Powering Science: NASA's Large Strategic Science Missions

DETAILS

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CONTRIBUTORS

Committee on Large Strategic NASA Science Missions: Science Value and Role in a Balanced Portfolio; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

Powering Science—NASA's Large Strategic Science Missions

Committee on Large Strategic NASA Science Missions: Science Value and Role in a Balanced Portfolio

Space Studies Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
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COMMITTEE ON LARGE STRATEGIC NASA SCIENCE MISSIONS: SCIENCE VALUE AND ROLE IN A BALANCED PORTFOLIO

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ANNE R. DOUGLASS, NASA Goddard Space Flight Center
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WILLIAM S. SMITH, ScienceWorks International
EDWARD L. WRIGHT, NAS, University of California, Los Angeles
GARY P. ZANK, University of Alabama in Huntsville

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MIA BROWN, Research Associate
ANESIA WILKS, Senior Program Assistant

MICHAEL H. MOLONEY, Director, Space Studies Board and Aeronautics and Space Engineering Board

[1] NAS, National Academy of Sciences.

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[1] National Academy of Sciences.
[2] National Academy of Engineering.

Dedicated to Neil Gehrels

Preface

In November 2014 the NASA Associate Administrator for the Science Missions Directorate expressed interest in having the National Academies conduct a study of the value of large strategic science missions. In spring 2016 the Space Studies Board was given approval to begin such a study. The Committee on Large Strategic NASA Science Missions1: Science Value and Role in a Balanced Portfolio was established in summer 2016 and held its first meeting in October, its second meeting in December, and its third meeting in February 2017. During these meetings the committee heard from various NASA space science officials as well as persons involved in various large, medium, and small space science missions over the past two decades, many of whom made slide presentations that are available on the committee's website. The committee began drafting its report in January 2017 and submitted it for review in May.

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Stuart D. Bale, University of California, Berkeley,
Robert Bitten, The Aerospace Corporation,
Jonathan B. Blake, The Aerospace Corporation,
Alan Dressler, NAS,[1] Observatories of the Carnegie Institution,
Larry W. Esposito, University of Colorado, Boulder,
Abigail Fraeman, Jet Propulsion Laboratory,
Alexander G. Hayes, Cornell University,
Franklin D. Martin, Aerospace Consultant,
Christopher S. Ruf, University of Michigan,
Harvey D. Tananbaum, NAS, Smithsonian Astrophysical Observatory, and
Warren M. Washington, NAE,[2] National Center for Atmospheric Research.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Ed Crawley of MIT and Martha Haynes of Cornell. Crawley was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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[1] National Academy of Sciences.
[2] National Academy of Engineering.

Contents

Summary

NASA's Science Mission Directorate (SMD) operates dozens of spacecraft performing many different missions. The most high profile of these are the large strategic space science missions often referred to as "flagship" missions. These include missions such as the Hubble Space Telescope and the Chandra X-Ray Observatory, *Curiosity* rover, Magnetospheric MultiScale (MMS), and *Terra* Earth observation satellite. These missions typically are billion-dollar class missions, the most costly, the most complex, but also the most capable of the fleet of scientific spacecraft developed by NASA. They produce tremendous science returns and are a foundation of the global reputation of NASA and the U.S. space program. Large strategic missions are essential to maintaining the global leadership of the United States in space exploration and in science because only the United States has the budget, technology, and trained personnel in multiple scientific fields to conduct missions that attract a range of international partners. A large strategic mission can be a single spacecraft, or coordinated constellation, designed to achieve a set of science goals. All large missions are by definition strategic, but not all strategic missions are large. Large strategic missions are critical for the conduct of space science in each of NASA's four divisions (astrophysics, Earth science, heliophysics, and planetary science) and are required for the pursuit of the most compelling scientific questions.

Large strategic missions are directed by NASA to a specific institution to develop, although their instruments and subsystems are often competed. Large strategic missions tend to

- Focus on reconnaissance and on conducting a broad suite of objectives;
- Have longer lifetimes and sustained attention to details regarding consistency of operations and calibration;
- Operate with an evolving science program that responds to what has been learned as the mission proceeds, as opposed to a more-fixed science program;
- Travel to hard-to-reach destinations or challenging environments; and
- Carry a large number of larger and heavier scientific instruments.

In contrast, smaller missions generally

- Focus on a single objective or on a small number of tightly related objectives;
- Travel to easier-to-reach destinations or to more benign environments; and
- Carry fewer and smaller instruments.

These characteristics for large strategic and medium and small missions are not exclusive. For example, medium-size missions such as NASA's New Horizons spacecraft have traveled to hard-to-reach locations such as the edge of the Solar System. In addition, some medium and small spacecraft have had long lifetimes. But capabilities and lifetimes generally scale with the size and cost of a mission.

In 2016 NASA asked the National Academies of Sciences, Engineering, and Medicine to examine the role of large, strategic missions within a balanced program across NASA SMD space and Earth sciences programs. (The statement of task is included as Appendix E.)

The Committee on Large Strategic NASA Science Missions: Science Value and Role in a Balanced Portfolio met three times, starting in fall 2016 and concluding in February 2017, and heard from NASA officials, the chairs of several previous Academies studies including the decadal surveys, and the managers of both large and smaller NASA space science missions. The committee also requested data from NASA about the cost and productivity of large and smaller missions across all four NASA SMD divisions. Based on the presentations made to the committee by a wide range of representatives from NASA, the scientific community, congressional staff, and others, the committee reached a number of findings and recommendations that are included in this report.

The committee determined that large strategic missions have multiple benefits. These benefits include the following:

- Capture science data that cannot be obtained in any other way, owing usually to the physics of the data capture driving the scale and complexity of the mission.
- Answer many of the most compelling scientific questions facing the scientific fields supported by NASA's SMD, and most importantly develop and deepen humanity's understanding of the Earth, our Solar System, and the universe.
- Open new windows of scientific inquiry, expanding the discovery space of humanity's exploration of our own planet and the universe, and providing new technology and engineering approaches that can benefit future small, medium-size, and large missions.
- Provide high-quality (precise and with stable absolute calibration) observations sustained over an extended period of time.
- Support the workforce, the industrial base, and technology development.
- Maintain U.S. leadership in space.
- Maintain U.S. scientific leadership.
- Produce scientific results and discoveries that capture the public's imagination and encourage students to pursue science and technical careers.
- Receive a high degree of external visibility, often symbolically representing NASA's science program as a whole.
- Provide greater opportunities for international participation, cooperation, and collaboration as well as opportunities for deeper interdisciplinary investigations across NASA science areas.

NASA's current SMD portfolio includes several large strategic missions: Hubble, Chandra, MMS, Terra, Aqua, Aura, Cassini, and Curiosity. It also includes dozens of small and medium-size missions.[1] These small and medium-size missions are usually selected via a competitive process as opposed to being called out as priorities by the decadal surveys in each of the space science disciplines.[2] The large strategic missions are directed to specific institutions for development with major elements and systems competed via request for proposals and the announcement of opportunities as appropriate. Small and medium-size missions can accomplish some of the goals of large strategic missions, such as continuing data collection for a single or small set of instruments. They also have unique benefits of their own, including

- Higher cadence;
- Greater agility and responsiveness to new scientific discoveries; and
- Different acceptance of risk.[3]

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[1] For this study the committee looked at missions currently in operation or development by the Science Mission Directorate (SMD). The committee did some historic budget analysis of large strategic missions back to the late 1960s that is reflected in Figure 1.1.

[2] This committee is addressing the space programs conducted by the four SMD divisions: Astrophysics Science Division, Earth Science Division, Heliophysics Science Division, and Planetary Science Division. The committee's reference to "science disciplines" is based on the general assumption that each of these divisions represents a science discipline. There are other science disciplines, and some overlap, but the categories are relatively distinct.

[3] NASA has different risk acceptance levels for payloads. Class A missions are considered high priority, very low (minimized) risk; Class B missions are considered high priority, low risk; Class C missions are considered medium priority, medium risk; and Class D missions are considered low priority, high risk. Risk level calculations

Smaller missions can often be developed in half a decade (or even less time in the case of the smallest missions), compared to large strategic missions that typically take a decade or more to develop.[4] This makes smaller missions better suited for responding to recent discoveries in some cases. The open competition aspect of smaller missions also encourages ingenuity. Large strategic missions have greater agility and flexibility than small missions to respond to discoveries during the mission (e.g., Enceladus's plume and Titan sea bathymetry for Cassini), while smaller missions have a faster response in terms of development.

The roles of large and small missions are different within each division, however, and are best determined by the decadal survey process. For example, within astrophysics, the "Great Observatories" have offered opportunities for widespread community participation as "guest observers," especially for missions like Hubble and Chandra that have had long lifetimes, although even smaller missions like Fermi have supported guest observers. Earth science has also been able to use its large strategic missions for broad community engagement. For planetary science, large strategic missions like Voyager, Galileo, Cassini, and Curiosity have supported multiple segments of the larger planetary science community, including atmosphere and magnetosphere studies as well as geochemistry and geophysics. Heliophysics has conducted many strategic missions, including Solar Dynamics Observatory (SDO), Van Allen Probes, MMS, Solar Terrestrial Relations Observatory (STEREO), and Voyager (which became a heliophysics mission after completing its planetary encounters). Not all of these have been "large" strategic missions. The longevity of some missions has helped support the heliophysics community.[5] Large strategic missions have also contributed to the development of large data archives that are used by many researchers. The HST's data archive, as one example, has increasingly been used by astrophysicists, who are able to mine nearly three decades of telescope observations.

Large strategic science missions support scientific investigations by teams of scientists and graduate students that support large fractions, in toto, of the research community. As a result, these missions sustain the development and the health of their respective scientific communities in ways that smaller missions cannot. They can also be vital for training new generations of scientists, instrumentalists and engineers, not only during initial mission development, but even when the missions have been operating for many years.

Large strategic missions are highly scientifically productive. Numbers of smaller missions can be scientifically productive as well, and they provide access to a diverse set of scientific questions that cannot all be accomplished with large missions. Smaller missions are often necessary to provide new insights, respond to recent discoveries, and refine the scientific goals of less frequent large strategic missions.

During the course of this study the committee gathered data that indicate that technology development occurs at many levels: large strategic missions, medium-size missions, and even small missions, as well as separate technology development programs. Large missions can have substantial budgets devoted to maturing technologies. In contrast, smaller missions can have faster turnaround times, introducing and maturing technologies at a faster pace. CubeSats are an example of a rapid technology incubator that helps to infuse new technology into the programs, although the benefits and limitations of CubeSats are still being learned. It is also possible for small missions to benefit from technology developed for large missions.

In terms of workforce development large missions are more advantageous than smaller missions primarily because they have the budgets, the scientific breadth, and the longevity to support more

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include such factors as redundancy for critical functions such as communications and propulsion. Large strategic missions are *always* Class A missions. Smaller missions are usually Class B, C, or D.

[4] For example, the initial contract for development of the James Webb Space Telescope was awarded in 2002, and launch is currently scheduled for 2018.

[5] Magnetospheric MultiScale (MMS) was originally proposed in the 2003 heliophysics decadal survey as a "moderate"-size mission. It later increased in cost and is generally considered to be a "large" mission.

researchers. Many small missions support only small teams of researchers and often cannot provide full support even for their principal investigators and co-investigators. In addition many small missions have relatively short lifetimes compared to larger missions, and they may not operate long enough to support researchers, particularly those early in their careers, before the mission expires.

Large strategic missions are critical for balance and form the backbone of the disciplines encompassed by the respective NASA science divisions. However, each discipline values these missions differently, and their valuation evolves as both the science and technology evolve.

RECOMMENDATION: NASA should continue to plan for large strategic missions as a primary component for all science disciplines as part of a balanced program that also includes smaller missions. (See Chapter 1.)

This committee was tasked with addressing "general principles that SMD could use (e.g., a figure of merit approach) to trade off within limited budget between development and operation of large strategic missions and the cadence and/or cost caps of medium-size and small principal investigator (PI)-led mission lines." After much deliberation, the committee concluded that there is no single figure of merit approach that could be developed to apply to all four scientific disciplines. The committee also considered whether it was possible to develop different figures of merit for different disciplines. Although that might be possible, it would require substantial expertise in each of the disciplines, which a cross-disciplinary committee cannot possess but discipline-focused committees could possibly provide.

The committee also determined that it was not appropriate for this committee to seek to supersede the guidance that is already provided to NASA by the decadal surveys. Balance can be decided only by the decadal surveys themselves. Their definition of balance is likely to change over time, and therefore has to be revisited over subsequent decadal surveys, and assessed during the relevant decadal midterm reviews. Furthermore, the definition of balance provided by the decadal surveys is likely the only one that will satisfy a diverse community.

However, the committee concluded that there are many general principles that can be applied to all of the NASA science mission divisions, and this report makes a number of recommendations about them. In particular, the committee was reminded of both the importance and the strength of the decadal survey process for each division, and sought to emphasize that fact and to further buttress the decadal survey process. The committee's recommendations encompass providing better inputs into the decadal surveys and noting that when a decadal survey is insufficient, NASA has other advisory paths to seek specific input—for instance, for reprioritization or redirection of a program during a midterm review. These advisory methods already have credibility, and NASA benefits by relying on them, particularly in unique circumstances where more general guidance may be insufficient. The committee also reaffirmed the value of the better costing mechanisms that NASA has adopted, and has recommendations concerning them as well.

The committee notes that if SMD seeks "general principles" to trade off within limited budget between development and operation of large strategic missions and its medium-size and smaller mission lines, any such principles cannot be too general or they will not be very useful. In addition those principles will be most helpful if they are timely and targeted to the areas most in need of help. NASA's advisory structure at the National Academies was recently revised to enable discipline committees for each of the space science disciplines to respond to the needs of NASA's science divisions in a more timely manner. This and other advisory structure changes could greatly assist NASA in making those required decisions.

RECOMMENDATION: When faced with the requirement to trade off between development and operation of large strategic missions and the smaller missions within their portfolios, NASA's Science Mission Directorate divisions should look first to their relevant decadal surveys and their midterm reviews for guidance. If these are insufficient, the SMD divisions should seek the advice of their relevant advisory groups. (See Chapter 2.)

Balance across the entire NASA science program includes an appropriate mix of small, medium-size, and large missions. The detailed meaning of "balance" for the upcoming decade is defined appropriately by each of the decadal surveys based on the required needs of that discipline for the pursuit of the most compelling science identified by the scientific communities by means of the surveys. For example, the most recent planetary science decadal survey defined a balanced program consisting of one or two large strategic missions, two medium-size New Frontiers missions, and at least three smaller Discovery class missions during the coming decade. Decadal surveys can establish a broader balance that includes scientific capabilities typically provided by other agencies such as the National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey (USGS). The decadal surveys are closer to their subjects and their communities than this study, and the repeating nature of the decadal surveys (as well as their midterm reviews) enables their recommendations to evolve as their discipline evolves. The committee determined that the decadal surveys can best address how large strategic missions will continue to fit into their programs in the future. But the committee determined as well that the surveys also need help to enable them to better evaluate such missions—for example, mission studies prior to the start of a decadal survey.

RECOMMENDATION: In preparation for the decadal surveys, large strategic mission proposal teams should consider describing ranges of scientific scope for their recommended large strategic missions, such as minimum science goals and maximum budgets, as well as identifying what science goals are most desirable at different budget levels. This approach may allow the scientific community and NASA to develop less expensive implementation strategies for mission concepts that do not exceed current budget limitations. (See Chapter 2.)

Science is the primary focus of the decadal surveys, and all of the recent decadal surveys have described in detail the highest priority science questions and frontiers. Although the science questions and opportunity change over time, the technology to address that science changes over time as well.

RECOMMENDATION: Budget constraints should be included in the development of a decadal scientific program. Flexibility in the "decision rules" that decadal surveys produce should allow for both the de-scoping of large strategic missions in the face of cost overruns or insurmountable technical barriers as well as the "up-scoping" of missions as new technological or other opportunities arise. (See Chapter 2.)

RECOMMENDATION: The decadal surveys should formulate mission concept variants or other means to assess the boundaries of cost and technical risk and recommend the application of decision rules to provide flexibility to the NASA science divisions and most importantly the scientific community. This will enable further refinement of mission concepts when pursuing the scientific priorities identified by the decadal surveys. (See Chapter 2.)

RECOMMENDATION: Decadal surveys should be informed by, but not narrowly restricted to, future projections of available budgets. Such flexibility may enable new and potentially revolutionary large strategic missions. (See Chapter 2.)

This flexibility may also help avoid inadvertent programmatic cul-de-sacs if future projections are overly optimistic. Past cost overruns of large strategic missions have had substantial impacts on the other programs in NASA's science portfolio—notably, the James Webb Space Telescope (JWST) and the *Curiosity* rover. (See Figure S.1.)

FINDING: Cost control of large strategic missions remains vital in order to preserve overall programmatic balance. (See Chapter 3.)

It is common for the public, the press, and the scientific community to cite low-fidelity cost estimates *made early in the proposal process*, thus creating a false impression that a mission's costs have grown substantially when the reality is that the early "estimates" were not actual estimates, or were made by project advocates rather than an independent authority. It can be difficult for the agency and a program to overcome this false impression. In the last decade NASA has introduced numerous cost control and cost evaluation mechanisms. As discussed in the body of this report, these mechanisms have been effective at limiting unexpected overruns and impacts on programmatic balance.

RECOMMENDATION: NASA should ensure that robust mission studies that allow for trade-offs (including science, risk, cost, performance, and schedule) on potential large strategic missions are conducted prior to the start of a decadal survey. These trade-offs should inform, but not limit, what the decadal surveys can address. (See Chapter 3.)

Although conducting such studies sufficiently in advance of a decadal survey may not always be feasible, the regular cadence of decadal surveys makes planning for them easier. Implementing them will be less troublesome if the decadals have more useful and earlier inputs.

NASA is often conceptualizing new approaches to increasingly ambitious science missions, many of which are first-of-a-kind, or taking advantage of new architectures or technologies. NASA is expected to push the state of the scientific and technological art and adopt new approaches in order to maximize science return. Cost models, whether empirical parametric tools or analogy-based approaches, are dependent on historical data for systems that have previously flown. New technologies and ways of operating can extend beyond the boundaries of the existing cost databases on which the tools and estimates are based, making it important to constantly revise and develop methods of estimating costs. NASA establishes a project's baseline budget at what the agency designates "Key Decision Point-C" (KDP-C). The formal decision to proceed with a project is made at KDP-C, and the independent estimates made at this point are the only valid ones.

RECOMMENDATION: NASA should continue to use its various cost estimation and cost management tools to assess and control the costs and risks of large strategic missions to ensure that they remain a viable option. As new technologies and new missions arise, new cost estimation tools will be required to enable NASA to determine their likely costs. NASA should support the development of new tools to perform robust cost estimates and risk assessment. These new cost estimation tools will also be helpful in support of the National Academies' decadal surveys. (See Chapter 3.)

New technologies, like CubeSats—particularly in large constellations—will require new methods of cost estimation, some of which are already being developed by industry. Although NASA has gotten better at estimating costs, the agency will have to adapt its methods as technology evolves. This is something that NASA already does—witness the evolution in cost estimation adopted within the past 10 years such as changing the confidence level for estimating new projects—but the committee's point is that as technology advances, cost estimation tools will, and will have to, advance as well.

While cost estimation and control are vital, the committee cautions that cost is best appreciated with respect to performance; many Earth and space science missions have operated long beyond their prime missions, providing tremendous value at relatively low operating costs. The agency deserves credit for enabling their long-term productivity.

This study was commissioned in part to examine and discuss the role and scientific productivity of different-size missions. The committee found this task particularly difficult to perform because of the different roles that missions play in different divisions, and the limitations of available data. However, the committee concluded that it is possible for NASA to make this case itself, by publicly presenting the voluminous data that the agency already collects about the missions it operates, particularly as part of its senior review process for extending missions. The committee notes that data collection on missions has improved substantially, particularly since the implementation of full cost accounting at NASA in the early 2000s. Therefore, much better cost data exists for more recent missions than for earlier missions that may still be operating. This will make it possible for NASA to better present such data in the future.

RECOMMENDATION: In order to demonstrate the role and scientific productivity of large strategic missions in advancing science, technology, and the long-term health of the field, NASA's Science Mission Directorate should develop a publicly accessible database, updated at least annually, that tracks basic data related to all confirmed missions in development as well as operational and past missions from each of the SMD divisions. These data should include development costs; publication numbers and other bibliographic data; outreach data (number of press releases and so on should be tracked); science, engineering, and other full-time equivalents (FTEs); and other routine data typically sought in senior review proposal submittals once prime missions have been completed. These data should be of sufficient detail and quality to enable basic analyses related to scientific productivity and contributions to the health of the respective fields. (See Chapter 4.)

