must accommodate new missions, such as RBSP [Radiation Belt Storm Probes] (renamed the Van Allen Probes) and SDO [Solar Dynamics Observatory], that finish their prime mission in or before [fiscal year] FY 2015; this will inevitably lead to forced termination of or severe cuts in current HSO missions. As a consequence, key systems-science objectives are endangered, and essential legacy data sets may be foreshortened at a time when solar activity is apparently evolving in unexpected ways. Multipoint observations throughout the heliosphere and from the Sun to geospace regions need to be maintained to enable systems science. The SHP [Solar and Heliospheric Physics] panel assigns high priority to augmenting MO&DA support by annual inflationary increases plus \$5 million to \$10 million per year to accommodate new missions so that senior-review decisions can be prudently based on strategic evaluations of existing and emerging assets.

E

Biographies of Committee Members and Staff

COMMITTEE

VICTORIA E. HAMILTON, *Co-Chair*, is a section manager in the Department of Space Studies at Southwest Research Institute (SwRI) in Boulder, Colorado. Dr. Hamilton has extensive experience with laboratory spectroscopy and Mars data analysis; she was an affiliate of the Mars Global Surveyor Thermal Emission Spectrometer science team, is the deputy principal investigator (PI) of the THEMIS instrument on 2001 Mars Odyssey, and was a participating scientist on the Mars Science Laboratory (MSL) mission. She is also a science team co-investigator and deputy instrument scientist on the OSIRIS-REx asteroid sample return mission. She has published on laboratory mineral and meteorite spectroscopy, numerical modeling of infrared spectra, martian surface composition, martian atmospheric aerosol composition, and surface thermophysical properties. Dr. Hamilton has built, operated, and managed a NASA-supported spectroscopy laboratory equipped with three spectrometers for measuring visible, near infrared, and thermal infrared properties of rocks, minerals, and meteorites in reflectance and emission. She has received the NASA Group Achievement Award for the MSL Science Office Development and Operations Team in 2013. She received her Ph.D. in geology from Arizona State University. She was a member of the Committee on Cost Growth in NASA Earth and Space Science Missions of the National Academies of Sciences, Engineering, and Medicine as well as a member of the Mars Architecture Review Committee for the Committee for Planetary Exploration.

HARVEY D. TANANBAUM, *Co-Chair*, is senior astrophysicist at the Smithsonian Astrophysical Observatory. Dr. Tananbaum is a pioneer of X-ray astronomy and was on the team that discovered stellar systems containing neutron stars and black holes and X-rays from quasars and clusters of galaxies. He has also been deeply involved in the development of the Chandra X-ray Observatory, from its conception to its birth. He has worked at the Smithsonian Astrophysical Observatory since 1973. Dr. Tananbaum has earned the NASA Exceptional Scientific Achievement Medal, the NASA Public Service Award, and the NASA Medal for Outstanding Leadership, as well as the Bruno Rossi Prize of the High Energy Astrophysics Division of the American Astronomical Society (AAS). Dr. Tananbaum earned his Ph.D. in physics from the Massachusetts Institute of Technology. He was elected to the National Academy of Sciences (NAS) in 2005, and has served on the Space Studies Board. As well, he has served on a number of National Academies studies, including the Committee on an Assessment of Balance in NASA's Science Programs, the Committee on the Scientific Context for Space Exploration, and the Committee on Physics of the Universe.

ALICE BOWMAN is a member of the principal professional staff at the Johns Hopkins University Applied Physics Laboratory (APL), serving both as the supervisor of APL's Space Mission Operations Group and as Mission Operations Manager (MOM) for NASA's New Horizons Mission. Ms. Bowman supervises approximately 40 staff members who operate deep-space and Earth-orbiting spacecraft that are gathering data and making key observations for NASA's Planetary Science and Heliophysics divisions. Ms. Bowman has also served as the New Horizons MOM since the mission's inception in the early 2000s; in this role she leads the team that commands and controls the New Horizons spacecraft, which made a historic close flyby of Pluto and its family of moons on July 14, 2015, and continues deeper into the solar system's distant Kuiper Belt region. Ms. Bowman has professional experience in national defense space operations, systems engineering, program management, engineering management, space systems, space instrument development and deployment, infrared detector development, and mission operations. Ms. Bowman earned her B.A. in physics and chemistry from the University of Virginia. She is a member of the American Institute of Aeronautics and Astronautics (AIAA) and the International SpaceOps Committee, serving as a co-chair on the workshop subcommittee.