Although it is difficult to collect and interpret historical data for many of NASA's missions, including such information in the database, with appropriate caveats and annotations, could be valuable for providing perspective on NASA's current and future missions. This could include, for example, the cost of servicing the Hubble Space Telescope, because including past data on servicing could be valuable for informing future missions that may include servicing as well. Although the committee acknowledges that establishing such a public database will require effort by NASA, it concluded that this would be useful to the agency in communicating the value and output of its missions as a whole, as opposed to via periodic press releases or at scientific conferences. The agency is in a better position today than it was only a decade ago to accurately report on its mission costs and performance across the entire SMD.

The first task in the committee's charge concerning guiding future prioritization of large strategic space and Earth science missions within a balanced program is addressed in Chapters 1 through 3. The second task, assessing the impact of current and recent SMD missions with a range of life cycle costs, is addressed in Chapter 4, and Appendixes A through D contain information primarily supplied by NASA in response to the committee's request in an effort to address this task. Chapter 1 of this report addresses the current and recent history of large strategic missions in NASA's SMD. Chapter 2 discusses the role that large strategic missions play in achieving balance in each of the four SMD divisions. Chapter 3 discusses the issues of cost estimation and control for space science missions, how the implementation of new procedures and methods has improved these over the past decade, and how cost control is vital to achieving programmatic balance. Chapter 4 addresses issues of comparing large strategic and smaller NASA space science missions in terms of technology development and transfer, workforce training, and scientific productivity.

During its deliberations the committee concluded that whereas some factors such as the cost of a mission are relatively easy to assess (assuming that the data have been collected and are consistent), other factors such as health of a scientific community and scientific productivity of a mission are essentially qualitative, not quantitative assessments. Science that is multidisciplinary, or multiplatform, complicates these measurements even further. In addition, missions with long operational lifetimes create a new dynamic of their own. Take, for example, the HST. Hubble's archive of collected data is now so large that it is being used by increasing numbers of scientists to produce new scientific discoveries. Quantifying the scientific return of a wide range of missions with different characteristics and goals and lifetimes is not an easy task and possibly not an achievable one. Nevertheless, the committee concluded that by supporting the creation of the proper tools, NASA can do a better job of communicating the value of large strategic space science missions.

Overall, the committee was impressed with the agency's extensive portfolio of science missions of all sizes. But it is the large strategic missions that have demonstrated some of the greatest science advances and the capabilities of the United States as a leader in scientific discovery and the exploration of space. Hubble's Deep Field observation and refinement of the Hubble Constant, Cassini's observations of Saturn's rings and Enceladus's plumes, Voyager's multiplanet tour and travel through the heliopause, and Curiosity's explorations of Mars's past habitability rank among the greatest scientific accomplishments of the past several decades and have become synonymous with American accomplishment.

FIGURE S.1 The James Webb Space Telescope at Goddard Space Flight Center. SOURCE: NASA.

1

Introduction

NASA's Science Mission Directorate (SMD) currently operates over five dozen missions, with approximately two dozen additional missions in development. These missions span the scientific fields associated with SMD's four divisions—namely, Astrophysics, Earth Science, Heliophysics, and Planetary Sciences (referred to in this report by the shorthand "space sciences"). Because a single mission can consist of multiple spacecraft, NASA-SMD is responsible for nearly 100 operational spacecraft.[1] Of these many dozens of spacecraft, very few receive significant public and political attention. Those that do tend to be NASA's large strategic missions, often referred to as "flagships."

Many of NASA's large strategic space science missions have become household names, such as the Hubble Space Telescope (HST) or the *Curiosity* rover on Mars. Other large strategic missions are less well known to the public but are famous within their respective scientific communities. These missions have led to many exciting discoveries, reported on in thousands of publications in the past decade. The data from these missions are widely distributed and influential, and are used not only in the United States but also in countries on every continent.

Owing to these achievements, the United States is seen as a leader both in building and in launching innovative, bold space missions and enabling scientific discovery that inspires and engages the public at home and around the world. NASA technical expertise used to develop these spacecraft is sought by other space agencies, leading to joint projects of benefit to all.

FINDING: Large strategic missions are essential to maintaining the global leadership of the United States in space exploration and in science.

In general, in the space sciences, NASA operates "directed" missions that are developed by a NASA center or Jet Propulsion Laboratory (JPL), "competed" missions that are selected as part of a competition and usually include a cost cap, and missions where NASA contributes instruments to spacecraft operated by other agencies of the U.S. government or non-U.S. space agencies. Large strategic missions in astrophysics and Earth sciences have been directed to NASA's Goddard Space Flight Center (GSFC), and planetary missions have been directed to Caltech's JPL, although the Johns Hopkins Applied Physics Laboratory (APL) currently plays a substantial role in the Europa Clipper and is building the Parker Solar Probe.[2] (The Chandra space telescope was directed to the Marshall Space Flight Center.) Although large strategic missions are usually directed, the instruments on these missions may be competed through the use of Announcements of Opportunity (AOs) and as a result, instruments may be developed by other institutions such as universities, research organizations, and other NASA centers. In addition, these major missions are done largely by NASA "out of house," involving job-creating competitive contracts with the

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[1] In some cases NASA uses the term "mission" to refer to space science instruments hosted on non-NASA spacecraft, or on platforms like the International Space Station. The committee is not using "mission" in that way in this report, and the numbers cited here do not refer to these instruments as missions.

[2] The Johns Hopkins Applied Physics Laboratory has played a major role in numerous NASA missions, including most recently the Parker Solar Probe, the New Horizons mission, and the Van Allen Probes. APL is not a NASA center, and most of the missions it has performed for NASA have been competed missions.

aerospace contractor community that often bring their technology, as well as facilities and skill, to these missions.

Competed missions are conducted through a process starting with an AO, and they can be led by non-NASA principal investigators (PIs). Large strategic missions are typically more expensive missions based on high-value science targets that have been identified in the decadal surveys conducted by the National Academies of Sciences, Engineering, and Medicine (National Academies). Competed missions are selected based on science value with a fixed cost cap. Although some competed missions can be of strategic importance to accomplishing science goals, they are not the most expensive missions the agency undertakes, and therefore are not often recognized for their strategic role.

The decadal surveys identify the highest priority science missions, which they generally refer to as "flagship" missions. Flagship missions are usually large and expensive—typically the most expensive mission within their science discipline. Starting around 2014, the SMD began using the term "large strategic missions" in place of "flagship" missions. According to former NASA associate administrator for the SMD John Grunsfeld, the agency introduced the term "large strategic missions" because these missions advance many parts of the science agenda. NASA can also implement "directed" missions that may not have been prioritized in a decadal survey but are considered by agency leadership to be important to agency goals.[3] NASA has a variety of different acquisition approaches and types of space science missions. Although the committee understands what the agency is referring to with the terminology "large strategic missions," it notes that "strategic" can also refer to other missions within the agency's portfolio, and in fact a coordinated campaign consisting of multiple missions—for instance, the multiple NASA Mars spacecraft launched between 1998 and 2011—can serve long-range, overarching strategic goals, such as the search for environments that could support life.

For the SMD, the term "strategic" is not necessarily defined by the size of the missions, but by their relationship to major science goals. Examples of different-size strategic missions can be seen in the James Webb Space Telescope (JWST; over $8 billion), Curiosity (over $2.5 billion), Spitzer (over $720 million), and Deep Space Climate Observatory (DSCOVR; $340 million).[4] DSCOVR was not a prioritized flagship mission, nor a large strategic mission, but nevertheless is strategic and also cost more than many other Earth science missions. According to a NASA official, all large missions are by definition strategic, but not all strategic missions are large.

Although the terminology can seem confusing to outsiders, within the science disciplines most members of the community understand what the largest missions are in terms of cost, and understand what constitute large, medium-size, and small missions within their respective divisions, although they may struggle with the definition of "strategic." Within astrophysics and planetary science, the large strategic missions are usually in excess of $1 billion. Within Earth science and heliophysics, the large strategic missions are usually in excess of $500 million. Within planetary science, "medium-size" missions cost approximately $1 billion, whereas "small" missions cost approximately $500 million. This is in contrast to Earth science and heliophysics, where "small" missions are generally defined as less than $250 million.

According to information presented to the committee by the Science Mission Directorate, over the years missions greater than $1 billion have accounted for approximately 30 percent of SMD's overall budget. About 46 percent of SMD's budget is used for the formulation and development of new missions of all sizes, while about 12 percent goes toward operating extended missions that are regularly reviewed

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[3] An example of a directed mission that was not prioritized in the decadal survey is the Lunar Reconnaissance Orbiter (LRO), which was funded by the Human Exploration Operations Mission Directorate with participation from the Science Mission Directorate. A primary objective of the LRO was to map possible landing sites for future human missions to the lunar surface. When this phase of the mission was complete, responsibility for LRO shifted to the Science Mission Directorate. LRO was therefore a directed mission, serving strategic requirements for human spaceflight.

[4] The Mars Science Laboratory (MSL) was not explicitly prioritized in the 2002 planetary decadal survey as a flagship mission, although it grew into one. But it was identified as a top-priority mission. In 2011 the MAX-C rover was clearly prioritized as a flagship mission.

to ensure relevant and cost-effective science. The remainder of SMD's budget covers a variety of subjects, including non-mission-specific research support.

Although space science missions are usually funded by a single division within the SMD, the SMD has an integrated program that enables scientific findings in the fields of astrophysics, Earth science, heliophysics, and planetary science, with scientists working across disciplines. According to current SMD Associate Administrator Thomas Zurbuchen, the interconnected nature of the SMD programs supports the asking and answering of many questions at the frontiers of the space sciences, and, in addition, the discoveries in one scientific discipline have a direct route/correlation to other areas of study. Indeed, a core aspect of strategic missions in astrophysics, such as Hubble and Spitzer, involves Solar System investigations by planetary scientists. Hubble discovered four of the five moons of Pluto, auroras in Jupiter's atmosphere, and much more. Spitzer discovered the largest ring around Saturn, and both telescopes (including others in astrophysics) have discovered and characterized Kuiper Belt objects (KBOs), dwarf planets, and asteroids; monitored clouds in outer gas giants; monitored the Martian atmosphere; and more. Large strategic missions can also be used to ensure the success of other NASA cross-disciplinary missions. For example, Hubble was key to the success and safety of the New Horizons mission by surveying for possible debris in the vicinity of Pluto that could have impacted the spacecraft. Hubble was also instrumental in finding a KBO target for New Horizons after the Pluto flyby.

There are other missions that also demonstrate this interconnectivity. For example, the Magnetospheric MultiScale (MMS) mission, which is funded within the Heliophysics Science Division, has provided science findings in heliophysics (solar dynamic), but also of value to Earth science, planetary science (history of water on Mars), and astrophysics (stellar formation). The *Juno* spacecraft, currently orbiting Jupiter, was funded within the Planetary Science Division, and is a medium-size mission within the planetary program's context. *Juno* is in the early stages of science operations and may provide individual benefits in the fields of heliophysics (strong magnetic fields and auroras), Earth science (cloud circulation formulation and dynamics), planetary science (water in the Jupiter formation region), and astrophysics (exoplanets). Large strategic missions also can contribute to multiple scientific disciplines and have a greater impact on them because of the amount of data they collect and the size of their science teams.

The committee developed a budget "sand chart" based on data provided to the committee by NASA. The chart shows yearly expenditures for development costs for large NASA missions, corrected for inflation. (See Figure 1.1.) Each band shows the cost of the given mission in fiscal year (FY) 2015 dollars, with the total plot running from FY1969 as projected though FY2026.[5] The chart illustrates that the Viking missions of the mid-1970s (left of chart) represented a substantial expenditure for the agency over a relatively short period of time. The Hubble and JWST missions (at bottom) also represent large budgetary expenditures. According to the committee's calculations, Hubble has been the most expensive large strategic mission developed by NASA when calculating the initial development costs and the development costs for the multiple servicing missions (while excluding launch and operations costs). Also notable is the emergence of several large Earth science missions, such as Terra in the 1990s.

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[5] Accounting changes have been dealt with in this chart as follows: (1) All figures prior to FY2004 include a rough estimate for Civil Service labor (actuals are not broken out in the records). (2) Launch services were not part of the Science budget before FY2000, but good data are available and are included here for each mission. Shuttle launch costs for Magellan, Galileo, CGRO, UARS, Hubble (launch and servicing missions), and Chandra were not consistently estimated and are not included as part of the mission costs here. (3) The "transition quarter" (TQ) between the end of FY1976 and beginning of FY1977 (July 1, 1976, to September 30, 1976), has been absorbed. The large peak in the decade of the 1970s is driven by the design, development, and launch of *Voyager 1* and *2* (to the outer solar system—both spacecraft still operating and returning data) and the *Viking 1* and *2* orbiters and landers to Mars (the *Viking 1* and *2* landers were still operational—the landers continued functioning until the early 1980s, when problems with the batteries on each lander resulted in termination of operations).

The top five missions in FY2015 dollars are (millions): Hubble, $11,288.124; JWST, $8,645.214; Viking, $6,790.746; Chandra, $3,440.968; Cassini, $3,188.699. The next five in order are: Galileo, MSL/Curiosity, WFIRST/AFTA, Europa Clipper (estimated, since the spacecraft has not yet been built), and Terra.

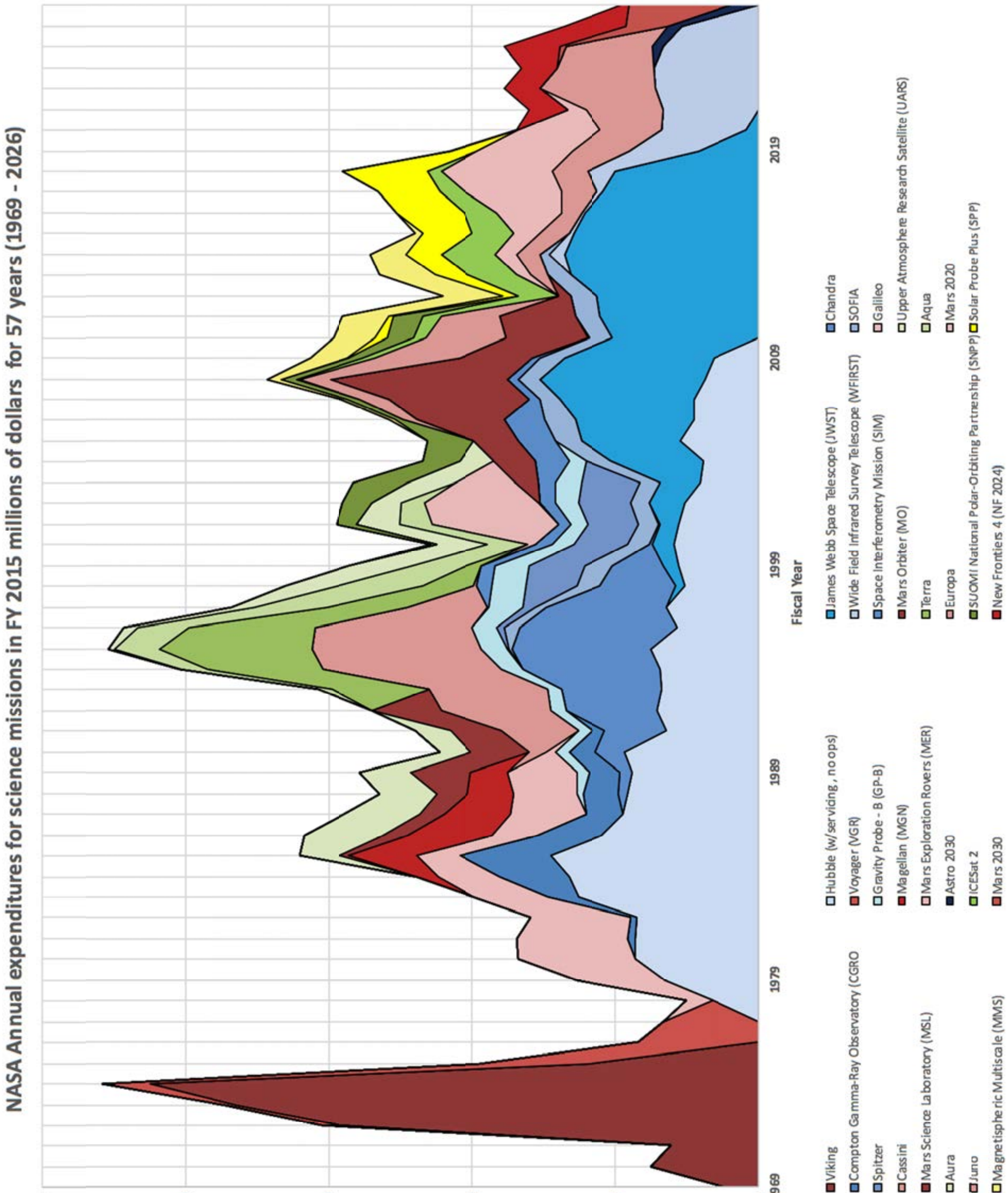

FIGURE 1.1 NASA annual expenditures for large strategic science missions in FY2015 millions of dollars for 57 years (1969-2026).

Each of NASA's four science divisions is currently operating or developing large strategic missions.

ASTROPHYSICS SCIENCE DIVISION

The objective of the study of astrophysics is to further humankind's scientific endeavor to understand the universe and humanity's place in it. Astrophysics seeks to answer questions such as: How did our universe begin and evolve? How did galaxies, stars, and planets come to be? Are we alone?[6]

The current astrophysics mission portfolio includes large and medium-size strategic NASA-led missions, and medium-size and small principal investigator (PI)-led missions. Astrophysics also is involved in supporting PI-led and strategic non-NASA missions.

The total NASA astrophysics budget for FY2016 was $1.33 billion (including the JWST development), with over half allocated toward mission development, and the remaining funds put toward missions in operation, research and technology, and infrastructure and other essentials.

Current astrophysics mission sizes vary greatly depending on the science goals. Small missions within the Astrophysics Science Division are PI-led and are selected through AOs through the Astrophysics Explorers Program (the Explorer program is actually part of the Heliophysics Science Division, and a small number of these missions are devoted to astrophysics); they typically do not exceed $250 million. Large strategic missions are recommended by the decadal survey and cost over $1 billion, the most recent example being the Wide-field Infrared Survey Telescope (WFIRST) mission.

According to the current director of the Astrophysics Science Division, Paul Hertz, within the division there are many benefits of large strategic missions to astrophysics. They have the ability to accomplish science that smaller missions would be unable to fulfill; they can provide general-purpose observatories for the community; and they can drive development of new capabilities that can be infused later into smaller missions without further technical development.

The committee notes that these attributes also generally apply to large strategic missions in fields other than astrophysics, although in astrophysics the "Great Observatories" aspect of such missions—that is, their ability as an ensemble to cover a broad range of wavelengths and to serve multiple users over a long period of time—may be greater than in some of the other science fields. Hertz stressed that large mission costs need to be carefully managed in order to preserve programmatic balance defined by the decadal survey, which is also true of the other divisions.

According to Hertz, large strategic missions should be managed by experienced management teams. These large missions can also provide development training opportunities for people to become principal investigators on smaller missions, instruments, and suborbital investigations. Large strategic missions also offer opportunities for international partnerships. Hertz explained that there is a general expectation within the astrophysics community that future large strategic missions will be the result of international collaboration, but there is no similar expectation for small and medium-size missions.

The instruments of large strategic missions are analogous to Explorer-class programs at universities. These are coherent $100+ million projects that combine science, engineering, and technology, largely developed at U.S. universities and other research institutions through PI teams involving faculty, postdoctorate candidates, and students. These instruments are an excellent method for training students.

Currently, the Astrophysics Science Division operates both the Hubble and Chandra missions, the Spitzer Observatory, as well as the airborne Stratospheric Observatory for Infrared Astronomy (SOFIA). It is also developing both the JWST and the WFIRST. Hubble was a decadal survey priority and was launched in 1990 and has become one of the most visible science programs in the world. Its science achievements span most of modern-day astrophysics and include countless discoveries that were not envisioned by its designers. The Hubble program has produced over 14,000 refereed science publications

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[6] Presentation by Paul Hertz, Astrophysics Science Division, NASA, to the Committee on NASA Large Strategic Space Science Missions, October 5, 2016.

with more than 600,000 citations. Hubble remains one of SMD's most scientifically productive missions, with 881 papers published in 2016, higher than any other year. There are more than 1000 research proposals being received each year at an oversubscription rate of 5:1 and an orbit oversubscription rate of 7:1 in 2016. There have been more than 15,000 users of the observatory.[7]

Guided by the science prioritization in the decadal surveys, large strategic missions in astrophysics drive the development of new and ambitious technologies. These are achieved through partnerships between NASA, industry, and academia. For example, for JWST, there were 10 technologies successfully invented to achieve the mission's design requirement. This includes the first space-based multi-object spectrograph with 250,000 shutters, segmented beryllium mirrors with nanometer precision, tennis-court-size sunshields to achieve hundreds of degrees of passive cooling, ultrasensitive infrared detectors, and more. Many of these technologies also have spinoff applications in aerospace, commercial research, and medical fields (i.e., the treatment of laser eye surgery and diagnosis of ocular diseases has been improved due to the application of JWST wavefront sensing techniques). Similarly, the future large strategic mission WFIRST is creating state-of-the-art light suppression techniques to directly image exoplanets that are one billion times fainter than their host stars. Although the Astrophysics Division has its own technology development program, it can also directly involve NASA's Space Technology Mission Directorate and often benefits from industrial partnerships where there is heritage of new technologies that have been successfully applied to non-NASA programs. The opportunity to create these technologies and apply them to future science missions (large or small) rests largely with the strategic missions. Smaller astrophysics programs are not expected to develop such new technologies, although they sometimes do so if necessary. The Astrophysics Science Division funds technology development via separate methods, including AOs.

EARTH SCIENCE DIVISION

The Earth Science Division provides critical insight into understanding the Earth as an integrated system, and for developing and testing applications to deliver direct societal benefit. There are four major components to the Earth Science Division: measurements, research, societal benefit and capacity building, and technology development.[8] The measurement component refers to the ability to monitor and observe the Earth and environment from space, which advances science, develops applications for societal benefit, and supports other mission agencies. The research component furthers the understanding of the Earth as an integrated system through research that is multidisciplinary and uses all relevant measurements (not limited to satellites). The societal benefit and capacity building component of the Earth Science Division develops and tests new information products, which are tailored to the needs of end users, and increases users' capacity to exploit the information. Finally, technology development advances instruments, information systems, and communications technologies that support new missions, research, and applications.

The Earth Science Division received $1.92 billion in FY2016. Currently, the division has several large strategic science missions in operation: the Aura, Aqua, and Terra missions. All three were implemented as part of the Earth Observing System (EOS) in the late 1980s, with launches starting in the late 1990s. A more recent example of a large mission is the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) Mission, which will use advanced ocean color and polarimetric technologies to understand and quantify global ocean biogeochemical cycling and ecosystem function in response to anthropogenic and natural environmental variability and change. The mission will allocate approximately $705 million to mission/project implementation and $100 million to science.

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[7] Space Telescope Science Institute, Summary 2016 Annual Report, p. 2, http://www.stsci.edu/institute/annual-reports/2016-annual-report.pdf.

[8] Presentation by Earth Sciences Division Director Michael Freilich to the Committee on Large Strategic NASA Science Missions, October 5, 2016.

The Earth Science Division has shifted its focus to development of smaller missions. According to Michael Freilich, the director of NASA's Earth Science Division, large strategic missions are not essential for the division's future work. A broad portfolio of smaller missions—launched, flown, and analyzed in coordinated and integrated ways—allows for optimization of resources and flexible provision of capabilities to achieve scientific objectives. For example, Ice, Cloud, and land Elevation Satellite (ICESat) and Soil Moisture Active Passive (SMAP) are strategic in the sense that they acquire needed information to fulfill important science objectives. In the case of SMAP, it was initially proposed as an Earth System Science Pathfinder (ESSP) mission with a cost cap in the $300 million range but was deemed important enough to warrant more investment.

According to NASA the capabilities provided by multiple smaller missions can be adjusted in an iterative fashion, providing mission implementation flexibility. However, it is not clear if this approach will support the extended investments over time across multiple Earth Science subdisciplines required to meet Earth science objectives related to high accuracy long-term trending and investigations into coupling and feedback mechanisms across the Earth system. As discussed in Chapter 2, the committee concluded that this is a subject that the current Earth science decadal survey is best equipped to address.

In recent years the Earth Science Division has also begun to explore smaller capabilities to conduct critical measurements. An example of a small satellite Earth Science mission is the Cyclone Global Navigation Satellite System (CYGNSS) (Figure 1.2). This mission comprises an 8-satellite microsatellite constellation that measures air-sea interactions in tropical storms using reflected GPS signals to achieve the horizontal coverage that is required to address scientific questions concerning hurricane formation and intensification. Another example is the Time-resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats (TROPICS), which is a 12-satellite CubeSat constellation and the first science-focused CubeSat constellation, now in development. Both of these missions have been developed under the Earth Ventures (EV) program.

FIGURE 1.2 One of the CYGNSS spacecraft during assembly. SOURCE: NASA.

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The ESSP program provides periodic opportunities to address new and emerging science priorities defined by the decadal surveys. ESSP missions are now part of the EV class of missions defined as being competitively selected, relatively low to moderate cost, and small to medium-size. They can be full orbital missions, instruments for orbital missions of opportunity, or suborbital projects. ESSP projects are high-return Earth science missions that include advanced remote sensing instrument approaches to achieve science priorities and can include partnerships with other U.S. agencies or international scientific research and space organizations. There are legacy ESSP projects selected under prior AOs in operation that do not perfectly align with the Venture Class concept as it is currently being implemented. These are noncompetitive, directed projects that are designed to meet unique needs. Examples of such missions include Aquarius, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), CloudSat, and Gravity Recovery and Climate Experiment (GRACE), which are all in extended operations; OCO-2 (Orbiting Carbon Observatory), still in its prime mission; and OCO-3, which is in formulation.

Large strategic missions are not typically used for technology development in the Earth Science Division. Instead, technology development is conducted in the Earth Science Technology Program (ESTP). Smaller missions can also provide opportunities for technology development. Currently, the Earth Science Technology Office (ESTO) has a separate technology development line with a budget of approximately $60 million per year. The development of Earth science technology within the ESTP plays a critical role in enabling Earth science research, applications, and flight missions. ESTO also enables new science investigations, improves existing measurement capabilities, and reduces the cost, risk, and development time of Earth science instruments and information systems. ESTO performs analysis of science requirements for technology needs, selects and funds technologies through competitive solicitations and partnership opportunities, actively manages funded technology development projects, and facilitates the infusion of mature technologies into science campaigns and missions.

HELIOPHYSICS SCIENCE DIVISION

Heliophysics can be defined as humankind's scientific endeavor to understand the Sun and its interactions with Earth and the Solar System. Questions that may be addressed by heliophysics include: What causes the Sun to vary? How do the geospace and planetary space environments and the heliosphere respond? What are the impacts on humanity? Heliophysics is a complex and sophisticated field that needs to be studied as a coupled system, which involves the different subdisciplines of heliophysics and how they interact and cause feedback with each other. For example, the Earth's ionosphere and magnetosphere are very closely coupled. To understand what is happening with the ionosphere requires studying the Sun to understand the solar wind and how it interacts with the magnetosphere.

NASA's enacted Heliophysics Science Division budget for 2016 was $649.8 million. Over half of the heliophysics budget (55 percent) is spent on development. Research, operating missions, and suborbital costs are each around 11 to 12 percent of the budget. The remaining 11 percent is spent on missions in the primary science phase, management, and data systems.

The Magnetospheric MultiScale mission (MMS), launched in 2015, uses four identical spacecraft flying in formation to examine the Earth's magnetosphere. It is an example of a currently operating large strategic mission in heliophysics. (See Figure 1.3.) Two large strategic heliophysics missions now in development are the Parker Solar Probe and the European Space Agency (ESA)'s Solar Orbiter, which includes NASA participation. The Parker Solar Probe, which is scheduled for launch in 2018, will make multiple close flybys of the Sun. It will employ a combination of in situ measurements and imaging to achieve the mission's primary scientific goal of understanding how the Sun's corona is heated and how the solar wind is accelerated.

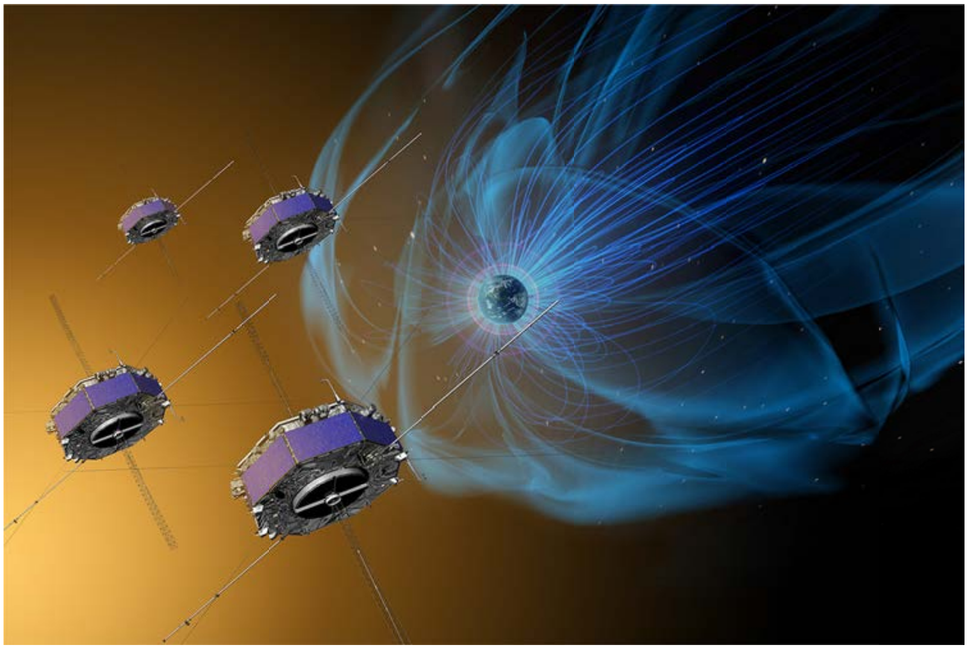

FIGURE 1.3 Artist concept of the MMS spacecraft constellation. SOURCE: NASA.

The Solar Orbiter Collaboration project will examine how the heliosphere is created and controlled by the Sun. The spacecraft will gather information about the Sun's magnetic field, solar energetic particles, the solar wind, the heliospheric magnetic field, and transient interplanetary disturbances. This project is a collaborative effort between NASA and ESA.

Currently, the size of heliophysics missions can vary and depend on a multitude of factors. There are small competitive missions of opportunity, small explorers (SMEXs), and medium explorers (MIDEXs). MIDEX missions range from $180-$200 million. The Solar Dynamics Observatory (SDO), launched in 2010 and costing $810 million, is an example of a large strategic mission, as is the Van Allen Probes mission, launched in 2012. The Heliophysics Division has also made investments in smaller spacecraft, such as MinXSS (Miniature X-Ray Solar Spectrometer) and CuSP (CubeSat to study Solar Particles), as precursors to future multipoint measurements of the interplanetary space environment and its impact on Earth.

Compared to the other NASA science disciplines, within the heliophysics field much training and education is accomplished with small Explorer-class and even suborbital flights. In addition, the heliophysics discipline includes ground-based solar observatories that can also provide training and education opportunities. Although these are not within NASA's portfolio, they do affect the overall health of the heliophysics community. Those observatories can in some cases rival the cost of smaller space missions, but are not funded by NASA.

PLANETARY SCIENCE DIVISION

The primary goal of planetary science is to ascertain the content, origin, and evolution of the Solar System and the potential for life elsewhere.[9] NASA currently operates spacecraft in orbit around the

[9] Presentation by Planetary Science Division Director Jim Green to the Committee on Large Strategic NASA Science Missions, October 5, 2016.

Moon, Mars, Jupiter, Saturn, and the minor planet Ceres. The agency also has two rovers operating on Mars, and the *New Horizons* spacecraft heading toward a rendezvous with a Kuiper Belt object (KBO).[10]

Cassini is one of two operating large strategic missions in planetary science. The spacecraft has been orbiting Saturn since 2004 and is scheduled to end its mission in September 2017. There have been over 5,250 publications based upon the Cassini mission, including its Huygens Titan probe mission. In addition to Titan the Cassini mission has also conducted critical studies on Saturn's moon Enceladus.

The Mars Science Laboratory (MSL)/Curiosity program is a large strategic mission that has made many contributions to the planetary science field, particularly within the global mineralogical and geomorphological context provided by the last 20 years of remote sensing and landed missions at Mars. *Curiosity* has identified a clearly habitable environment with the necessary ingredients for life, demonstrated the first radiometric age dating of exposure ages of Martian rocks, constrained deuterium/hydrogen ratios of ancient Martian water, and identified unexpected (and unexplained) variability in methane concentrations over time. (See Figure 1.4.)

FIGURE 1.4 The *Curiosity* rover on Mars. SOURCE: NASA.

The Mars 2020 rover currently in development is an international collaborative program that includes instruments from France, Spain, and Norway. The other large strategic mission in development is the Europa Clipper mission scheduled for launch in 2022, which is planned to make multiple flybys of Jupiter's moon Europa.

The Planetary Science Division also operates the Discovery and New Frontiers program lines. The Discovery program was established in 1992 and had a cost cap of $450 million per mission (excluding the launch vehicle) in FY2015 dollars for the most recent announcement of opportunity. Discovery is an open science competition for all Solar System objects except the Earth and the Sun. The New Frontiers program was established in 2001 and has a cost cap of $850 million per mission (excluding launch vehicle). Both of these programs address high-priority science objectives in Solar System exploration. The planetary science division is also investigating the potential of small satellite missions to meet some

[10] Kuiper Belt objects (KBOs) orbit the Sun at the edge of the Solar System, from the orbit of Neptune at 30 astronomical units (AU) out to 50 AU.

exploration goals. Under the NASA Planetary Science Deep Space SmallSat Studies (PSDS3) program, 10 studies to develop mission concepts using small satellites to investigate Venus, Earth's moon, asteroids, Mars, and the outer planets were selected. The total value of the awards is $3.6 million, where flight systems are defined as less than 180 kilograms.

The Planetary Science Division's large strategic missions can support technology development, although the division's goal is to support technology development via other methods than in the programs. The division uses targeted instrument calls and a mid-Technology Readiness Level (TRL) technology call, which are funded by the Research and Analysis (R&A) program to help both strategic and PI-led missions. PI-led mission proposals requiring new technology development are typically not considered. The Planetary Science Division has a separate technology development program and also seeks to benefit from projects funded by NASA's Space Technology Mission Directorate. Some newly developed technology has been transferred from separate development programs into operational missions. However, the need to be competitive has also driven PI teams to propose missions containing no new technology. The Planetary Science Division has thus sought opportunities to make new technology attractive to proposal teams.

According to the head of the Planetary Science Division, Jim Green, there have been clear differences in cost overruns between large strategic missions and smaller class missions. In the past large strategic missions were typically considered too scientifically important to cancel, depending on when the cost overrun occurs, and overruns need to be handled through de-scopes and replanning (cost and schedule readjustments). But from the start of the Mars 2020 rover program a cost cap concept was developed and used for strategic missions for the Planetary Science Division. This approach is also being applied to the Europa Clipper mission. The basic concept is to limit a strategic mission's ability to affect other missions in the division's portfolio and manage them like a PI-led mission. Smaller, PI-led missions have a cost cap and are usually terminated if there are significant cost overruns before confirmation. Examples of canceled small missions include the Clark Earth science mission, and the GEMS, FAME, and SPIDR Explorer missions. (The issue of cost estimation and overruns is addressed in Chapter 3.)

THE DECADAL SURVEYS AND LARGE STRATEGIC MISSIONS

The National Academies undertakes the decadal surveys in each of the four space science disciplines. NASA uses the decadal surveys to guide its programs, particularly new mission development and new science explorations. All of the decadal surveys have prioritized large strategic science missions and they may be explicitly directed to do so in their statements of task.

In 2015 the National Academies produced a study of its most recent decadal surveys. The report, *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, outlined the importance of large strategic missions for each of the space science divisions. The report stated that the costs of such missions and facilities have increased, posing a substantial challenge for future decadal surveys.

Among the questions that the study addressed were the following:

- How can robust evaluations of the costs of such missions be made, and cost growth be contained, to protect other missions and activities?
- How can multi-decade programs be managed successfully?
- How might we protect important human resources—for example, the education and research support of the next generation of scientists, especially those with skills in technology development?

The report stated the positives related to high-profile, strategic missions. Large strategic missions can have large-scale impacts by addressing critical science goals or questions for the decade. Large strategic missions continue to be critical to their scientific disciplines because certain missions cannot simply be broken down in an efficient or effective manner into smaller components and still accomplish the science goal.

The characteristics of these large-scale missions are unique, and they follow an implementation strategy that is performance driven rather than cost constrained. This is in contrast with PI-led cost-capped missions where de-scopes are required if a performance requirement cannot be met within preestablished cost constraints (in fact, many PI-led missions require a de-scope plan at their initiation, indicating which instruments or functions will be eliminated to keep a mission within the cost cap). Because a large part of science research originates in smaller missions, the decadal surveys attempt to strike a balance between larger, noncompeted, high-profile missions and the competed line of smaller missions. (The issue of balance is discussed in Chapter 2.)

The report concluded that based on the contributions seen from various missions across the disciplines, large strategic missions are important and critical for advancing science. The report also noted that the importance of large strategic science projects is not unique to space science. For example, Fermilab, the Large Hadron Collider, and the Laser Interferometer Gravitational-Wave Observatory (LIGO) have all made significant contributions to fundamental physics, and ITER is a major project in applied physics. Their investigations could not have been accomplished at smaller scales.

While there are many positives that derive from large strategic missions, the report also discussed and summarized the challenges they may face. The main challenges come from difficulties in the organization, management, building, and operation of an unprecedentedly complex machine. Often large strategic missions become what the report referred to as "high-profile missions." These are missions of significant importance to a program and can have substantial negative impact on program health if not implemented successfully or within fiscal constraints. (See Box 1.1.) Their importance to the community's science ambitions means that large strategic missions have the potential for a significant negative impact on performance across all activities within a division, and possibly across the SMD.

BOX 1.1
The James Webb Space Telescope

The James Webb Space Telescope (JWST) will be the most powerful telescope ever launched into space. (See Figure 1.5.) JWST is a deployable telescope with four complex science instruments optimized for infrared astronomy. These instruments include multiple imaging, spectroscopic, integral field unit, and coronagraphy modes. The mirror of the telescope is 6.5 meters in diameter, 7 times larger in area than Hubble. The observatory will operate at cryogenic temperatures and will orbit at L2, a million miles from Earth.

JWST is designed to find the "first light" in the universe from the very first stars and galaxies after the Big Bang, to trace the evolution of galaxies across cosmic time, to reveal newborn stars and planets enshrouded in their dust clouds, and to provide the first spectroscopy of rocky exoplanets to determine their atmospheric composition. These foundational science themes and JWST's sensitivity, resolution, and multiplexing are revolutionary for science programs across the entire spectrum of astrophysics.

The telescope was first prioritized in the 2001 astrophysics decadal survey *Astronomy and Astrophysics in the New Millennium*. The initial cost discussions for JWST were on the order of $500 million to $1 billion. These estimates were unreliable and later served as a motivation for producing more robust cost estimates prior to decadal surveys. By 2009 NASA began requesting more money to cover cost increases for the telescope. This led to an independent assessment: the James Webb Space Telescope Independent Comprehensive Review Panel (ICRP) published a report in October 2010. The review found that baseline funding for the 2008 confirmation review was "flawed." The report also found that "the project budget presented for confirmation contained no allowance for known threats." The report also concluded that the cost growth and schedule delays were mainly due to budgeting and program management and were not a result of technical performance.

The report stated that "NASA management thought there was a 70% probability of launching in June 2014 at a total lifecycle cost of nearly $5 billion with confirmation budget profile. In fact, the project had no chance of meeting either the schedule or the budget profile." As a result of the report, JWST was restructured and designated as an "agency-wide priority mission." Funding was moved from the Astrophysics Science Division into a separate JWST funding compartment within the SMD.

The James Webb Space Telescope is a recent instance of a large strategic mission that received significant political and public attention after it experienced substantial cost growth. The large increase in costs for the mission had an impact on the entire astrophysics program—as well as the SMD as a whole—and delayed launch by many years. JWST produced many lessons learned, including the requirement to mature technology early in development, the need for early de-scope of the mission to effectively assess requirements, and a need for adequate budget reserves on a year-by-year basis.

Since the ICRP report, over six years of extremely complex manufacturing, state-of-the-art integration, and large cryogenic testing campaigns, the project has remained on schedule and budget and is set to launch in 2018, at a total cost of $8 billion up to launch and an $8.8 billion life cycle cost. (Including contributions from the European and Canadian Space Agencies, the total cost of JWST is approximately $10 billion.)