JOHN R. CASANI is a consultant who is retired from the Jet Propulsion Laboratory (JPL). He has managed major flight projects, including Voyager, Galileo, and Cassini, and is a recipient of several NASA awards, including the Distinguished Service Medal. He received the AIAA Space System Award, the von Karman Lectureship, the National Space Club Astronauts Engineer Award, the AAS Space Flight Award, and the Smithsonian National Air and Space Museum's Lifetime Achievement Award. He held senior project positions on many of the Mariner missions to Mars and Venus, and in 1970 he became project manager of Mariner 6 and 7. Later, Dr. Casani managed NASA's Voyager mission to the outer planets, the Galileo mission to Jupiter, and the Cassini mission to Saturn, as well as the Jupiter Icy Moons Orbiter mission. He is an honorary fellow of the AIAA, a member of the National Academy of Engineering (NAE), and a recipient of the NAE Founder's Award. Dr. Casani holds a B.S. in electrical engineering, an honorary D.Sc. from the University of Pennsylvania, and an honorary degree in aerospace engineering from the University of Rome, Italy. He has previously served on the National Academies' NASA Technology Roadmap: Entry, Descent, and Landing Panel and the Planetary Science Decadal Survey: Giant Planet Panel.

JAMES H. CLEMMONS is the principal director of the Space Science Applications Laboratory at the Aerospace Corporation. In his 18 years at Aerospace, Dr. Clemmons has led development of more than 20 scientific instruments and flown on sounding rockets and satellites to investigate a variety of phenomena in Earth's magnetosphere as well as its ionosphere-thermosphere-mesosphere system. He is the author of numerous publications, including studies of observations conducted with the Freja satellite and other missions characterizing electric, magnetic, and plasma phenomena in the space environment. Before joining Aerospace, he worked at NASA Goddard Space Flight Center, the Swedish Institute for Space Physics, and the Max-Planck-Institute for Extraterrestrial Physics on related research. He has participated in several NASA advisory groups and is the recipient of several awards by NASA and the Aerospace Corporation. Dr. Clemmons is a member of the American Geophysical Union (AGU), the American Physical Society (APS), and the American Chemical Society. He was a Fulbright Scholar and a resident associate of the National Research Council. Dr. Clemmons received B.S. degrees in physics and chemistry from the University of Illinois, Urbana-Champaign, and an M.S. and Ph.D. in physics from the University of California, Berkeley. Dr. Clemmons previously served on the National Academies' Panel on Atmosphere-Ionosphere-Magnetosphere Interactions.

NEIL GEHRELS is the chief of the Astroparticle Physics Laboratory at NASA's Goddard Space Flight Center. He is also a professor of astronomy at the University of Maryland, College Park, and an adjunct professor of astronomy and astrophysics at Pennsylvania State University. He is a member of the American Academy of Arts and Sciences and the NAS. Dr. Gehrels is the PI of the NASA Swift satellite observing gamma-ray burst and supernova explosions. He is a deputy project scientist for Fermi, project scientist for WFIRST, and previous project scientist for the Compton Observatory (1991-2000). He has organized nine major conferences and been an editor on the proceedings books, has more than 500 articles in science journals and popular science magazines, and has given

many invited talks. He has been on 20 working groups and committees in various positions. He served as chair of the Astronomy Section of the NAS, past chair of the AAS High Energy Astrophysics Division, past chair of the APS Division of Astrophysics, and past chair of the COSPAR (Committee on Space Research) Commission E. Numerous awards have been bestowed upon Dr. Gehrels, including the COSPAR Massey Award in 2012, SPIE Goddard Award 2009, NAS Draper Medal in 2009, AAS Bruno Rossi Prize in 2007, *Popular Science* Magazine's Best of What's New Award for Swift satellite research in 2006, and NASA Exceptional Scientific Achievement Medal in 2005. Dr. Gehrels received his B.S. in physics and music from the University of Arizona and his Ph.D. from the California Institute of Technology. He serves on the National Academies' U.S. National Committee for the International Astronomical Union.