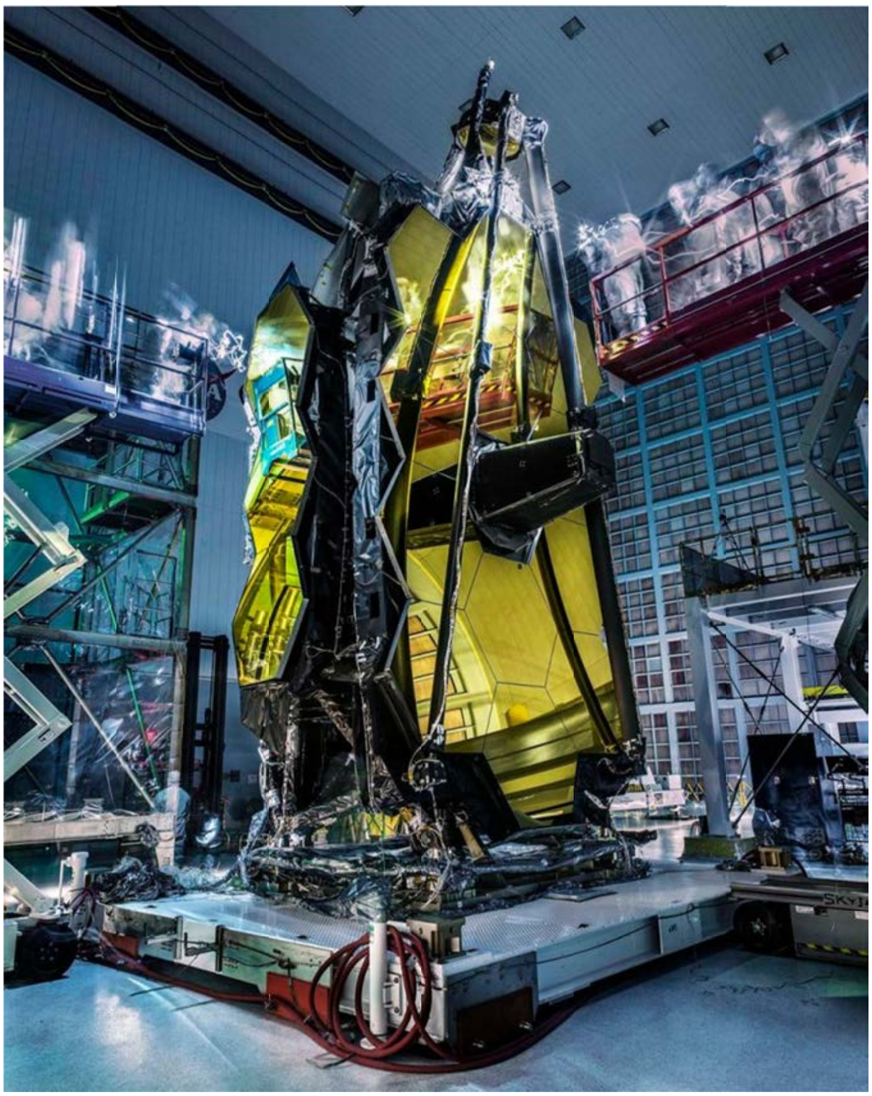

FIGURE 1.5 The James Webb Space Telescope undergoing testing at the Goddard Space Flight Center in March 2017. SOURCE: NASA.

END BOX 1.1

INTERNATIONAL COOPERATION AND LARGE STRATEGIC MISSIONS

It is common for NASA to engage international partners in the development and operation of its large strategic missions. Both the HST and the JWST have included international partners who have provided support in return for observing time on the telescope. The Cassini-Huygens mission included the ESA Huygens probe that descended to Titan in January 2005. Conversely, the United States will participate in the European Euclid dark energy mission and will contribute three detector systems for the spacecraft's near-infrared instrument. These are only a few examples, and international cooperation is common for NASA space science missions of all sizes.[11]

NASA currently has international partnerships on smaller missions, including competed missions. Large strategic missions offer greater opportunity for international participation in some instances because the spacecraft carry more instruments, some of which could be contributed by international partners. They also are higher profile and more attractive missions for potential partners. For example, the ability to gain observing time on a world-class space telescope appeals to astrophysics communities around the world.

International participation in a large strategic mission can create complications, but it also has advantages. One obvious advantage is that including international partners in a mission that the United States initiates, develops, and is responsible for demonstrates U.S. leadership in the field. Practically by definition, leading requires partners. But equally important, such partnerships also enable NASA to access scientific capabilities and expertise around the world, potentially including some that the United States may not possess itself.

Because of the intricacies of international affairs, cooperative agreements have usually been negotiated on a "no exchange of funds" basis, with the cooperation taking the form of an exchange of services or equipment. For example, the JWST will be launched on a European-supplied Ariane 5 rocket, and the Huygens probe was supplied by the ESA. In practice, NASA, ESA and other space agencies have approached international collaboration on large strategic missions such that that one partner is a clear leader and the other partners play a supporting role. This approach allows clean management interfaces and unambiguous decision making and accountability.

At least one manager of a large strategic mission noted that the international partnership made their mission less vulnerable to cancellation. The committee heard no evidence indicating that international partnerships can reduce the cost of a mission, and the transaction costs for partnerships are difficult, perhaps impossible to measure. But as one NASA official noted, there is often an expectation within the scientific community that any large strategic mission will have a substantial international component.

THE VALUE OF LARGE STRATEGIC SCIENCE MISSIONS

Although each of NASA's four science divisions has different requirements for and experiences with large strategic missions, it is possible to generalize their roles across all four divisions. Large strategic missions and small competed missions have different purposes. Large strategic missions tend to

- Focus on reconnaissance and on conducting a broad suite of objectives;
- Have longer lifetimes and sustained attention to details regarding consistency of operations and calibration;
- Operate with an evolving science program that responds to what has been learned as the mission proceeds, as opposed to a more-fixed science program;
- Travel to hard-to-reach destinations or challenging environments; and
- Carry a large number of and larger and heavier scientific instruments.

[11] For further information, see *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*, The National Academies Press, Washington, D.C., 2011.

In contrast, smaller missions generally

- Focus on a single objective or a small number of tightly related objectives;
- Travel to easier-to-reach destinations or to more benign environments; and
- Carry fewer and smaller instruments.

A strategic mission that can achieve an order of magnitude gain in capability (e.g., sensitivity, resolution, field of view, wavelength coverage, multiplexing) can tackle foundational research questions and open new discovery space. Large strategic missions provide unique opportunities to perform critical scientific observations. Large strategic missions are one approach to achieve such goals, but challenges of complexity, expense, and cadence have drawn interest within the science community to explore emerging alternative small and medium-size mission designs, and in some cases some science questions require small spacecraft. Technology and capability advancements are rapidly changing how unique scientific measurements can be performed, where small and medium-size missions are emerging as competitive ways to contribute to critical scientific measurements. The ability to lead small and medium-size missions is compelling for the recent generation of scientific investigators, and the level of creativity within this community to conceive new, unique, and critical measurements (independent of what a large mission may be capable of performing) is growing rapidly.

The committee heard from congressional staff that an additional difference between large strategic "flagship" missions and medium-to-small-size missions is that the large missions are usually the only ones that members of Congress are familiar with and get engaged with. Smaller-size missions are below a budget and prestige threshold for them.

FINDING: Large strategic missions have multiple benefits. These benefits include the following:

- Capture science data that cannot be obtained in any other way, owing usually to the physics of the data capture driving the scale and complexity of the mission.
- Answer many of the most compelling scientific questions facing the scientific fields supported by NASA's Science Mission Directorate, and most importantly develop and deepen humanity's understanding of the Earth, our Solar System, and the universe.
- Open new windows of scientific inquiry, expanding the discovery space of humanity's exploration of our own planet and the universe, and providing new technology and engineering approaches that can benefit future small, medium-size, and large missions.
- Provide high-quality (precise and with stable absolute calibration) observations sustained over an extended period of time.
- Support the workforce, the industrial base, and technology development.
- Maintain U.S. leadership in space.
- Maintain U.S. scientific leadership.
- Produce scientific results and discoveries that capture the public's imagination and encourage young scientists and engineers to pursue science and technical careers.
- Receive a high degree of external visibility, often symbolically representing NASA's science program as a whole.
- Provide greater opportunities for international participation, cooperation, and collaboration as well as opportunities for deeper interdisciplinary investigations across NASA science areas.

Although it is possible for smaller missions to provide some of the benefits in the preceding list, large strategic missions are more likely to provide more of them due to their more challenging goals, their larger size (i.e., supporting more instruments), and larger budgets.

Each division has different mission sizes in terms of cost, and therefore what qualifies as "small" in one division might qualify as a large mission in another. The best evaluation of mission sizes is within the respective division relative to the division's total budget.

FINDING: Small and medium-size missions can accomplish some of the goals of large strategic missions. They also have unique benefits of their own, including

- Higher cadence;
- Greater agility and responsiveness to new scientific discoveries; and
- Different acceptance of risk.[12]

The open competition aspect of smaller missions also encourages ingenuity. There have been dramatic capability improvements in what small and medium-size missions can accomplish, particularly within the last few years. Nevertheless, large strategic missions remain vital to all of NASA's space science disciplines because these lie at the cutting edge of the possible.

In the past decade there has been dramatic growth in the capabilities of small satellites, often generically referred to as CubeSats, but including both smaller and larger satellites than the formal CubeSat definition. This improvement in capabilities has created the impression among some people that large spacecraft are no longer required for the space sciences. But in many fields of space science, large spacecraft represent the only way to answer the most important and challenging questions.

In 2016 the Academies produced the report *Achieving Science with CubeSats: Thinking Inside the Box*, which noted that many high-priority science investigations of the future will require data from constellations or swarms of 10 to 100 spacecraft. The report noted that in the past, large constellations of satellites were prohibitively expensive, but that this may be changing. In the near future, constellations of many small satellites collectively addressing important strategic science goals will qualify as "large strategic missions." The committee concluded that this will be particularly true for heliophysics and Earth sciences. These scientific communities are already discussing future mission proposals of this type, and CubeSats can be useful for training future generations of scientists and engineers.

RECOMMENDATION: NASA should continue to plan for large strategic missions as a primary component for all science disciplines as part of a balanced program that also includes smaller missions.

Any focus on missions by their size, complexity, and cost naturally leads to questions about how to accommodate the largest missions without draining all available resources for other smaller-size missions. That requires a discussion of the proper balance between large and small missions and how to achieve such balance, particularly when resources become constrained. That is the topic of the next chapter.

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[12] NASA has different risk acceptance levels for payloads. Class A missions are considered high priority, very low (minimized) risk; Class B missions are considered high priority, low risk; Class C missions are considered medium priority, medium risk; and Class D missions are considered low priority, high risk. Risk level calculations include such factors as redundancy for critical functions such as communications and propulsion. Large strategic missions are always Class A missions. Smaller missions are usually Class B, C, or D.

2

Balancing Strategic Missions

As noted in Chapter 1, NASA's Science Mission Directorate (SMD) is divided into four divisions. Each division has different requirements and approaches to large strategic missions and to how their large strategic missions compare to smaller missions within their portfolio.

Generally, the Astrophysics Science Division and Planetary Science Division have similar approaches toward large strategic missions. For these divisions, large strategic missions are a major portion of their budgets and science observations, and their scientific communities believe that such missions are vital to making the greatest advances within their fields. The Heliophysics Science Division and Earth Science Division are more similar to each other in their approaches to and requirements for large strategic missions, although this has evolved over time. For heliophysics the spacecraft have tended to be small and medium-size, in part because a major goal for the discipline is to make simultaneous multiple measurements of many different phenomena over a long period of time, and heliophysics instruments can be smaller and less expensive. For Earth science, most scientific observations are conducted from low Earth orbit and the spacecraft have similar operating environments. However, although both heliophysics and Earth science generally rely more on smaller missions than large strategic missions than astrophysics and planetary science, they *have* operated large strategic missions, and these missions, as well as future ones, are still considered by some members of their communities to be vital for some major scientific breakthroughs in their respective fields. Furthermore, both Earth science and heliophysics are likely to operate constellations of multiple smaller spacecraft pursuing strategic science goals and having the cost and complexity common to large strategic missions.

This chapter discusses the role of large strategic science missions in each of the four divisions, examines a specific example for each, and discusses the respective roles played by smaller missions in the divisions. (Note that a list of acronyms is included as Appendix G.)

THE IMPORTANCE OF BALANCING LARGE, MEDIUM-SIZE, AND SMALLER MISSIONS WITHIN THE DIVISIONS

The concept of "balance" has evolved as a vital part of the recommended programs within each NASA science discipline.[1] "Balance" is a subjective term that can have many nuances, but the committee has adapted and expanded the definition as used in the recent report *New Worlds, New Horizons: A Midterm Assessment*, which "interprets balance to refer to a viable mix of small, medium, and large initiatives on the ground and in space that optimizes the overall scientific return of the entire U.S. astronomy enterprise viewed collectively. It does not refer to a balance of wavelengths, nor of astronomy subtopics."

As that report stated: "Decadal surveys also attempt to establish an optimal balance of programs and activities. First and foremost, a discipline strives to achieve balance among its different scientific areas so that even if one or more of the sub-disciplines has gained priority through the survey process, the others

[1] See *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, The National Academies Press, Washington, D.C., 2015, pp. 58ff.

are able to continue to do important science, maintain technical expertise, and, most importantly, attract good students. It is also desirable and necessary to have a component of exploratory science to complement the more common goal-oriented approaches that push particular parts of the discipline forward." The committee fully agrees with this statement. This committee similarly interprets "balance" to mean a viable mix of small, medium-size, and large missions that optimizes the overall scientific return of the entire science program within each respective NASA-SMD division.

A portfolio that contains only large initiatives is not as sustainable scientifically or economically. Large strategic missions may directly impact the ability to maintain a balanced portfolio because single missions may place high demands on personnel resources, facilities, or funds. "Balance" is a multifaceted term that includes cost, number of missions, priority, and cadence. Thus, a balanced portfolio reflects how these factors form a successful observational program, providing mission flexibility for program managers. In order to understand balance, it is necessary to look over a period of time, because implementation of new projects can make a program appear to be unbalanced for short periods (i.e., less than five years). Small and medium-size missions are also essential elements of a balanced portfolio. As noted in Chapter 1, they can provide vital observations that guide the development, and the science observations, of larger missions.

Such considerations of balance have played a prominent role in all of the recent decadal surveys and have served community and other stakeholder interests and NASA planning well. Key to such implementation is an adherence to budgets during project and program development—a subject that is further discussed in Chapter 3.

ASTROPHYSICS SCIENCE DIVISION

Astrophysics has traditionally depended on large strategic missions for most of its major scientific advances. NASA's Great Observatories program established in the 1980s was centered on the development of several large strategic missions: the Hubble Space Telescope (HST), the Compton Gamma Ray Observatory, the Spitzer Observatory (CGRO), and the Chandra X-Ray Observatory. (Spitzer's original development cost was over $2 billion, but because of redesign, it was reduced to approximately $720 million, making it a medium-size strategic mission.) Large strategic missions in astrophysics have made many of the biggest scientific discoveries.

For the Astrophysics Science Division, the current decadal survey science priorities for large missions include the following: searching for the first stars, galaxies, and black holes; seeking nearby, habitable planets; and understanding scientific principles of the physics of the universe. Larger general-purpose observatories can be used by the general observer community in ways that were not envisioned by the designers nor captured in the original science requirements, and they drive development of new capabilities that can be infused later into smaller missions without further technical development.

Currently, NASA's Astrophysics Science Division operates two large strategic missions, both in extended mission operation: the HST and the Chandra X-Ray Observatory, as well as the Stratospheric Observatory for Infrared Astronomy (SOFIA) airborne observatory. Hubble is one of the most well-known scientific instruments ever developed. In many ways it is unique, having been designed for updating over a long period of time, unlike any other robotic spacecraft. But this uniqueness in itself demonstrates the high visibility such large strategic missions can attract. Hubble has become a well-known, positive symbol of U.S. technological and scientific achievement. It has also become symbolic for both NASA and the astrophysics field.

The Hubble Space Telescope

The Hubble Space Telescope (HST) has been in orbit for more than 26 years and has been upgraded five times with improved instruments. Hubble was launched on April 24, 1990, 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 its inception, Hubble was designed to be serviceable via the space shuttle. In order to keep the observatory at the forefront of scientific capabilities, new instruments replaced the originals, and broken or outdated hardware has been replaced over the course of five servicing missions from 1993 to 2009.

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. The high-profile nature of the Hubble mission resulted in considerable controversy over its planned demise and led to several studies, including a 2005 National Research Council report: *Assessment of Options for Extending the Life of the Hubble Space Telescope*. Ultimately, NASA's leadership reinstated the servicing mission leading to a May 2009 launch. Two major instruments were replaced, with the Wide-field Camera (WFC) 3 replacing WFPC2 and the Cosmic Origins Spectrograph (COS) replacing the no longer needed Corrective Optics Space Telescope Axial Replacement (COSTAR) system. In addition, repairs were made to the Space Telescope Imaging Spectrograph (STIS) and to the Advanced Camera for Surveys (ACS), which had replaced FOS. To ensure the longevity of the telescope, astronauts replaced all six gyroscopes, all six of the original batteries, and another fine guidance system. (See Figure 2.1.) These actions have illustrated, perhaps most clearly, how the human and robotic aspects of NASA can interact to the betterment of the agency overall.

Hubble currently carries a suite of six complementary instruments:

1. *ACS*, or the Advanced Camera for Surveys, is responsible for Hubble's profound images in deep space. Since its installation in 2002, it has doubled Hubble's field of view of the universe and improved its ability to see the far ultraviolet to visible light, making Hubble capable of studying some of the earliest activity in the universe.
2. *COS*, or the Cosmic Origins Spectrograph, is excellent at observing points of light throughout the universe, breaking the light into colors, and measuring the intensity of that color. This allows scientists to detect the object's temperature, density, velocity, and chemical composition. Examples of points of light include stars and quasars.
3. *FGS*, or the Fine Guidance Sensor, assists in accurately conducting celestial measurements. There are three sensors total: two point to an astronomical target and hold the target in Hubble's field of view, and one performs scientific observations to measure the position of the telescope relative to the object being viewed.
4. *NICMOS*, or the Near Infrared Camera and Multi-Object Spectrometer, acts as Hubble's heat sensor. The instrument is designed to see objects in near-infrared wavelengths, making it a crucial tool to observe objects in the deepest parts of the universe. This is because light from the most distant objects moving away from Earth in our universe appears red by a process known as redshift.
5. *STIS*, or the Space Telescope Imaging Spectrograph, is best at observing large areas of light and separating the light into its component colors. This instrument is especially useful for observing galaxies and black holes throughout the universe.
6. *WFC3*, or the Wide-field Camera 3, brought new depth and range to Hubble's image production since its installation in 2009. This instrument has the ability to see multiple wavelengths at a higher resolution than any other previous Hubble cameras. It is paired with the *ACS* to produce a complete and complex view of the universe.

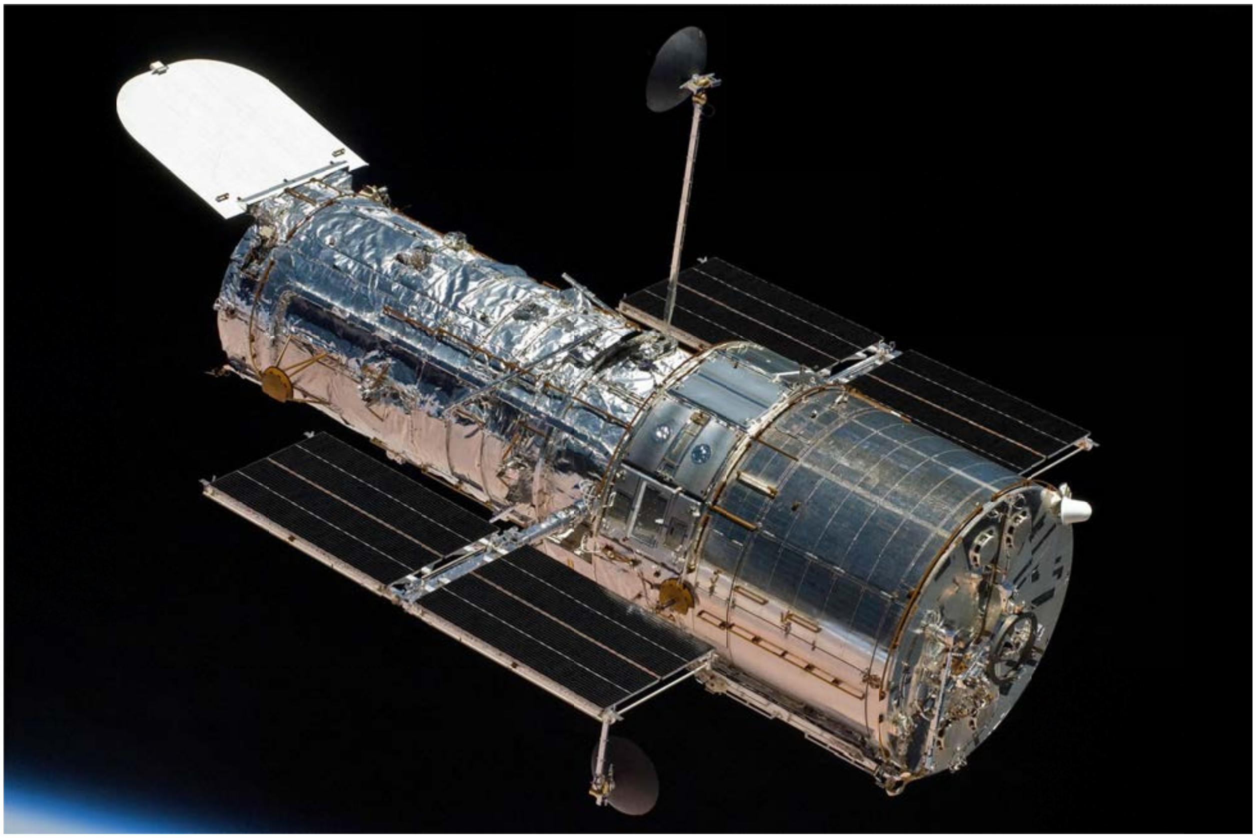

FIGURE 2.1 The Hubble Space Telescope in orbit. SOURCE: NASA.

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 one year of overlap with the James Webb Space Telescope (JWST). When it is finally retired, Hubble will have been in operation for three decades, a feat made possible because of multiple servicing missions. It is possible that future large strategic missions may be serviced as well, either by humans or robotically. The decision to design such missions to be serviced, and the decision to actually conduct servicing missions, will require substantial discussion and evaluation of their costs and benefits. Certainly the Hubble experience will offer important insight and perspective.

The scientific success of Hubble is unparalleled. With a 2.4-meter mirror and ultrasensitive instruments spanning from the ultraviolet to near-infrared, Hubble continues to transform most areas of modern-day astrophysics and remains the most popular telescope in the world for doing astronomical research. Recent science highlights include the imaging and spectroscopic discovery of possible geysers on Jupiter's moon Europa indicating plumes from a subsurface ocean, the discovery of a redshift 11.1 galaxy providing a glimpse of the earliest stellar systems that the universe formed, a refined measurement of the Hubble constant that shows the universe is expanding faster than expected, and the detection of molecules in the atmospheres of nearby exoplanets. Hubble's efficiency is at an all-time high, and its operation now includes several new observing modes and other improvements (spatial scanning, rapid tiling, enhanced point spread functions, etc.) that are motivating entirely new research themes.

Astronomers envisioned the importance of implementing a space telescope beyond Earth's atmosphere to examine infrared and ultraviolet light—a phenomena difficult to observe from Earth because this light is heavily absorbed by the Earth's atmosphere. Hubble's goal of producing detailed images of galaxies beyond our own was deemed critical for the advancement of our understanding of the universe for scientific knowledge and societal benefit. The lack of a consistent, extensive telescope for data collection was hindering our ability to understand how distant stars, planets, and galaxies are formed and interact with one another throughout the universe. Hubble has produced thousands of observations specifically designed to meet its objectives. The science highlights of Hubble include the following:

- *Cosmology*: Hubble paved the way for the discovery of the age and expansion of our universe. The development of Hubble allowed for scientists to see many more and much fainter stars, many of which are some type of variable star. This revelation helped pinpoint the age of the universe to approximately 13.7 billion years old. In turn, this established the foundation for creating future models of how the universe and all of its elements formed. Similarly, the rate at which the universe is expanding was also refined by the HST. Hubble was used to detect past deceleration of the expansion of the universe. This fundamental discovery about the evolution of the universe and the role of dark energy has generated over 3000 citations.
  Observing distant galaxy clusters and quasars through the breakdown of light received by Hubble illustrate that the luminous light centers are produced by black holes. Additionally, discoveries in cosmology include dark matter and dark energy. Long-term observations resulted in the Hubble Deep Field. This discovery launched two decades' worth of deep field studies to explore the universe at the earliest times. This image from Hubble has transformed the study of galaxies and has generated over 1000 citations to date.
- *Planetary science and exoplanets*: Hubble's capabilities allowed scientists to observe the formation of stars and planets, discover exoplanets, and identify comet impacts on other planets. Hubble was the pioneer for taking the first light-visible image of distant planets. Hubble observations revealed the first exoplanet atmosphere. Other planetary discoveries include the uncovering of icy objects in the Kuiper Belt and underground oceans on Jupiter's moons Ganymede and Europa.
- *Galactic science*: Hubble introduced a new approach to identifying the lifetime progression of supernovas and stars. The light observed from a supernova in one of the Milk Way satellite galaxies paved the way to better explain star and galaxy formation. The discovery of how supernovas, neutron stars, and black holes relate to one another has advanced our understanding of how the universe was formed and continues to interact. Likewise, the interaction of neighboring galaxies to the Milky Way, such as Andromeda, has depicted the history of each system of stars and promotes the further advancement of future discoveries and predictions in this field.

As a large strategic mission, Hubble has set the bar that future astrophysics missions such as JWST will have to clear. The Hubble program has produced over 14,000 refereed science publications (at a current rate of over 800 publications per year), with more than 600,000 citations. Similar to other Great Observatories such as Chandra and Spitzer and as expected for JWST and the Wide-field Infrared Survey Telescope (WFIRST), within the Astrophysics Science Division large strategic missions support a range of science through a vast user community. Each year, there are hundreds of programs allocated to small principal investigator (PI) projects at U.S. and international universities, and yet there are also a few large collaborative programs involving many dozens of U.S. and international community members. Only large strategic missions can support such a large distribution of programs. This is the foundation of U.S. astronomy research in most American universities. Each year there are more than 1000 research proposals for Hubble observations submitted by the community at an oversubscription rate of 5:1. There have been more than 15,000 users of the observatory to date.

Hubble's unique capabilities (high ultraviolet [UV] and visible sensitivity) will not be reproduced by any current or planned ground or space telescopes, and after Hubble is retired there will be no equivalent coverage of these observing modes in the JWST era.

Hubble's science operations model included significant investments in workforce development. Hubble has provided over $750 million of research grants to the science community to analyze and publish observations from the observatory, and this investment continues today at a rate of $30 million per year (one-third of the operating budget). With this investment, Hubble has trained nearly 1000 graduate students, and there are 600 Ph.D. theses based on Hubble data (40 to 50 per year). Hubble has also supported a vibrant postdoctoral fellowship community, including prized postdoctoral fellowships (Hubble Fellows).

Alternatives to Large Strategic Missions in Astrophysics Science

The astrophysics branch has been assessing the scientific value of missions in the $0.5-$1 billion range, referred to as "Probe class" concepts. A recent Announcement of Opportunity (AO) for astrophysics probe concepts has met with considerable enthusiasm, and proposal evaluation in the first half of 2017 will provide further insight on their potential value. This is an area in which a committee external to NASA may provide advice and recommendations with regard to the advantages of such intermediate cost missions, appropriate cost sizes, and cadence.

The history of astronomy and astrophysics has involved the development of larger and more powerful telescopes. This is due to the requirement to gather more photons to study—aperture has determined capability. But many astrophysics questions do not require increasingly larger apertures. Whereas the Hubble Space Telescope's 2.4-meter diameter mirror remains the largest ultraviolet/optical/infrared (UVOIR) space telescope ever placed in orbit, there have been many smaller space observatories that have answered vital questions. For example, the Cosmic Background Explorer (COBE) spacecraft launched in 1989 provided data vital to confirming the Big Bang theory of the origin of the universe. COBE was an Explorer-class spacecraft, with a launch mass of only 2,270 kilograms (compared to Hubble's mass of 11,110 kilograms). The Nobel Prize committee stated that "the COBE-project can also be regarded as the starting point for cosmology as a precision science."[2] Another astrophysics mission, Kepler, originally started in NASA's Planetary Science Division but has operated as part of the astrophysics program. Kepler has discovered many new planets around stars, refining scientific understanding of Solar System formation and contributing to the dramatic growth in the study of exoplanets. Kepler has been the sole source of Earth-size planets, which cannot be found in the other programs. Many of the observations conducted with smaller astrophysics spacecraft ultimately lead to more focused investigations with larger spacecraft—for example, Kepler's discoveries of exoplanets is informing plans for use of the JWST.

Other currently operating NASA astrophysics missions include Nuclear Spectroscopic Telescope Array (NuSTAR), Fermi, Swift, and Spitzer. Spitzer is a medium-size mission, whereas NuSTAR, Fermi, Kepler, and Swift are smaller.

Balance in Astrophysics Science

NASA's experience with the James Webb Space Telescope, which increased in cost substantially over initial estimates, has created the impression that astrophysics is conducted only with large aperture spacecraft. More significantly, the need to cover these cost increases reduced resources available for other NASA astrophysics missions. This has created the perception within the astrophysics community that the NASA astrophysics portfolio was unbalanced and required redress. Recent National Academies astrophysics reports have addressed this topic.

The question of balance in astrophysics concerns the relative resources devoted to small, medium-size, and large missions. The small and medium-size Explorer mission lines have cost caps that differ by about a factor of two, but the large strategic missions like HST and JWST have costs more like five powers of two higher than a medium-size Explorer. This large gap has led to concerns about balance.

A probe class line with a cost cap more like the planetary division New Frontiers line is an option to bridge this gap, and the inclusion of this class of mission within Astrophysics will be considered by the

[2] The Nobel Prize in physics, 2006, http://www.nobelprize.org/nobel_prizes/physics/laureates/2006/.

next decadal survey. There are also important factors that already mitigate the concern over balance: the other Great Observatories like Spitzer and Chandra have costs that are much lower than JWST and HST. Also, the Great Observatories support a very wide range of small research projects through their guest observer programs. Certainly, a balanced program in astrophysics will always have a role for large strategic missions.

EARTH SCIENCE DIVISION

In the Earth science field, large strategic missions provide a centralizing and organizing force around which research and development activities can coalesce. Guided by the science community, the concentration of resources dedicated to the mission goals provides a wide reach both inside NASA as well as in industry and academia. As an example, the Terra mission, within the Earth Observing System (EOS) suite of missions, funded science team PIs inside NASA and in academia, internships, postdoctorates, and graduate and undergraduate students on a decadal time scale throughout all phases of the mission.

Having resources centered on a large strategic mission provides both continuity and critical mass supporting the science and engineering communities as well as providing science data needed to accomplish the goals and objectives of the science community. In Earth science the ability to collect consistent, well-calibrated, validated data over decadal time scales is critical for understanding Earth's climate, physical, and biogeochemical systems. This remains a primary requirement for Earth science and the large strategic missions that generate hundreds of community-defined science products, and continuously receive very high marks in the senior review process.[3]

Currently, NASA's Earth Science Division operates three large strategic missions: Terra, Aqua, and Aura. (Figure 1.1, earlier, demonstrates the emergence of these programs in the 1990s.) The experience of the Terra mission demonstrates the way NASA has approached large strategic missions in the past.

Terra

NASA launched the Earth Observing System AM-1 mission in late 1999, after almost a decade of planning and development. This was NASA's largest Earth science mission. The spacecraft was renamed *Terra* and the mission was directed out of NASA's Goddard Space Flight Center (GSFC). *Terra* included both facility and PI-class instruments from multiple NASA centers, academia, and significant international participation (facility-class instruments are also "directed," meaning that instead of a principal investigator, the instrument science team is led by an assigned project scientist). Terra was still operational at the time of this report, over 18 years after launch. (See Figure 2.2.)

As the first in the EOS series, Terra was meant to collect a rigorous multidisciplinary set of measurements required to identify and quantify the physical and biogeochemical interactions between Earth's atmosphere, biosphere (terrestrial and marine), cryosphere, hydrosphere, and interior. The community-defined measurement requirements were deemed critical for the advancement of our understanding of Earth's complex systems for scientific knowledge and societal benefit. The lack of data was hindering scientists' ability to understand how the Earth system functions, delaying understanding historic trends in climate, weather, and the functioning of the biosphere, to model important interactions among processes, and to use improved models to project future trends. Most importantly, data were needed of sufficient quantity and quality to separate potential anthropogenic influences from the complex

[3] The senior review process is the method by which NASA determines if missions that are completing their primary phase of operations should enter into an extended mission phase, and by which missions already in extended phase are further extended. For over a decade NASA has conducted senior reviews in all four science divisions every 2 years as required by law—recently extended to 3 years—and each mission is evaluated according to its scientific productivity.

FIGURE 2.2 The *Terra* spacecraft undergoing final testing at Goddard Space Flight Center in the late 1990s. SOURCE: NASA.

natural system. In the 1980s and 1990s the ability to identify and quantify the possible human component in global change was deemed to be time critical, and only a very large mission or suite of missions like EOS could provide the enormous amount of data required. Terra's initial science mission objectives were as follows:

- Detect human impacts on climate and the ability to distinguish them from natural variability.
- Measure the effects of clouds on Earth's energy balance.
- Measure the effect of aerosols and greenhouse gases (including CO) on the Earth's energy balance and air quality.
- Measure global carbon storage due to terrestrial and marine productivity and changes in surface characteristics.
- Measure and monitor global land and sea surface temperatures, albedo, snow cover, and so on.
- Improve medium- and long-range weather forecasts.
- Improve prediction, characterization, and risk reduction for wild fires, volcanoes, floods, and droughts.

Terra carries a suite of five complementary instruments:

1. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), contributed by the Japanese Ministry of Economy, Trade, and Industry with a U.S.-led science team at the Jet Propulsion Laboratory (JPL), is a multispectral imager that provides a unique benefit to *Terra*'s mission as a stereoscopic and high-resolution instrument required to measure and verify processes at fine spatial scales.
2. Clouds and the Earth's Radiant Energy System (CERES), originally a PI instrument at Langley Research Center and now a facility-class instrument with similar sensors on several platforms, investigates the critical role clouds, aerosols, water vapor, and surface properties play in modulating the radiative energy flow within the Earth-atmosphere system.
3. Multi-Angle Imaging Spectroradiometer (MISR), a PI-led instrument from JPL, characterizes physical structure from microscopic scales (aerosol particle sizes and shapes) to the landscape (ice and vegetation roughness and texture) to the mesoscale (cloud and plume heights and 3-D morphologies).
4. Moderate Resolution Imaging Spectroradiometer (MODIS), a facility-class instrument directed by GSFC*,* acquires daily, global, and comprehensive measurements of a broad spectrum of atmospheric, ocean, and land properties, improving and supplementing heritage measurements needed for processes and climate change studies.
5. Measurements of Pollution in the Troposphere (MOPITT), sponsored by the Canadian Space Agency (CSA) with a science team at University Corporation for Atmospheric Research (UCAR), retrieves carbon monoxide total column amounts as well as mixing ratios for seven pressure levels, and its gas correlation approach still produces the best data for studies of horizontal and vertical transport of this important trace gas.

With five instruments co-located on one platform, *Terra* produces 81 community-defined, well-calibrated, validated, temporally and geospatially overlapping Earth observations specifically designed to meet the mission objectives. Many of these objectives were met or surpassed by the merger of data from the instruments on the Terra platform taking advantage of temporal and spatial simultaneity as well as using data from other satellites and sources to exploit differences in perspective. Also, most objectives require many years of observations to accomplish and the science community benefitted greatly by the longevity of Terra (and other missions).

In addition to creating a very large library of measurements supporting the objectives listed earlier, highlights of the Terra mission (shared with other Earth science missions) organized by NASA's Earth Science Focus Areas (NASA's 2014 Science Plan) include the following:

- *Climate variability and change (CERES, MISR, MODIS, includes Aqua CERES and MODIS):* Enabling better understanding of the role of clouds (height, density, composition, and diurnal variation), aerosols (size, density and injection heights), and Earth surface characteristics (land, sea, and ice) and their interactions on Earth's radiation budget and climate. This was accomplished through the creation of radiance data sets with the accuracy, precision, and stability required to show trends and establish the physical bases for developing, testing, and improving climate models.
- *Atmospheric composition (ASTER, MISR, MODIS includes Aqua MODIS, MOPITT, Ozone Measuring Instrument [OMI], Microwave Limb Sounder [MLS], Tropospheric Emission Spectrometer [TES], High Resolution Dynamics Limb Sounder [HIRDLS]):* A greatly enhanced understanding of how fire, aerosols, clouds, and human activities and natural phenomena (such as ENSO – El Niño Southern Oscillation) interact to affect atmospheric composition and human health. This includes an archive of volcanoes, glaciers, aerosol sizes and injection heights, CO maps, and a better understanding of global atmospheric circulation through tracking CO as related to fires and industrial activity.
- *Carbon and ecosystems (ASTER, CERES, MISR, MODIS including Aqua, and MOPITT):* First multispectral retrievals of CO elucidating the global atmospheric circulation and

transport of CO and sources from fires and industrial activity. Greatly enhanced understanding of the impact of weather, climate, and human activity on ecosystem state and function and the carbon cycle. First global sets of vegetation and other surface parameters such as land surface temperature, emissivity, primary production, and so on, required for understanding the physical and biogeochemical interactions between the biosphere and atmosphere. These data have allowed the development of new models of the fluxes of carbon, water, nitrogen, and other important elements and compounds as well as for assessing the impacts of changes on agriculture, weather, climate, and human health.

- *Energy and water cycle (ASTER, CERES including Aqua, MISR, MODIS including Aqua, MOPITT):* Related to the previous focus areas, Terra data have created a decade-plus record of sea surface temperatures, land surface temperatures, land emissivity, flooding (inland and coastal), snow and ice cover (land and sea), and cloud and aerosol data, enabling a new era of modeling Earth's hydrological cycle at many scales.
- *Weather (ASTER, MISR, MODIS):* MODIS-derived polar winds have had a positive impact on numerical weather forecasts in high latitudes and in the tropics, as have the combination of MODIS and MISR wind data at different levels in the atmosphere.
- *Earth's surface and interior (ASTER, MISR, MODIS, MOPITT):* Data from ASTER has created a massive library of Earth's topography and volcanoes and glaciers. including the extent, surface temperatures, and rate of change over time. These data combined with MISR injection heights and MODIS surface area maps have enabled a better understanding of volcanoes and their impact on both the surrounding landscape (human and natural ecosystems) and the atmosphere, including an enhanced warning system for aircraft at risk from volcanic plumes.

In 2005 Terra entered extended mission phase and was one of the first Earth science missions to undergo the senior review process. During multiple subsequent senior reviews, Terra has been consistently rated very highly for both its contribution to science and applications.

Terra is an example of a large strategic Earth science mission with international, multi-NASA center, and academic participation. Co-location of the instruments on one platform provides the opportunity to make simultaneous measurements required to elucidate important functional links between and among processes in the Earth system. Co-location also allows for each of the instruments to benefit from robust on-orbit services such as redundant power and communication systems and a dedicated mission operations team capable of coordinating on-orbit management and station keeping activities benefitting all five instruments. While the overall mission was directed from Goddard Space Flight Center, Terra hosted both PI-class and facility-class instruments on one platform.

The Terra science team was commensurately quite large and composed of teams representing each instrument in proportion to their separate investment and science goals. MODIS, representing a very broad set of science disciplines and with a sister sensor on Aqua (the second in the series of EOS missions), has a science team of nearly 100 scientists.

In 2005 the EOS Project Office estimated that EOS (Terra, Aqua, and Aura collectively) was supporting more than 330 separate investigations with over 770 researchers. Of those, 260 were graduate students or post-doctorate level staff. While just a snapshot, this approximate level of support persisted for these missions, providing a stable environment for learning and skill development across a meaningful period of time inside academia and the agency. In contrast, the science teams for principal investigator instruments are much smaller and supported for a shorter period of time.

Historically, Terra's mission budget was divided into two components: mission operations, and Research and Analysis (R&A). Initially, the science or R&A portion of the Terra mission was closely tied to and managed by the mission itself. Announcements of opportunity issued through NASA/HQ were specifically designed to address the mission and its science requirements. In extended mission phase, efforts were made to reduce mission operations costs, and the R&A portion of the Terra mission not directly tied to mission science management or PI instruments was folded back into the Earth science budget.[4]

Alternatives to Large Strategic Missions in Earth Science

The Earth science community has grown out of a broad set of academic disciplines distributed over the focus areas in Earth science that include climate variability and change, atmospheric composition, carbon cycle and ecosystems, water and energy cycle, weather, and Earth surface and interior. Earth science as a singular discipline or academic entity has evolved to incorporate a wide range of what were once separate classic science disciplines, and therefore significant differences in perspective, methods, and vocabulary still exist within it. As a result, it is difficult for a single or even several large strategic missions to satisfy all perspectives or goals, let alone distribute resources to such a large, varied community.

Even though the large strategic missions get very high ratings during mission extension senior reviews, the community has been calling for more opportunities via smaller, faster, and less expensive missions. Smaller missions allow for new approaches, new measurements, and new players to get involved. Smaller missions can definitely provide opportunity for new approaches and measurements in shorter time scales over the large strategic scale missions, but do not necessarily provide better or "more fair" access to funding resources for scientists. How funds are made available within either the large strategic or smaller mission approaches can be managed in such a way as to minimize the differences. The Earth Science Division has done this by maintaining the highly rated large strategic missions in extended mission phase and separately managing the R&A components. Not having to build new missions to provide the data output by these missions and detaching a portion of the R&A budgets formerly allocated to them frees up funding for new analysis opportunities.

Keeping new missions smaller allows for a more rapid response to changing community-led science goals and measurement requirements. The potential pitfall in this approach is that with no centralizing large strategic missions, NASA may lose the opportunity to lead both scientifically and internationally.