FIONA A. HARRISON is the Benjamin M. Rosen Professor of Physics and Astronomy in the Space Radiation Laboratory and the Kent and Joyce Kresa Leadership Chair, Division of Physics and Mathematics at the California Institute of Technology. She is the PI of NASA's Nuclear Spectroscopic Telescope Array (NuSTAR), a small explorer-class mission launched in 2012. Dr. Harrison's primary research interests are in experimental and observational high-energy astrophysics. In addition, she has an active observational program in gamma-ray, X-ray, and optical observations of gamma-ray bursts, active galaxies, and neutron stars. She was awarded the Robert A. Millikan Prize Fellowship in Experimental Physics in 1993 and the Presidential Early Career Award in 2000. She was named one of America's Best Leaders by U.S. News and the Kennedy School of Government in 2008, and received the NASA Outstanding Public Leadership Medal in 2013. She received her Ph.D. in physics from the University of California, Berkeley. She was elected to the NAS in 2014, is a member on the Division Committee on Engineering and Physical Sciences, was a member on the Space Studies Board, and chaired the Committee on an Assessment of the Astrophysics Focused Telescope Assets (AFTA) Mission Concepts.

MICHAEL D. KING is senior research scientist in the Laboratory for Atmospheric and Space Physics at the University of Colorado, Boulder. Dr. King is the science team leader for the MODIS instrument that flies on the Aqua and Terra satellites. Before joining the University of Colorado, he worked as a physical scientist at NASA's Goddard Space Flight Center, where he served as project scientist of the Earth Radiation Budget Experiment (ERBE) and later senior project scientist of NASA's Earth Observing System (EOS). His research experience includes conceiving, developing, and operating multispectral scanning radiometers from a number of aircraft platforms in field experiments ranging from arctic stratus clouds to smoke from the Kuwait oil fires and biomass burning in Brazil and southern Africa. Dr. King is also interested in surface reflectance properties of natural surfaces as well as aerosol optical and microphysical properties. Earlier, he developed the Cloud Absorption Radiometer for studying the absorption properties of optically thick clouds as well as the bidirectional reflectance properties of many natural surfaces. Dr. King is a fellow of the AGU, the American Meteorological Society (AMS), the Institute of Electrical and Electronic Engineers (IEEE), and the American Association for the Advancement of Science (AAAS), and is a recipient of the Verner E. Suomi Award of the AMS for fundamental contributions to remote sensing and radiative transfer, and the Space Systems Award of the AIAA for NASA's Earth Observing System. He received his M.S. and Ph.D. in atmospheric sciences from the University of Arizona. He was elected to the NAE in 2003 and is currently a member of the National Academies' Committee on Earth Science and Applications from Space. He previously served on the Committee on a Framework for Analyzing the Needs for Continuity of NASA-Sustained Remote Sensing Observations of the Earth from Space, the Board on Atmospheric Sciences and Climate, and the Climate Research Committee.

MARGARET G. KIVELSON is professor of space physics, emerita, at the University of California, Los Angeles, in the Department of Earth and Space Sciences as well as at the Institute of Geophysics and Planetary Physics at the University of California, Los Angeles. She is also 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 ultralow frequency waves. She is a co-investigator on the THEMIS and Europa missions and a collaborator on the fluxgate magnetometer on Cassini. She is the recipient of the Alfvén Medal of the European Geophysical Union and the Fleming Medal of the AGU. She earned her Ph.D. for physics from Radcliffe

College. She was elected a member of the NAS in 1999 and has served on the Plasma Science Committee, the 2014 NAS Nominating Committee, the Committee on Women in the Academy, and numerous other committees.

RAMON E. LOPEZ is a professor of physics at the University of Texas, Arlington. His research focuses on solar wind-magnetosphere coupling, magnetospheric storms and substorms, and space weather prediction. Dr. Lopez is also working in the areas of teacher education, national science education standards, and physics education research. Dr. Lopez is a fellow of the APS and the AAAS. He received his Ph.D. in space physics from Rice University. His previous National Academies' service includes membership on the Committee on Solar and Space Physics, Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics), the Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences, and the Committee on Solar and Space Physics.

AMY MAINZER is a senior research scientist at JPL in the astrophysics division. She has been employed as a scientist at JPL since 2003. At JPL, she serves as the PI for the NEOWISE mission, which is a NASA spacecraft dedicated to observing near-Earth asteroids and comets using a thermal infrared space telescope. As the NEOWISE PI, her research focuses on characterizing the population of asteroids and comets through statistical measurements of their sizes, orbits, albedos, and rotational states. The mission began life as the Wide-Field Infrared Survey Explorer (WISE), and its original purpose was to carry out an all-sky survey at four infrared wavelengths from 3 to 22 microns. After a nearly 3-year hibernation phase, the survey was restarted using its 3 and 4 micron channels and renamed NEOWISE. Dr. Mainzer served as the deputy project scientist for the WISE mission; her responsibilities included flowing down top-level science requirements to the WISE payload components, interpreting payload verification test data, and designing the in-orbit checkout procedures. In 2012 she received the NASA Exceptional Scientific Achievement medal for her work on near-Earth objects and the NASA Exceptional Achievement medal in 2011 for her work on NEOWISE. Prior to joining JPL, Dr. Mainzer worked as a systems engineer at the Lockheed Martin Advanced Technology Center in Palo Alto. She was responsible for the design, construction, testing, and in-orbit checkout of the Spitzer Space Telescope's fine guidance sensor. This instrument has been in continuous use since Spitzer's launch in 2003, including during the original Spitzer prime mission and the Warm Mission that began in 2008. Dr. Mainzer is also the principal investigator of a NASA Discovery mission proposal, the Near-Earth Object Camera. This proposal was awarded technology development funding in 2011 to mature 10 micron HgCdTe megapixel detectors. Additionally, she served on the National Academies' Committee to Assess Near Earth Object Hazards and Mitigation Strategies, and she is a member of the NASA Planetary Science Subcommittee. She was a member of the NASA Small Bodies Assessment Group Steering Committee from 2011 to 2013.

ALFRED S. McEWEN is professor for the Lunar and Planetary Laboratory at the University of Arizona (UA). He has studied planetary surfaces for more than 25 years, including time at the U.S. Geological Survey prior to joining UA in 1996. Current research interests include volcanology, cratering, slope processes, and remote sensing of planetary surfaces. His experience with spacecraft science experiments includes service as a member of the Voyager imaging team at Neptune; a Galileo interdisciplinary scientist associated with the Solid State Imaging team; a Cassini Imaging Science Subsystem team member; a Mars Observer/Mars Global Surveyor participating scientist for the Mars Orbital Camera; a member of the Clementine advisory committee and science team; a participating scientist on Mars Odyssey THEMIS; a PI of High Resolution Imaging Science Experiment (HiRISE), Mars Reconnaissance Orbiter; a co-investigator on Lunar Reconnaissance Orbiter Camera (LROC); a principal investigator for the High resolution Stereo Color Imager (HiSCI) on the ExoMars Trace Gas Orbiter; a co-investigator on TGO/CaSSIS; and a deputy PI for the Europa Imaging System on the still unnamed Europa mission. He was awarded NASA's distinguished public service medal in 2011 and AGU's Whipple award in 2015. He has a Ph.D. for planetary geology from Arizona State University. Prior National Academies studies include the 2003 Planetary Science Decadal Survey (chair of large satellites panel, 2001-2002) and COSPAR (2008-2010).

DEBORAH G. VANE is deputy program manager at JPL in the Office of Operating Earth Science Missions. She is also the project manager of the NASA CloudSat Mission. At JPL, Ms. Vane manages a portfolio of 13 Earth

science missions/experiments operating in Earth orbit with a combined annual budget of over \$70 million dollars. She oversees the JPL bi-annual Earth Science Senior Review proposal process for mission-operation extensions. She also manages the CloudSat mission that was launched, and she has submitted CloudSat proposals to the senior review multiple times. Her involvement in CloudSat began as the proposal manager in 1998. She has also served as the deputy PI; and she has served as project manager since the launch. She has been co-author on a number of journal articles on the application of CloudSat data to clouds and climate, atmospheric radiation, and applications to hurricane intensity estimation. Ms. Vane has over 35 years of experience at JPL in a variety of technical, management, and scientific roles. Previously, she was a member of the Mars Viking Mission Lander Imaging Team and was scientific assistant to the JPL chief scientist. Ms. Vane received the NASA Individual Award for Exceptional Achievement as deputy PI and project manager for the CloudSat mission, and she has received several group achievement awards. She earned her B.S. in physics from the University of Colorado.