As this study was concluding, the second Earth science decadal survey was still under way. This committee concluded that the issue of the future role of large strategic missions in Earth science was best left to the decadal survey to address. However, this committee notes that large strategic missions have served Earth science as a sort of laboratory facility that can be accessed by many members of the community, in some ways similar to the way NASA's astrophysics Great Observatories have served their community. This may be harder to achieve with a series of smaller, more numerous spacecraft with shorter lifetimes.

Balance in Earth Science

Large strategic missions are important to maintaining a balanced program in Earth science, as they provide needed high-quality data across interdisciplinary boundaries on the time scales required, and create the conditions for leadership within a highly diverse set of disciplines. In the late 1980s NASA created the Earth Observing System (EOS), consisting of several large strategic Earth science missions. These EOS missions—Terra, Aqua, and Aura—with their multi-instrument suites enabled discoveries about the Earth's interconnected bio-geochemical, climate, weather, and solid Earth systems.

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[4] Senior reviews are designed to assess and justify mission continuation beyond the original scheduled budgetary lifetime of the mission. Senior reviews not only cover the success of the mission for meeting its defined science goals and cost, but also the scientific value of both the goals and results of the mission are reassessed by the scientific community at that point. The cost versus value of continuing the mission must be justified and a window of opportunity can be defined (if budget allows) to make use of the mission to create new measurements or data products called for by the science community.

Collectively, the EOS missions, and the associated distributed active archive system for disseminating data, laid the groundwork for the evolution of Earth system science supported by satellite observation, and engendered the development of Earth system science research centers in government agencies and academia worldwide. Large strategic Earth science missions also benefit continued technological development. The instruments on the EOS platforms are widely emulated internationally, and the results from the research and development of EOS instruments are fueling the next generation of Earth science missions from large to small.

The A-Train, a constellation of spacecraft including large missions Aqua and Aura and smaller missions CloudSat and CALIPSO, demonstrates how Earth system science goals can be achieved with instruments on multiple spacecraft, as opposed to requiring a single platform for all instruments making complementary measurements.

The study of fundamental Earth system processes requires studying an enormous range of spatial and temporal scales. This can sometimes be accomplished only by using large strategic missions capabilities. However, the global coverage and multiple sensors requested in Earth sciences call for a variety of missions in different orbital inclinations and altitudes, with a large variety of instruments sometimes mutually exclusive, a goal that obviously cannot be fulfilled by a single large mission.

Large strategic missions provide opportunities for advancing science around an organizing entity that have not commonly been achieved by smaller missions. A large centralizing mission focusing the community on a specific set of issues with resources sufficient to train and maintain a scientific workforce over longer time scales is a key element of leadership (e.g., EOS). A larger enterprise can bring stability to the community. A portfolio of constellation missions could provide similar focus and stability to the community, but only if sufficient resources were allocated and rapid replenishment of the small missions was ensured. While they provide excellent opportunities to make quick advances, weighting a portfolio toward many small missions runs the risk of becoming diffuse, difficult to manage, and leaderless. These risks can be and are, to some extent, addressed by expanding the definition of a “mission” to include an “enterprise” structure that integrates missions of various sizes, both at the same time (e.g., the A-Train) and between missions over decades to support long-term trending and satellite and algorithm intercalibration. This would require a structure and would be different from simple augmentation of the R&A budgets supporting small and medium-size missions. Whether the enterprise concept needs to be vetted by the decadal surveys can be debated, but the enterprise concept could provide a structure to a portfolio less constrained by mission size yet support both the agility and stability required to serve the goals of the science community and maintain a talented workforce.

HELIOPHYSICS SCIENCE DIVISION

Almost by definition, heliophysics requires taking many different measurements in many different locations in order to build up a systematic understanding of heliophysical phenomena. Heliophysics instruments themselves are generally not large, but some measurements require that the instruments be taken to difficult locations, which can require more complicated and expensive spacecraft.

Not all NASA heliophysics is conducted within the Heliophysics Science Division or even within NASA. There is currently important heliophysics science being conducted on the *MAVEN* (Mars Atmosphere and Volatile Evolution) spacecraft orbiting Mars, the *Juno* spacecraft orbiting Jupiter, and the *New Horizons* and *Voyager* spacecraft at the edge of the Solar System. These spacecraft all started out as planetary missions that benefit the study of heliophysics overall. *Voyager* was reconfigured in 1990 as the Voyager Interstellar Mission to reflect its new role of exploring the edge of the Solar System. In addition, the National Science Foundation (NSF)’s Geospace Section started work with solar and space physics CubeSats that is now being taken over by NASA. The NSF’s Astronomy Section has also funded ground-based solar observations.

Although heliophysics still requires large strategic missions to make important advances in the field, these are not necessarily large single spacecraft like the *Parker Solar Probe* currently under development.

Scientists have proposed developing large constellations of small spacecraft to take many measurements across great distances. The development and integration of dozens to potentially hundreds of small spacecraft can result in a mission that is both strategic—vital to the development of the science discipline—and also large in terms of cost and complexity.

As in Earth sciences, the study of fundamental heliospheric processes requires studying an enormous range of spatial and temporal scales that can sometimes be accomplished only by using large strategic mission capabilities.[5] To understand why the solar wind exists, for example, requires placing a spacecraft into the atmosphere of the Sun, within at least 11 solar radii of the Sun's center. To understand the complex interaction of the solar wind with the interstellar medium requires measurements be made out to 200+ astronomical units (AU). Heliophysics processes can have natural multidimensional spatial gradients of 1 to several AU (e.g., cosmic ray modulation) and time scales that range from electron and ion inverse gyrofrequencies (magnetic reconnection over milliseconds) to the 11- and 22-year solar cycle time scales, meaning that spacecraft instrumental capabilities need to have very high cadences (spatial and temporal), the ability to make simultaneous multipoint measurements, as well as great longevity. To accomplish measurements and observations over such spatial and temporal heliophysical scales often demands complex instrument suites, clusters of spacecraft, multiple widely separated spacecraft, and challenging orbits, meaning that large strategic missions, defined in many different ways, are necessary to further advance the field of heliophysics.

Parker Solar Probe

NASA currently is operating the Magnetospheric MultiScale (MMS) mission, which the heliophysics decadal survey considered to be a "major space mission." The previous large strategic mission in heliophysics was the joint European Space Agency (ESA)-NASA Ulysses mission to the Sun launched in 1990 and operated until 2009. In 2009 NASA began development of the Parker Solar Probe mission, which is scheduled to launch in 2018 and will send a spacecraft to within 3.67 million miles of the Sun's photosphere. (Solar Probe Plus was renamed Parker Solar Probe in May 2017.) This will be the closest any spacecraft has traveled to the Sun and requires a spacecraft specifically designed to deal with the intense heat it will encounter. (See Figure 2.3.)

The ability to identify and quantify detailed information regarding the Sun is critical for the advancement of our understanding of stellar properties for scientific knowledge about distant stars in our universe. The lack of data on our Sun has created a gap in the knowledge that we have on stellar bodies throughout our universe. The *Parker Solar Probe* spacecraft is designed to withstand temperatures up to 1370 degrees Celsius and solar radiation intensities 475 times higher than encountered on Earth. In order to gain enough momentum to reach a close distance from the Sun, the spacecraft will have to complete seven flybys of Venus and plans to conclude its first approach of the Sun in the winter of 2024.

The goals of the Parker Solar Probe mission include the following:

- Determining the structure and dynamics of the magnetic fields at the sources of solar wind;
- Tracing the flow of energy that heats the Sun's corona and accelerates the solar wind; and
- Determining what mechanisms accelerate and transport energetic particles.

[5] *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C. 2012.

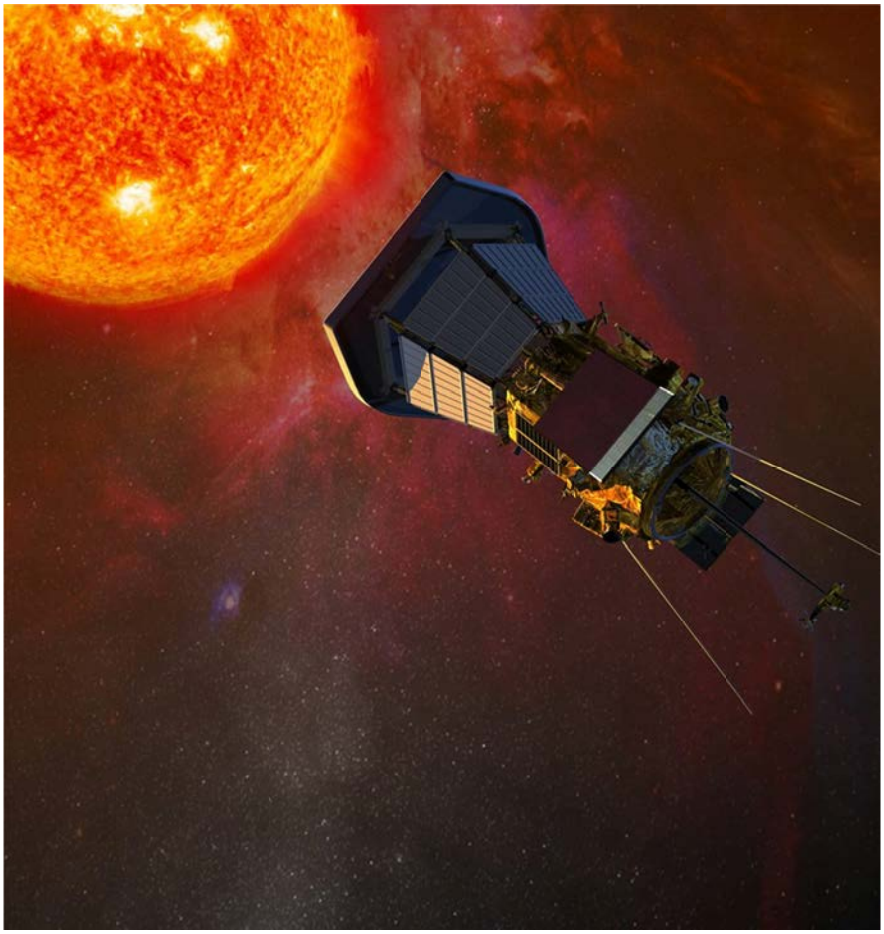

FIGURE 2.3. Artist impression of *Parker Solar Probe*. SOURCE: JHUAPL.

The payload on the *Parker Solar Probe* includes four instruments:

1. Field Measurement Experiment (FIELDS)—field measurements, led by the University of California, Berkeley.
2. Integrated Science Investigation of the Sun (ISIS)—energetic particle mass spectrometer, led by Princeton University.
3. Solar Wind Electrons Alphas and Protons (SWEAP)—plasma and solar wind particle counter, led by the University of Michigan.
4. Wide-field Imager for Parker Solar Probe (WISPR)—coronal imager, led by the Naval Research Laboratory.

Alternatives to Large Strategic Missions in Heliophysics Science

NASA operates many smaller-size heliophysics missions, including Advanced Composition Explorer (ACE), Solar Terrestrial Relations Observatory (STEREO), Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS), Van Allen Probes, Wind Experiment (WIND), and others. Although many heliophysics spacecraft are physically small, some missions, such as the four-spacecraft Magnetospheric MultiScale (MMS) mission, involve multiple spacecraft gathering data in concert, thereby increasing the mission's cost and complexity. The advent of CubeSat technology has already demonstrated the potential of this platform to support science measurements with small constellations of spacecraft for very targeted measurements. Larger small satellite constellations will continue to evolve to support specific multipoint large spatial-scale observations as the technology continues to mature.

Balance in Heliophysics Science

In the field of heliophysics, some of the most foundational discoveries of the Sun-Earth interaction have not been made and can be made only with large strategic missions.

Where heliophysics differs somewhat from the other space science fields is that the definition of what qualifies as a large strategic mission is changing. Rather than a single spacecraft, or a pair of spacecraft, in the future heliophysics may require the development of constellations of multiple spacecraft, perhaps even dozens of them. The overall cost and complexity of such missions will probably approach the level of the more traditional large strategic mission class.

PLANETARY SCIENCE DIVISION

Planetary science is conducted with large strategic as well as competed missions. Planetary science requires large strategic missions for several reasons: because the destinations/targets are difficult to reach, and because of a need to carry a comprehensive instrument suite to a far or difficult destination to make multiple observations. For example, although Mars is relatively easier to reach in terms of distance, with travel times of less than a year, actually landing on the planet is difficult. Furthermore, the types of science goals NASA is pursuing for Mars are more complex than before. In general, outer planet missions represent both of these qualities because they are distant and may require special power sources, and because after traveling all that distance it is more cost effective to carry multiple instruments. Some outer planets missions can encounter very harsh environments, such as high radiation, which increases mission costs.

Although both Mars landers and orbiters have been conducted as competed missions, Mars exploration also requires large strategic missions, which increase access to a wide range of important science objects at high-priority targets. For example, the Mars Science Laboratory (MSL)/Curiosity mission consists of a large rover with a substantial onboard scientific laboratory.

These missions also have an impact on current and future scientific communities through contributions to development and the demonstration of new technologies that are applicable to new missions and can answer fundamental science questions. There are different types of mission campaigns, and a series of competed missions launched over a long period of time (such as the numerous NASA Mars missions launched between 1998 and 2011) can serve a strategic purpose as well.

NASA currently has two large strategic missions under development, the Mars 2020 rover and the Europa Clipper. Mars 2020 is part of NASA’s ongoing study and exploration of Mars to seek to provide answers to critical questions such as: Did life ever arise on Mars and, if so, is it still there? Was the early climate more Earth-like and why did it change? Is Mars an appropriate destination for human exploration?[6] Europa Clipper is the current iteration of a Europa mission that was prioritized in the 2011 planetary science decadal survey. Europa has one of the youngest surfaces in the Solar System, with copious cryovolcanism, Earth-like tectonic activity, and potentially geysers and plumes. The subsurface ocean on Europa may provide the best chance for extant life beyond Earth. The Europa mission’s science goal and objective is primarily to investigate Europa’s habitability.

The complexity needed for a large strategic mission depends on the maturity of exploration of the target, and the level of detail necessary to move forward on answering the most fundamental questions of the mission. As the information and observation becomes more sophisticated, so do the questions. For

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[6] See, for example, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011, p. 76.

example, the observation that Mars may be habitable would lead to the question of whether it was ever inhabited. Deciding between a large mission with many instruments or several smaller missions with more focused science depends on the risks and accessibility, in addition to cost variances, surrounding the missions. Larger missions can provide both the infrastructure and framework for smaller missions to fill strategic gaps.

The value and breadth of large strategic missions for planetary science is demonstrated by NASA's Cassini mission to Saturn.

Cassini

At the time this report was being written, NASA was preparing the end of life for the Cassini spacecraft. The mission is supported through international collaboration, with contributions of hardware and scientists from over 27 countries. A major aspect of the mission was the Huygens probe, which was funded by the European Space Agency (ESA) and descended to the surface of Titan in 2005, providing unprecedented information about the moon.

The Cassini-Huygens mission comprised a Saturn orbiter from NASA and the Huygens Titan probe from ESA, with 18 instruments (12 for the orbiter, and 6 for the probe). With 27 investigations, there were 10 interdisciplinary scientists, and over 300 scientists on investigation teams, half in Europe. (See Figure 2.4.)

Cassini carries a suite of 12 complementary instruments:

1. CIRS, or the Composite Infrared Spectrometer, captures infrared light, breaks it down into component wavelengths, and measures the strength of the light. This instrument assists in determining the celestial object's temperature and composition.
2. ISS, or the Imaging Science Subsystem, serves as the main camera for observing the Saturn system. The instrument consists of two digital cameras: one of a wide-angle range and one of a narrow-angle range to primarily observe visible light.
3. UVIS, or the Ultraviolet Imaging Spectrograph, creates images by capturing ultraviolet light, breaking it down into component wavelengths, and measuring the strength of the light. Scientists use this instrument to study Saturn's rings, atmosphere, and multiple moons.
4. VIMS, or the Visible and Infrared Mapping Spectrometer, captures visible and infrared light and separates the two to determine characteristics in the Saturn system such as the content and temperature of the atmospheres, rings, and surfaces.
5. CAPS, or the Cassini Plasma Spectrometer, comprises three sensors: the electron sensor, the ion mass sensor, and ion beam sensor, in which a particle travels and then is assessed on its kinetic energy and the direction it was traveling. Additionally, the ion mass spectrometer measures the particle's mass. This instrument gives scientists insight on the composition, density, flow, velocity, and temperature of the ions and electrons in Saturn's magnetosphere.
6. CDA, or the Cosmic Dust Analyzer, detects small dust particles and determines their charge, velocity, size, and composition. This instrument is helpful to examine the dust that orbits in Saturn's system—some of which is from the surface of a celestial object in the system, whereas other particles are from beyond our Solar System.
7. INMS, or the Ion and Neutral Mass Spectrometer, determines the composition and structure of positive ions and neutral molecules in Titan's atmosphere, Saturn's magnetosphere, and the ring environment.
8. MAG, or the Magnetometer, records the direction and strength of magnetic fields around Cassini. As the spacecraft orbits Saturn, this instrument collects data regarding the varying strength and direction of the planet's magnetic field in different locations. This helps scientists learn about the composition and density of the celestial bodies in Saturn's system.

9. MIMI, or the Magnetospheric Imaging Instrument, captures information regarding the charged particles of Saturn's magnetosphere and how the magnetosphere interacts with the solar wind. This instrument comprises three sensors that detect protons, electrons, ions, and neutrons.
10. RPWS, or the Radio and Plasma Wave Science, uses a suite of antennas and sensors to detect radio and plasma waves through Cassini's path. The instrument uses three types of sensors to study the intensity of waves across a broad frequency range in order to better understand the relationship between celestial objects in the Saturn system.
11. Radar, or Radar instrument, has the ability to send radio waves at the surface and create pictures of the landscape by recording the differences in the signal's arrival time and wavelength at the spacecraft. This instrument is primarily used to study Titan.
12. RSS, or the Radio Science Subsystem, sends radio signals to objects within the Saturn system in order to depict the composition of those objects. This instrument transmits the radio signals back to Earth, where scientists can determine the gravity fields, atmospheric structure, composition, ring structure, particle sizes, and surface properties within the Saturn system.

Cassini's mission to Saturn studied many different aspects of the planet, including Saturn's magnetic field, gravity field, ionosphere, radiation belts, and the rings. Huygens and Cassini had different prime mission science objectives. Beyond the prime mission objectives, there were also multiple priorities for seasonal and temporal change, and new questions asked during the solstice mission that followed the prime mission. Cassini Saturn science also complements the Juno mission to Jupiter. Current study opportunities include analyzing the gravitational and magnetic fields of Saturn's internal structure, age and mass of the main rings, and direct sampling of Saturn's atmosphere.

- *Rings*. Cassini has captured extraordinary observations regarding Saturn's ring-moon interactions, such as observing the lowest ring temperature ever recorded on Saturn, discovering that the moon Enceladus is embedded in Saturn's E-ring, and viewing images of the rings at Saturn's equinox when the Sun strikes the objects in orbit. The close-up interactions with Saturn's rings have uncovered information regarding their composition—the rings are composed of particles ranging in size from micrometers to meters.
- *Titan*. Cassini was the first space mission to map Titan's surface, study its atmosphere, discover liquid water beneath its surface, and send a probe to Titan's surface. Cassini-Huygens revealed that Titan has lakes and seas of liquid methane and ethane that are replenished by rain from hydrocarbon clouds and that Titan has a liquid ocean beneath its surface likely composed of water and ammonia.
- *Enceladus*. Cassini's discoveries uncovered the unsolved mysteries of the luminescent moon. Cassini revealed that both the coating on its surface and materials in the E-ring originate from a subsurface saltwater ocean. Cassini identified geyser-like jets that expose water vapor and ice particles beneath the surface of the moon. In turn, this discovery has become a promising lead for life exploration in other worlds.
- *Moons*. Cassini uncovered knowledge regarding Saturn's dozens of moons. These moons vary in size—they could range anywhere from the size of the planet Mercury to the size of a sports arena. This greatly enhanced our understanding of Saturn's planetary and ring composition.
- *Magnetosphere*. The revelation of Saturn's giant magnetosphere encompassing the gas giant has provided powerful insights to the planet's atmosphere. This magnetosphere exerts a powerful influence on the space environment around Saturn, making it complicated to determine the planet's rotation. However, this discovery has given scientists a great deal of insight on how the magnetic field around Earth operates.

FIGURE 2.4 The *Cassini-Huygens* spacecraft during final integration and testing in the late 1990s. The Huygens atmospheric probe is the large gold disk at center. SOURCE: NASA.

Cassini provides significant contributions in advancing science:

- There is now extensive data on Saturn's system.
- There is also more insight into other gas giant systems that could provide more questions and answers about Jupiter and the ice giants.
- With the calibration of exoplanet observations, there could be further observations into the use of ground theoretical models for exoplanet researchers.
- Science data and results are complementary in both cost and responsibility across international space organizations and countries.

The Cassini program scientist identified many advantages to the international collaborative approach used for Cassini. The Huygens probe included in the mission and built and paid for by European partners would probably not have been affordable. In addition, European funding prevented Cassini from being cancelled in the 1990s, and later, U.S. support enabled extended mission funding for European scientists.