STAFF

DWAYNE A. DAY, *Study Director*, a senior program officer for the Aeronautics and Space Engineering Board (ASEB), has a Ph.D. in political science from the George Washington University. Dr. Day joined the Academies as a program officer for the Space Studies Board (SSB). He served as an investigator for the Columbia Accident Investigation Board in 2003, was on the staff of the Congressional Budget Office, and worked for the Space Policy Institute at the George Washington University. He has also performed consulting for the Science and Technology Policy Institute of the Institute for Defense Analysis, and the U.S. Air Force. He is the author of *Lightning Rod, A History of the Air Force Chief Scientist*, and editor of several books, including a history of the CORONA reconnaissance satellite program. He has held Guggenheim and Verville fellowships at the National Air and Space Museum, and was an associate editor of the German spaceflight magazine *Raumfahrt Concrete*, in addition to writing for such publications as *Novosti Kosmonavtiki* (Russia), *Spaceflight*, and *Space Chronicle* (United Kingdom), and the *Washington Post*. He has served as study director for over a dozen Academies reports, including *3-D Printing in Space* (2013), *NASA's Strategic Direction and the Need for a National Consensus* (2012), *Vision and Voyages for Planetary Science in the Decade 2013-2022* (2011), *Preparing for the High Frontier-The Role and Training of NASA Astronauts in the Post-Space Shuttle Era* (2011), *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies* (2010), *Grading NASA's Solar System Exploration Program: A Midterm Review* (2008), and *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008).

NATHAN BOLL served as the 2016 Christine Mirzayan Science and Technology Policy Graduate Fellow for the SSB. Mr. Boll is a graduate fellow at the Space Policy Institute of George Washington University where he is completing an M.A. in international science and technology policy at the Elliott School of International Affairs. His current focus is on building international and intergovernmental cooperation toward the exploration and development of outer space. He holds an M.S. in space science and a graduate certificate in science, technology, and public policy from the University of Michigan, as well as a B.S. in mathematics from the University of Montana Western. His research has included environmental analysis of Venus and Mars and the development of the CYGNSS satellite constellation. Mr. Boll has recently served in various divisions of NASA, including the Office of International and Interagency Relations and the Office of Education Infrastructure Division at NASA Headquarters, the NASA Space Academy, the Multidisciplinary Aeronautics Research Team Initiative programs at the Glenn Research Center, and the Planetary Science Division of JPL.

KATIE DAUD is a research associate for the SSB and the ASEB. Previously, she worked at the Smithsonian National Air and Space Museum's Center for Earth and Planetary Studies as a planetary scientist. Ms. Daud was a triple major at Bloomsburg University, receiving a B.S. in planetary science and Earth science and a B.A. in political science.

MICHAEL MOLONEY is the director for Space and Aeronautics at the SSB and the ASEB of the National Academies. Since joining the ASEB/SSB, Dr. Moloney has overseen the production of more than 40 reports, including

four decadal surveys—in astronomy and astrophysics, planetary science, life and microgravity science, and solar and space physics—a review of the goals and direction of the U.S. human exploration program, a prioritization of NASA space technology roadmaps, as well as reports on issues such as NASA's Strategic Direction, orbital debris, the future of NASA's astronaut corps, and NASA's flight research program. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the Board on Physics and Astronomy (BPA) and study director for the decadal survey for astronomy and astrophysics (Astro2010). Since joining the Academies in 2001, Dr. Moloney has served as a study director at the National Materials Advisory Board, the BPA, the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. In addition to his professional experience at the National Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at the Irish Embassy in Washington and the Irish Mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics.

ANESIA WILKS joined the SSB as a program assistant in 2013. Ms. Wilks brings experience working in the National Academies conference management office as well as other administrative positions in the D.C. metropolitan area. She has a B.A. in psychology, magna cum laude, from Trinity University in Washington, D.C.