Since 2004 the Cassini-Huygens mission has conducted research in five separate science disciplines with multiple targets and cross-disciplinary discoveries with international collaboration among 27 countries.

Cassini's program scientist also stated that larger missions with higher overall life cycle costs clearly have a much greater scientific impact than smaller missions. There have been thousands of published papers to date on various topics, and numerous Ph.D.s and post-doctorates produced and trained as a result of the mission. Also, many collaborative efforts and international relationships formed, while also increasing the depth and breadth of discoveries. In addition, longer duration missions provide better opportunities to develop effective processes, procedures, and tools that can be used for future missions. The wealth of data collected by Cassini will provide study opportunities and materials for many years into the future, something previously demonstrated by prior large missions such as Voyager and Galileo.

Alternatives to Large Strategic Missions for Planetary Science

NASA's Planetary Science Division has two other mission classes, both led by principal investigators: Discovery and New Frontiers. Discovery has a cost cap of approximately $425 million (excluding launch costs), and New Frontiers has a cost cap of approximately $850 million (excluding launch costs). Discovery mission targets are entirely at the discretion of teams proposing the missions and in the past have included asteroids, comets, and Moon and Mars missions. There have also been Discovery proposals for Venus and outer planet missions that were not selected. In general, the cost cap has limited Discovery missions to inner Solar System targets. New Frontiers missions are competitively selected based on a list that has been developed by the decadal survey process. The most recent decadal survey recommended two New Frontiers AOs for the coming decade and a cadence of one new Discovery mission approximately every 36 months. Thus, generally speaking, the planetary decadal survey recommended a program of one large strategic mission, two New Frontiers, and at least three Discovery missions for the 2013-2023 period. To date, the Discovery program cadence has been lower than recommended by the last decadal survey, with only two missions selected during the period. This will decrease the amount of science return. This subject is likely to be addressed by the planetary science midterm study, which was under way at the time this report was published.

An example of technology development occurring in smaller-size missions is NASA's Dawn mission. Thanks to NASA's prior investment in solar electric propulsion (SEP), which was tested extensively on the Deep Space 1 mission, this technology enables Discovery-class missions now to reach Solar System destinations that previously would have been available only to large strategic missions, or even entirely unattainable. Dawn's use of SEP allowed it to become the only spacecraft ever to have the capability to orbit and explore two distant destinations, Vesta and the dwarf planet Ceres, the two largest objects in the main asteroid belt. This mission would have been impossible for a single spacecraft with conventional chemical propulsion, even for a large strategic mission. The Discovery mission Psyche has recently been selected and will orbit the main belt asteroid of the same name to investigate whether it is the exposed metal core of a protoplanet that has broken up. These missions illustrate how goals that would have been very expensive or unaffordable can be accomplished by smaller missions with new technologies.

Recently, the Planetary Science Division implemented a program to explore the development of CubeSats for planetary missions. In March 2017 NASA selected 10 studies under the Planetary Science Deep Space SmallSat Studies (PSDS3) program. These studies involve mission concepts using small satellites at the Moon, asteroids, Mars, Venus, and the outer planets. The studies involve small satellites weighing less than 180 kilograms. CubeSats have many limitations for planetary missions. What tends to make them attractive for Earth-orbiting applications—their inexpensiveness and small size—comes at the price of short lifetimes and relatively low reliability (although both are improving). CubeSats, or even small satellites like those being evaluated as part of the PSDS3 program, are unlikely to conduct planetary science missions on their own, but will probably be carried to their destination aboard larger spacecraft.

Prior to 2011 NASA had a separate Mars Scout line of missions that was approximately equivalent to the Discovery program in size and scope. The Mars Scout missions were part of a coordinated Mars exploration campaign and demonstrated the benefits of a more rapid cadence of small missions, including the ability to adapt new missions to recent discoveries and to rapidly produce scientific results, creating a robust and dynamic scientific community. The Mars Scout line was discontinued after two missions (Phoenix and MAVEN) and Mars missions were allowed to compete as part of the Discovery program.

Balance in Planetary Science

Planetary science relies on large strategic missions both for accessing distant and unforgiving targets and also for carrying large suites of instruments to conduct synergistic observations in planetary environments. These missions have provided a key component of scientific productivity across all aspects of the field. Cassini and the Mars Science Laboratory (MSL)/*Curiosity* rover both support hundreds of scientists and have produced thousands of publications during their lifetimes. In addition, these large missions host tens of participating scientists each, providing an on-ramp to junior scientists and others not involved in the design and development of the mission. These participating scientists infuse the missions with diverse insight and expertise while gaining important experience in leadership in mission planning and execution. New Frontiers and Discovery-class missions, as well as other Mars missions, are smaller in scale and scientific scope. Nevertheless, these smaller missions provide the community with more frequent mission opportunities with focused scientific investigations. All of these investigations provide the opportunity for technology development and advancement.

An unbalanced planetary science program could occur if either a single (or in rare cases, two) large strategic missions consume the majority of the planetary science budget and NASA cannot fund smaller missions. Alternatively, an unbalanced program would be one where there are no opportunities for large strategic missions during a decade.

ASSESSING BALANCE FOR NASA'S FOUR DIVISIONS AND THE ROLE OF THE DECADAL SURVEYS

Each scientific discipline—and the NASA division responsible for it—has different goals, interests, cultures, and history. This committee was tasked with addressing "general principles that SMD could use (e.g., a figure of merit approach) to trade off within limited budget between development and operation of large, strategic missions and the cadence and or/cost caps of medium size and small PI-led mission lines."

After much deliberation, the committee concluded that *there is no single figure of merit approach that could be developed to apply to all four scientific disciplines, nor was it appropriate for this committee to seek to supersede the guidance that is already provided to NASA by the decadal surveys.* Balance can be decided only by the decadal surveys themselves. Their definition of balance is likely to change over time, and therefore has to be revisited over subsequent decadal surveys, and assessed during the relevant decadal midterm reviews. Furthermore, the definition of balance provided by the decadal surveys is likely the only one that will satisfy a diverse community.

The committee also considered whether it was possible to develop different figures of merit for different disciplines. Although that might be possible, it would require substantial expertise in each of the disciplines, which a cross-disciplinary committee cannot possess but discipline-focused committees could possibly provide. The committee notes that if SMD seeks "general principles" to trade off within limited budget between development and operation of large, strategic missions and its medium and smaller mission lines, any such principles cannot be too general or they will not be very useful. In addition, those principles will be most helpful if they are timely and targeted to the areas most in need of help. The committee notes that NASA's advisory structure at the National Academies was recently revised to enable discipline committees for each of the space science disciplines to respond to the needs of NASA's science divisions in a more timely manner. This and other advisory structure changes could greatly assist NASA in making those decisions.

Although the committee did not think that a "figure of merit" approach was wise or possible, the committee did conclude that there are many general principles that can be applied to all of the NASA science mission divisions. The committee was reminded of both the importance and the strength of the decadal survey process for each division and impressed that NASA has previously sought to have the decadal surveys learn from each other. The committee's recommendations encompass providing better inputs into the decadal surveys and noting that when a decadal survey is insufficient, NASA has other advisory paths to seek specific input—for instance, for reprioritization or redirection of a program during a midterm review.

This report cannot have the credibility that specifically tailored advice will have for unique problems that arise, and NASA benefits by relying on its advisory structure where the relevant scientific communities will have the most input.

FINDING: Specialized, focused advisory groups can provide the best, and the most relevant and timely, advice on how to make trades while still maintaining the balance that is described by the relevant decadal surveys.

RECOMMENDATION: When faced with the requirement to trade off between development and operation of large strategic missions and the smaller missions within their portfolios, NASA's Science Mission Directorate divisions should look first to their relevant decadal surveys and their midterm reviews for guidance. If these are insufficient, the SMD divisions should seek the advice of their relevant advisory groups.

Having examined the data that the committee requested from NASA, the committee did conclude that there were approaches (discussed later) that could be adopted by the decadal surveys and adapted to their specific requirements that could be of benefit to the Science Mission Directorate in achieving or maintaining balance. Each of the four scientific disciplines approaches their investigations differently. Nevertheless, there are some common characteristics to all of the disciplines.

FINDING: Large strategic missions are critical for the conduct of space science in each of NASA's four divisions (astrophysics, Earth science, heliophysics, and planetary science) and required for the pursuit of compelling scientific questions. The role of, and drivers for, large strategic missions for the scientific priorities of each division, however, are different, and best determined by the decadal survey process.

FINDING: Large strategic missions are often critical for scientific balance and form the backbone of their discipline. A large strategic mission can be a single spacecraft, or a coordinated constellation, to achieve a set of science goals.

Decadal surveys provide community-consensus science priorities and recommendations for space and Earth science, principally to NASA and the National Science Foundation (NSF), but also to the U.S. Department of Energy (DOE), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the White House, and Congress.[7] The National Academies have conducted decadal surveys for more than 50 years, since astronomers first developed a strategic plan for ground-based astronomy in 1964. The committees and panels that carry out the decadal surveys are drawn from the broad community associated with the discipline in review, and involve many of the leading scientists and engineers in that discipline. The National Academies' decadal surveys are notable in their ability to thoroughly sample the research interests, aspirations, and needs of a scientific community. Decadal survey reports to agencies and other government entities play a critical role in defining the nation's

[7] See, for example, *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, The National Academies Press, Washington, D.C., 2015.

agenda in that science area for the following 10 years, and often beyond. In particular, decadal surveys have become the accepted guidance documents to the divisions within NASA's Science Mission Directorate.[8] The decadal surveys are now mandated by law in the NASA authorization acts. For example, the National Aeronautics and Space Administration Transition Authorization Act of 2017 states that "the Administrator should set science priorities by following the guidance provided by the scientific community through the National Academies of Sciences, Engineering, and Medicine's decadal surveys." Each division is charged with advancing the state of knowledge in the relevant fields of astrophysics, Earth science, heliophysics, and planetary science. To accomplish that goal, each division is also charged with advancing the state of technology, as appropriate, which may include both hardware (e.g., instrumentation and techniques) and software (e.g., modeling and processing techniques and implementations and simulations).

The decadal surveys' recommended science programs are constructed by their relevant committees based on assumptions about available budgets in the forthcoming decade. To be successfully implemented, programs advocated in decadal surveys also have to be flexible to budgetary realities, but also based on sound, adequate cost estimates. Such realities can take the form both of external forcings such as evolving current and out-year available budgets, as well as internal forcings, such as cost overruns or unexpected inefficiencies in a given program line or mission implementation. To minimize the latter, it is crucial that the responsible NASA division adequately fund and carry out preliminary (pre-Phase A and Phase A) studies for such missions in a way comparable to those executed by proposal teams working on competed missions. At the same time, in order to enable progress on a wide variety of fronts in a timely fashion, and maintain programmatic flexibility, each division has historically implemented a variety of missions, projects, and initiatives, which can roughly be divided into small, medium-size, and large cost categories. Exact definitions of these categories in terms of absolute costs and kinds of missions have varied over the decades (from the establishment of NASA), and they vary across the SMD divisions and the corresponding decadal surveys.

FINDING: Balance across the entire NASA science program includes an appropriate mix of small, medium-size, and large missions. The detailed meaning of "balance" for the upcoming decade is defined appropriately by each of the decadal surveys based on the required needs of that discipline for the pursuit of the most compelling science identified by the scientific communities by means of the surveys. Decadal surveys establish a broader balance that includes scientific capabilities typically provided by other agencies such as the National Science Foundation, NOAA, and the U.S. Geological Survey. Implicit in the definition is also the role played by funds for Mission Operations and Data Analysis (MO&DA) for missions in primary and extended missions, non-mission-research funding lines, and technology development and funding required to successfully implement future missions vital to the discipline.

The nature of decadal surveys is that the budget projections that are provided to the decadal survey steering groups are developed by the executive branch, not by Congress. Thus, if decadal surveys are tasked by the agencies to narrowly confine their recommendations to fit within the budget projections, they could be prone to excluding mission implementations that might offer revolutionary science results by the application of advanced technologies that could have been developed if the scientific community makes a convincing case for them and budgets are provided. Decadal surveys thus have competing objectives to both be realistic and to have "a license to dream."

In order to enable decadal committees to propose new and potentially revolutionary missions that might not fit within existing budget projections, the recent decadal surveys have been tasked to project different possible budget levels and what can be accomplished for each. These budget levels can accommodate different numbers and mixes of missions, but they could also accommodate different *implementations* of large strategic missions, *if* those missions have design and implementation flexibility.

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[8] National Aeronautics and Space Administration Transition Authorization Act of 2017 (P.L. 115-110).

At the same time, budget projections provided to the surveys can turn out to be optimistic, in which case it is also imperative for there to be in place decision rules that minimize any potential damage to a decadal survey's science plan. Such scenarios must be discussed with extreme caution in order that they not become self-fulfilling. Nonetheless, simply ignoring such possibilities can lead to even more harm to the affected disciplines.

RECOMMENDATION: The decadal surveys should formulate mission concept variants or other means to assess the boundaries of cost and technical risk and recommend the application of decision rules to provide flexibility to the NASA science divisions and most importantly the scientific community. This will enable further refinement of mission concepts when pursuing the scientific priorities identified by the decadal surveys.

All of the recent decadal surveys have described in detail the highest priority science questions and frontiers, and science is the primary focus of the decadal surveys. However, although the science questions and opportunity change over time, technology also changes over time, sometimes providing opportunities that were not apparent or available when a decadal survey was initiated.

RECOMMENDATION: Budget constraints should be included in the development of a decadal scientific program. Flexibility in the "decision rules" that decadal surveys produce should allow for both the de-scoping of large strategic missions in the face of cost overruns or insurmountable technical barriers as well as the "up-scoping" of missions as new technological or other opportunities arise.

In general terms, missions prioritized in the decadal surveys aim to be aspirational and visionary while still being feasible and affordable. Several of the last round of decadal surveys were created under challenging budget constraints, as required by their statements of task. Looking forward, when developing statements of task for future surveys it will be necessary to ensure that the charges to the decadal committees do not lead to their being overly cautious and conservative in the missions they prioritize.

The use of decision rules by recent decadal surveys provides an opportunity to consider more ambitious science goals and associated missions. For example, the planetary science decadal survey provided decision rules that articulated science goals associated with Mars, Europa, and Uranus with a decision tree where missions were prioritized contingent upon reaching certain budget targets.[9] In some cases these were difficult challenges—such as directing that the proposed baseline mission cost half as much as the mission concept that was originally evaluated using the survey's cost and technical evaluation (CATE) process. The objective of the CATE process is to perform a cost and technical risk analysis for a set of concepts that may have a broad range of maturity, and to assure that the analysis is consistent, fair, and informed by historical data. Typically, concepts evaluated via the CATE process are early in their life cycles, and therefore are likely to undergo significant subsequent design changes. Historically, such changes have resulted in cost growth. Therefore, a robust process is required that fairly treats a concept of low maturity relative to one that has undergone several iterations and review. CATEs take into account several components of risk assessment. Because the CATE is best suited to the comparative evaluation of a family of pre-Phase A concepts, it was the methodology used in the decadal surveys and is best suited to the early phase analysis of strategic missions. After the release of the

[9] The decision rules included flying the MAX-C rover only if the mission could be conducted at a cost to NASA of less than or equal to $2.5 billion FY2015, and flying the Jupiter Europa Orbiter mission only if changes to both the mission and the NASA planetary budget make it affordable without eliminating other recommended missions. If less overall funding was available, NASA was advised to de-scope or delay "flagship" missions, slip New Frontiers and/or Discovery missions only if adjustments to "flagship" missions could not solve the problem, and place high priority on preserving R&A and technology development funding.

planetary decadal report several project teams were able to redesign or de-scope their mission concepts to fit a cost goal. (This is discussed further in Chapter 3.)

These kinds of opportunities for de-scoping are best accomplished if the decadal survey stipulates the boundary conditions such as minimum science and maximum budget, and what science may be accomplished at different levels of technical capability (which can translate to cost), allowing NASA and the scientific community to make trade-offs within the provided guidelines. There is also the possibility that new technology or a less-costly approach may emerge within a decade, and therefore providing the decision makers with an "on-ramp" would be beneficial for the pursuit of the scientific program. Allowing for opportunities to de-scope large strategic missions would result in the opportunity for more new mission concepts to be initiated within the decade within the boundaries of the recommended scientific program from the decadal survey.

RECOMMENDATION: In preparation for the decadal surveys, large strategic mission proposal teams should consider describing ranges of scientific scope for their recommended large strategic missions, such as minimum science goals and maximum budgets, as well as identifying what science goals are most desirable at different budget levels. This approach may allow the scientific community and NASA to develop less expensive implementation strategies for mission concepts that do not exceed current budget limitations.

RECOMMENDATION: Decadal surveys should be informed by, but not narrowly restricted to, future projections of available budgets. Such flexibility may enable new and potentially revolutionary large strategic missions.

Flexibility in mission implementation may identify opportunities where small and medium-size missions can provide measurements as effective as large strategic missions—for example, where constellations of simultaneous (i.e., multipoint) measurements are desired in solar and space physics as well as in Earth science. Small and medium-size missions offer the capability to make high-priority measurements where metrics such as cost, development time, observation cadence, and ability to integrate new technology can be optimized. Smaller missions can also accept greater development and operational risk. Furthermore, they can also provide benefits when compared to large strategic missions where sustained/continuity measurements are needed and enabled by rapid deployment/replacements of spacecraft, as well as to scientific objectives that are more easily reached.[10]

CONCLUSION

Large strategic missions continue to have value for all of NASA's space science disciplines. It is not possible for NASA to abandon large strategic missions simply because they can be challenging, and still maintain world leadership in the space sciences. The primary argument that has emerged against such large strategic missions is their cost, particularly when costs run far over the original estimates. However, large cost overruns on large missions are not inevitable. There are methods both to better predict and plan for a mission's cost, and to better manage missions so that costs can be controlled. NASA has achieved success at both of these efforts in the past decade. That is the subject of the next chapter.

[10] For further information, see *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, The National Academies Press, Washington, D.C., 2015.

3

Risks and Realities of Cost Overruns for Large Strategic Missions

A major community concern about large strategic missions is their cost, particularly cost overruns. Because of this, they can have major impacts on space science budgets. One of the reasons why NASA asked the National Academies to undertake this study was because of what happened with large strategic missions during the previous decade, particularly when both the James Webb Space Telescope (JWST) and the Mars Science Laboratory (MSL)/*Curiosity* rover experienced significant cost growth. Both projects received considerable publicity and scrutiny because of this cost growth, and they had impacts upon their respective divisions' portfolios. Even today some stakeholders consider that there is a lingering stigma to large strategic missions because of recent experience. As this chapter explains, NASA, Congress, and the decadal surveys all took actions in response to these cost overruns, and the positive results of these actions are now becoming apparent.

The four NASA divisions have a different portfolio mix and vary in their amount of reliance on large, strategic missions to achieve their overall science goals. The committee examined NASA's allocation of missions over the past 20 years using acquisition approach as a figure for comparison, relying on a recent analysis conducted by The Aerospace Corporation.[1]

NASA benefits from having a variety of different acquisition approaches which can be adapted to the needs of the project. NASA missions are acquired by being directed to NASA centers or competed through an Announcement of Opportunity. Additionally, NASA develops contributed instruments to be flown by other organizations (ESA, JAXA, DOD, NRO, etc.), relying on them to ensure that the science is implemented. Directed missions are typically more expensive missions based on high science value targets. Competed missions are selected based on science value with a fixed cost cap. For purposes of this comparison, large strategic missions are synonymous with directed missions.[2] (See Figure 3.1.)

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[1] Bob Bitten, Justin Yoshida, Elliott Tibor, and Christopher May (The Aerospace Corporation), Portfolio Mix of NASA Science Missions, December 7, 2016.

[2] One factor in cost prediction and control is how budget reserves are managed. Prior to the instigation of the new policy, limited budget reserves were maintained at NASA headquarters and the majority of funding flowed down to the implementing center or lead organization. The policy of maintaining reserves in the form of unallocated future expenses (UFE)—shown here as the difference between the 50-percentile and the 70-percentile estimates—resulted in flexibility with resources held at different levels within the agency. For example, if one project team was successful in delivering the system at or below the 50-percentile estimated budget, then the UFE remained unallocated at the directorate level and could be applied to other missions that were experiencing a larger amounts of cost growth. By budgeting at the 70-percentile and holding reserves at higher levels, funds were essentially fungible and cost performance improved at the portfolio level. Furthermore, the policy resulted in a significant reduction in breach of the Nunn-McCurdy Amendment and thus less disruption to the development team.