F

Acronyms

ACE	Advanced Composition Explorer
ACRIMSAT	Active Cavity Radiometer Irradiance Monitor Satellite
ACS	Advanced Camera for Surveys
AIM	Aeronomy of Ice in the Mesosphere
APL	Johns Hopkins Applied Physics Laboratory
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
ASD	Astrophysics Division
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
Caltech	California Institute of Technology
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CINDI	Coupled Ion Neutral Dynamic Investigation
CO	carbon monoxide
COS	Cosmic Origins Spectrograph
COSTAR	Corrective Optics Space Telescope Axial Replacement
CXC	Chandra X-Ray Center
DSN	Deep Space Network
EO-1	Earth Observing-One Mission
EOS	Earth Observation System
EPOXI	Extrasolar Planet Observation and Deep Impact Extended Investigation
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
ESA	European Space Agency
ESD	Earth Science Division
ESS	Earth System Science

EUVE	Extreme Ultraviolet Explorer
FAST	Fast Auroral Snapshot Explorer
FGS	Fine Guidance Sensor
FOC	Faint Object Camera
FOS	Faint Object Spectrograph
FUSE	Far Ultraviolet Spectroscopic Explorer
FY	fiscal year
GALEX	Galaxy Evolution Explorer
Geotail	Geomagnetic Tail Lab
GHRS	Goddard High Resolution Spectrograph
GPS Science	Global Positioning System Science
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GRAIL	Gravity Recovery and Interior Laboratory
GSFC	Goddard Space Flight Center
HD	Heliophysics Division
HiRISE	High Resolution Imaging Science Experiment
HSO	Heliophysics System Observatory
HSP	High Speed Photometer
HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
ICE	International Cometary Explorer
ICESat	Ice, Cloud, and Land Elevation Satellite
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
INTEGRAL	International Gamma-Ray Astrophysics Laboratory
IRIS	Interface Region Imaging Spectrograph
ISEE-3	International Earth-Sun Explorer-3
IUE	International Ultraviolet Explorer
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LAGEOS	Laser Geodynamics Satellites
LRO	Lunar Reconnaissance Orbiter
LROC	Lunar Reconnaissance Orbiter Camera
MAVEN	Mars Atmosphere and Volatile Evolution
MaxWise	Refers to a proposed Wide-Field Infrared Survey Explorer mission
MER	Mars Exploration Rover
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MGS	Mars Global Surveyor
MIDEX	Medium-class Explorer
MISR	Multi-angle Imaging Spectroradiometer
MIT	Massachusetts Institute of Technology
MMS	Magnetospheric Multiscale
MODIS	Moderate Resolution Imaging Spectroradiometer

MOPITT	Measurement of Pollution in the Troposphere
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NAC	Narrow-Angle Camera
NASA	National Aeronautics and Space Administration
NEN	Near Earth Network
NEO	near Earth object
NEOWISE	Near-Earth Object Wide-field Infrared Survey Explorer
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NOAA	National Oceanic and Atmospheric Administration
NPR	NASA Procedural Requirement
NRC	National Research Council
NuSTAR	Nuclear Spectroscopic Telescope Array
O ₃	ozone
OSTM	Ocean Surface Topography Mission
PI	principal investigator
PPBE	Planning, Programming, Budget and Execution
PSD	Planetary Science Division
QuikSCAT	Quick Scatterometer
R&A	research and analysis
RapidScat	Rapid Scatterometer
RHESSI	Reuven Ramaty High Energy Solar Spectroscopic Imager
ROSES	Research Opportunities in Space and Earth Sciences
RSL	recurring slope lineae
RXTE	Rossi X-ray Timing Explorer
SAGE	Stratospheric Aerosol and Gas Experiment
SAMPEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SDO	Solar Dynamics Observatory
SM	Servicing Mission
SMD	Science Mission Directorate
SMEX	Small Explorer
SOHO	Solar and Heliospheric Observatory
SORCE	Solar Radiation and Climate Experiment
SSR	Solid State Recorder
Stardust-NExT	Stardust New Exploration of Tempel 1
STEREO	Solar Terrestrial Relations Observatory
STIS	Space Telescope Imaging Spectrograph
Suomi NPP	Suomi National Polar orbiting Partnership, formerly the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project or NPP
TDE	tidal disruption event
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TIM	Total Irradiance Monitor
TIMED	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics

TOMS	Total Ozone Mapping
TRACE	Transition Region and Coronal Explorer
TRMM	Tropical Rainfall Measuring Mission
TWINS	Two Wide-angle Imaging Neutral-atom Spectrometers
UARS	Upper Atmosphere Research Satellite
WFC	Wide Field Camera
WFIRST	Wide-Field Infrared Survey Telescope
WFPC	Wide Field and Planetary Camera
WISE	Wide-Field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
XMM-Newton	X-ray Multi-Mirror Mission-Newton