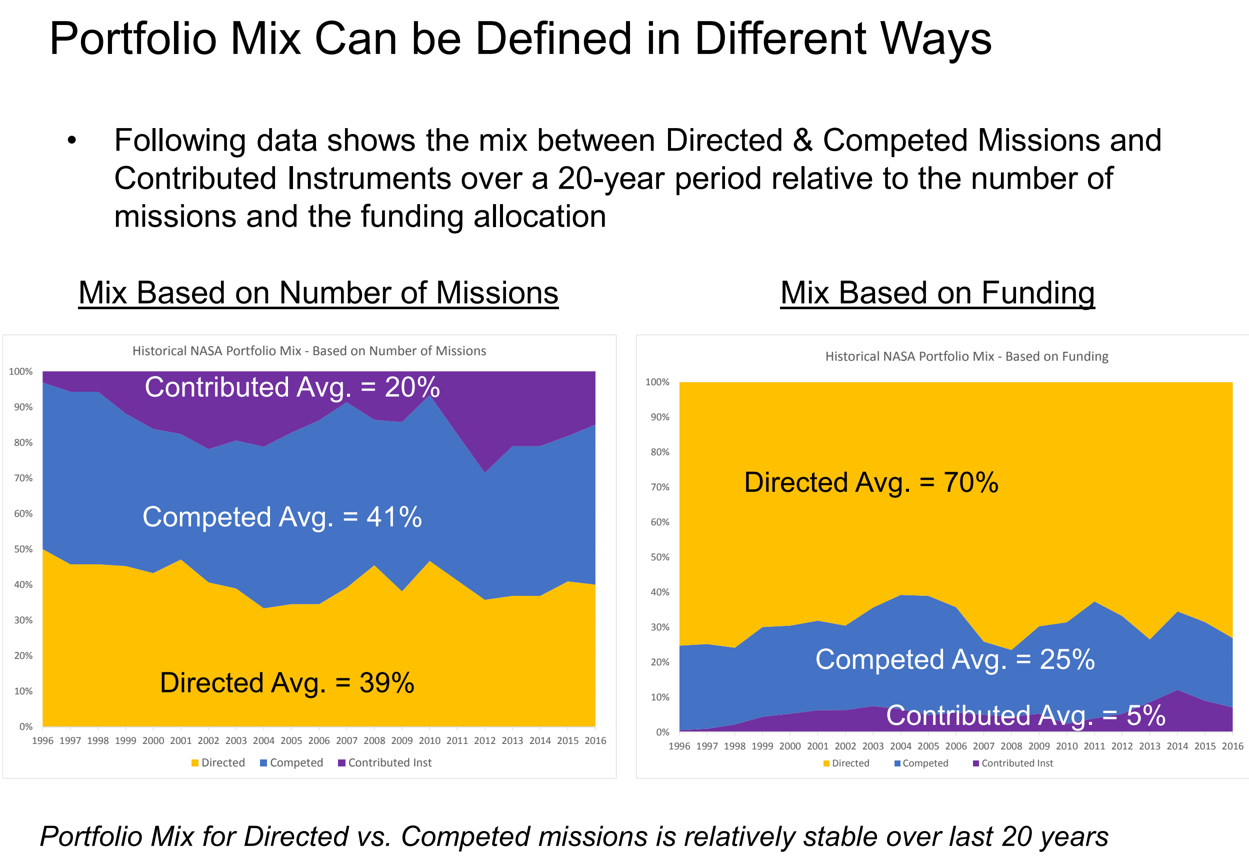

FIGURE 3.1 The different ways that directed and competed missions are defined in NASA's portfolios. SOURCE: Bob Bitten, Justin Yoshida, Elliott Tibor, and Christopher May (The Aerospace Corporation), Portfolio Mix of NASA Science Missions, December 7, 2016.

As noted in Chapter 1, according to the Science Mission Directorate, approximately half of the SMD's budget—46 percent—is devoted to new missions. Of this budget for new missions, directed missions make up an average of 70 percent of the funding and the remainder is devoted to competed missions. Clearly directed missions consume a significant portion of the overall NASA science mission budget and a major portion of the new mission funding. Figure 3.2 shows this same data broken out against the four science themes. What it also shows is that when the portfolio mix is evaluated by number of missions, the mix is much more evenly distributed, both within each division, and when the divisions are compared to each other. The difference between evaluating the portfolio mix by budget amounts versus numbers of missions highlights one of the difficulties of trying to assess "balance," especially across divisions—is balance determined by the percentages of money spent, or by the number of missions, or by some other factor? As noted in Chapter 2, the committee concluded that balance is an issue that is best defined by individual decadal surveys, both because they are closer to the requirements of the scientific discipline, and because definitions of balance change over time. This study cannot presume what balance will be for a specific scientific discipline and by extension a SMD division 3, 5, or 7 years from now.

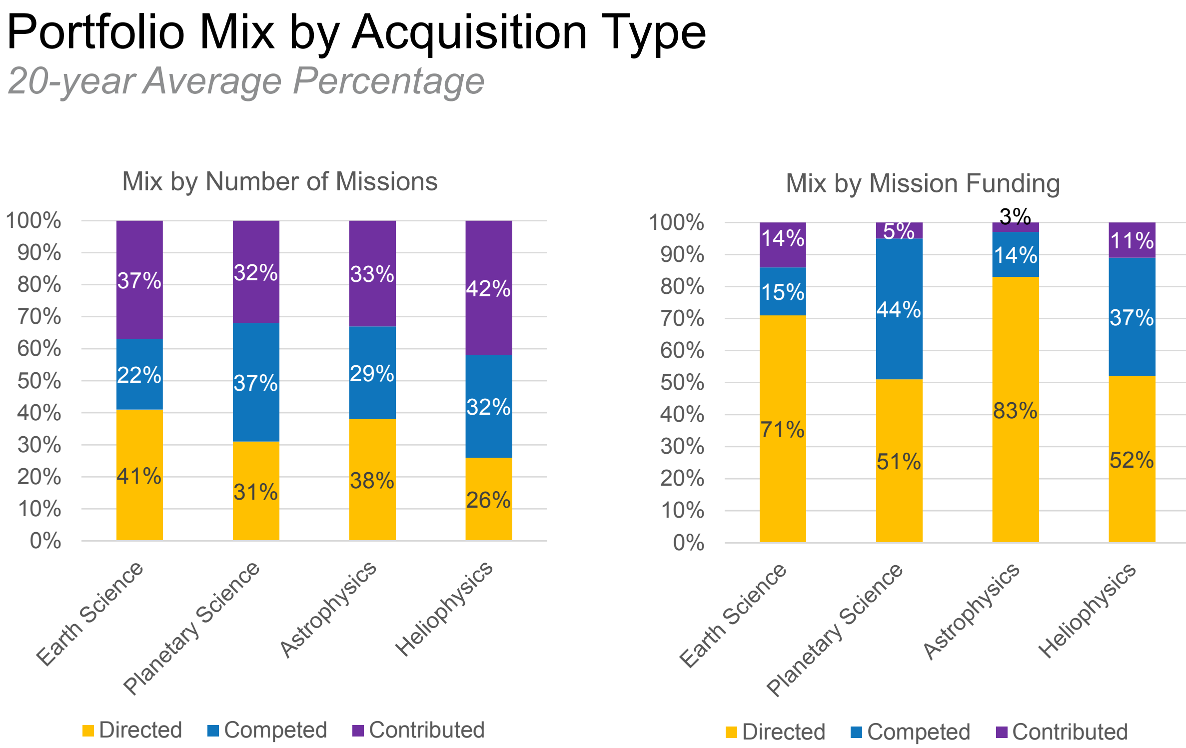

FIGURE 3.2 Portfolio mix by mission type. The two graphs show that in terms of mission funding as an overall percentage of the division's budget, astrophysics spends the most on directed missions, whereas planetary science and heliophysics have the lowest percentages. SOURCE: Bob Bitten, Justin Yoshida, Elliott Tibor, and Christopher May (The Aerospace Corporation), Portfolio Mix of NASA Science Missions, December 7, 2016.

The balance of the astrophysics portfolio has been exacerbated in the past decade by the James Webb Space Telescope experience. JWST grew substantially from its early budget estimates and had major effects on NASA's astrophysics budget, prompting the agency to remove JWST from the astrophysics budget and treat it as a separate program. The JWST experience also helped lead to reforms in the way that NASA estimates costs for missions, and how the agency manages missions. Those reforms, and the current state of cost estimation for NASA space science missions, are the subject of later sections in this chapter. Although the majority of SMD's new mission funding (approximately 70%) goes to directed missions; these missions do not consume all the new mission budget within NASA divisions. They range from 51 percent for the Planetary Science Division to 83 percent for the Astrophysics Science Division.

An Aerospace Corporation study performed in 2013 compared development costs of principal investigator (PI) managed missions and center-managed missions. For this study, PI-managed missions represent smaller missions and center-managed missions represent large, strategic missions. The purpose of the study was to identify relative cost between implementation modes. Comparisons were based on development cost, development cost growth, and relative complexity using the complexity-based disk assessment (CoBRA) tool. The study focused on missions launched between 1998 and 2011.

A comparison of center-led and PI-led missions is shown in Figure 3.3. PI-led missions are generally less complex than center-led missions, and their average cost is commensurately lower than the average cost of center-led missions. The average cost of PI-led missions in the study is FY2012 $226 million, while the average cost of center-led missions in the study is FY2012 $620 million.

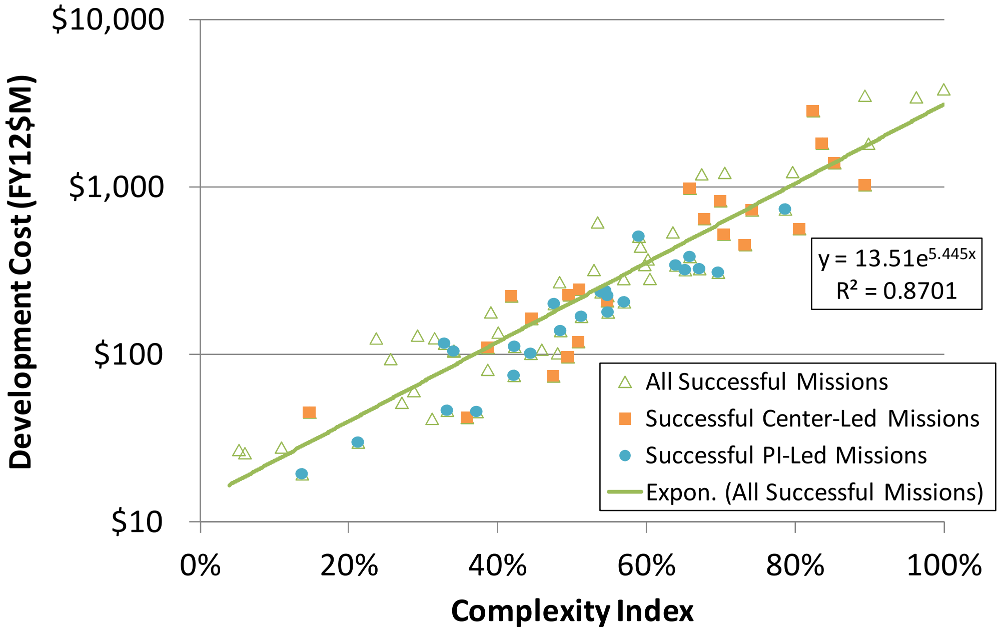

FIGURE 3.3 The Aerospace Corporation conducted a complexity analysis of the cost effectiveness of NASA PI-led science missions. The green triangles are the complete data set, which includes PI-led, center-led, and other non-NASA missions. The orange squares are superimposed on green triangles. The blue circles are likewise superimposed on green triangles. The curve fit utilizes the complete data set and represents an "average" for visual comparison of PI-led and center-led relative to the data set as a whole. SOURCE: Bearden, Kellogg, Cowdin, Yoshida, and Mize, Complexity Analysis of the Cost Effectiveness of PI-led NASA Science Missions, 2013 IEEE Aerospace Conference.

The committee notes that the best way to control costs is not by not selecting risky missions, but by providing for sufficient funds up front to retire the risks definitively prior to mission confirmation (i.e., elevating all systems to above technology readiness level [TRL] 6 by the Preliminary Design Review [PDR]). This at first may seem like it merely increases the cost of a mission, but in reality *it is an exercise to uncover true costs earlier in the entire mission development cycle, rather than later*. Uncovering costs earlier rather than later provides NASA management with more options on how to address them and maintain balance across their entire portfolio.

Capturing the inherent complexity of a program can assist decision makers and analysts in developing more realistic risk assessments and technology readiness assessments that can influence cost estimates and overall evaluation of program balancing. The study also examined the historical development cost growth (from Phase B start to launch) of the two mission subsets. While the difference in average costs between the two mission types drives a relatively large difference in absolute dollars of the growth, there is no significant difference between the development-cost growth averages. (See Figure 3.4.)

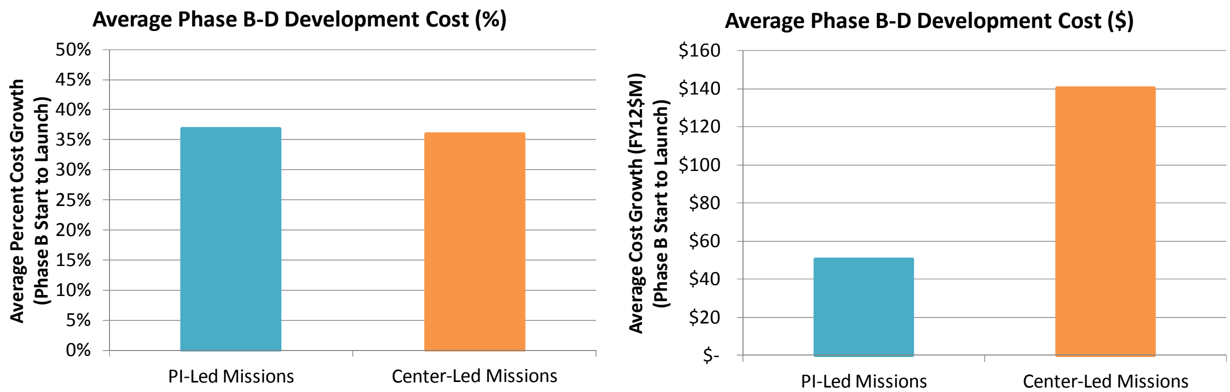

FIGURE 3.4 The average cost growth of PI-led and center-led missions. The study demonstrated that both PI-led missions and center-led missions had similar cost growth. SOURCE: Bearden, Kellogg, Cowdin, Yoshida, and Mize, Complexity Analysis of the Cost Effectiveness of PI-led NASA Science Missions, 2013 IEEE Aerospace Conference.

Although both center-led and PI-led missions have experienced similar cost growth, there may be different factors causing cost growth in these different missions. This could require different approaches to limiting cost growth. It is beyond the scope of this study to recommend how to control cost growth in NASA missions, the committee merely notes that failing to control cost growth for the largest missions poses the biggest threat to maintaining balance, as even a modest percentage increase in the cost of a large mission could eliminate an entire small mission.

NASA has initiated studies called Explanations of Change (EoCs) to get at the issue of what portion of cost growth might be attributable to external (less controllable or uncontrollable) versus internal (controllable by the project management). Understanding this will be valuable to improving the accuracy of future cost estimates.

What these studies of cost growth in NASA missions demonstrate is that both small and large missions have similar percentage cost overruns, large missions naturally cost more than small missions, and the entire budget of the Science Mission Directorate is not consumed by large missions. Although the committee has stated throughout this report that the proper definition of balance is best determined by the relevant decadal surveys and their midterm reviews, the committee did not detect substantial imbalances within NASA's science divisions.

PROGRAM LIFE CYCLES

NASA projects have life cycles defined by different phases ranging from pre-Phase A concept studies to Phase E science operations and Phase F end of life. (See Figure 3.5.) The phases are further divided into Key Decision Points and Project Life-Cycle Reviews.[3] NASA establishes a project's baseline budget at Key Decision Point-C (KDP-C). However, it is not uncommon for the public, the press, and the scientific community to cite low-fidelity cost estimates *made prior to KDP-C*, thus creating the false impression that a mission's costs have grown substantially when the reality is that the early "estimates" were not actual estimates, or were made by project advocates rather than an independent authority. The formal decision to proceed with a project is made at KDP-C, and the independent estimates made at this point are the only valid ones.

NASA holds KDP-C after the mission has undergone a Preliminary Design Review (PDR) that comprehensively evaluates the overall mission design. Establishing a baseline budget at KDP-C—after

[3] NASA/SP-2014-3705, NASA Space Flight Program and Project Management Handbook.

the PDR—is important because mission concepts can substantially evolve prior to the PDR. Estimates at an early stage, even when done with the best procedures and best intentions, still represent a snapshot of a design that experience has demonstrated will evolve considerably before reaching PDR.

Establishing a mission's cost is vital because at any given time NASA divisions have multiple missions under development or in future planning. If a mission's cost increases beyond the initial plan, this will have impacts on future projects, leading to delays in those projects. Because large strategic missions are so expensive, their cost increases can have a greater impact than smaller missions, rippling through a division, or even the entire agency, with negative effects, and damaging NASA's reputation. (See Figure 3.6.)

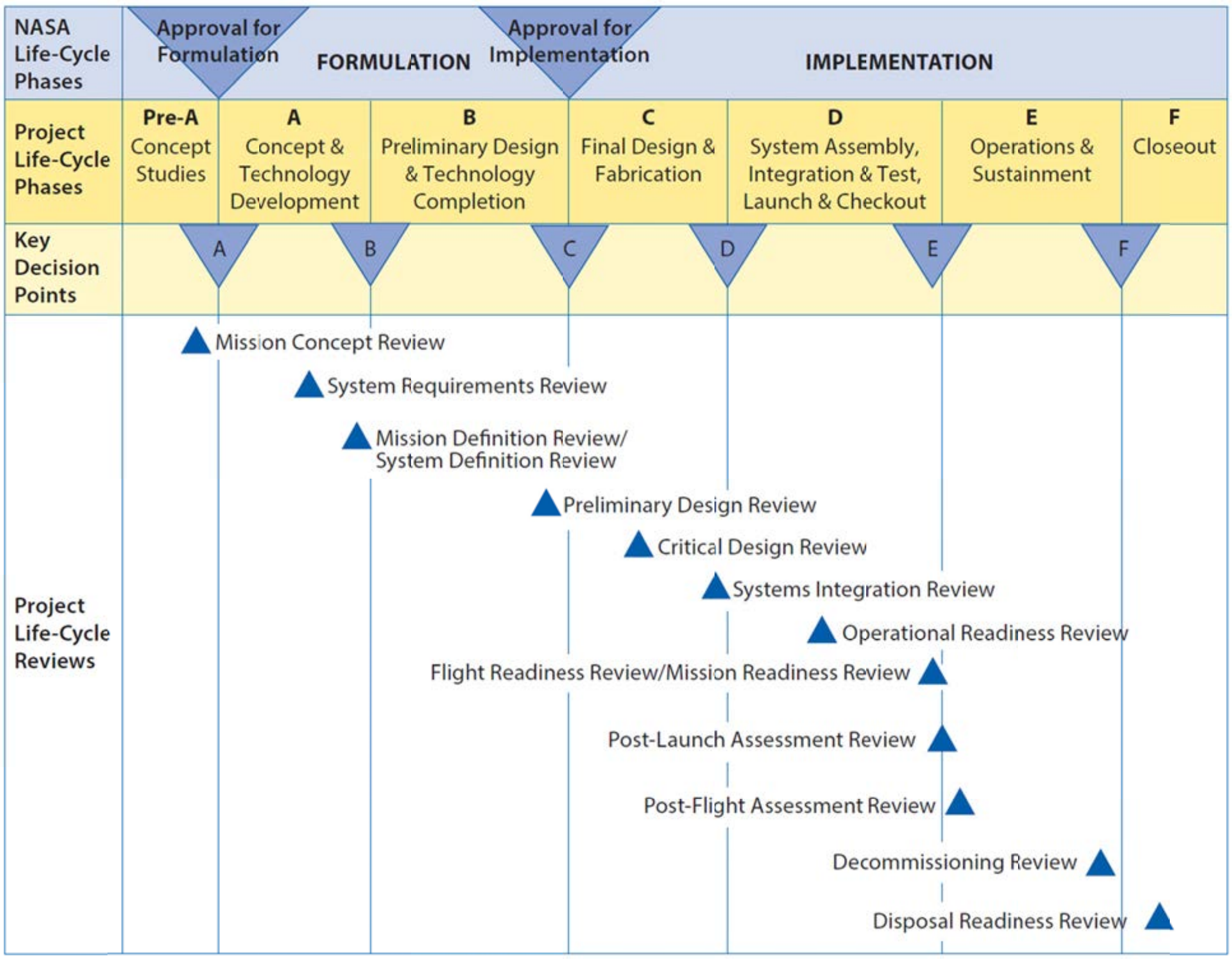

FIGURE 3.5 The different phases of a NASA space science mission. The Preliminary Design Review is a major milestone in development. Key Decision Point C is when NASA conducts an independent cost estimate of the mission. This is usually the point at which the agency commits to further development of the mission or reevaluates the mission. SOURCE: The Aerospace Corporation.

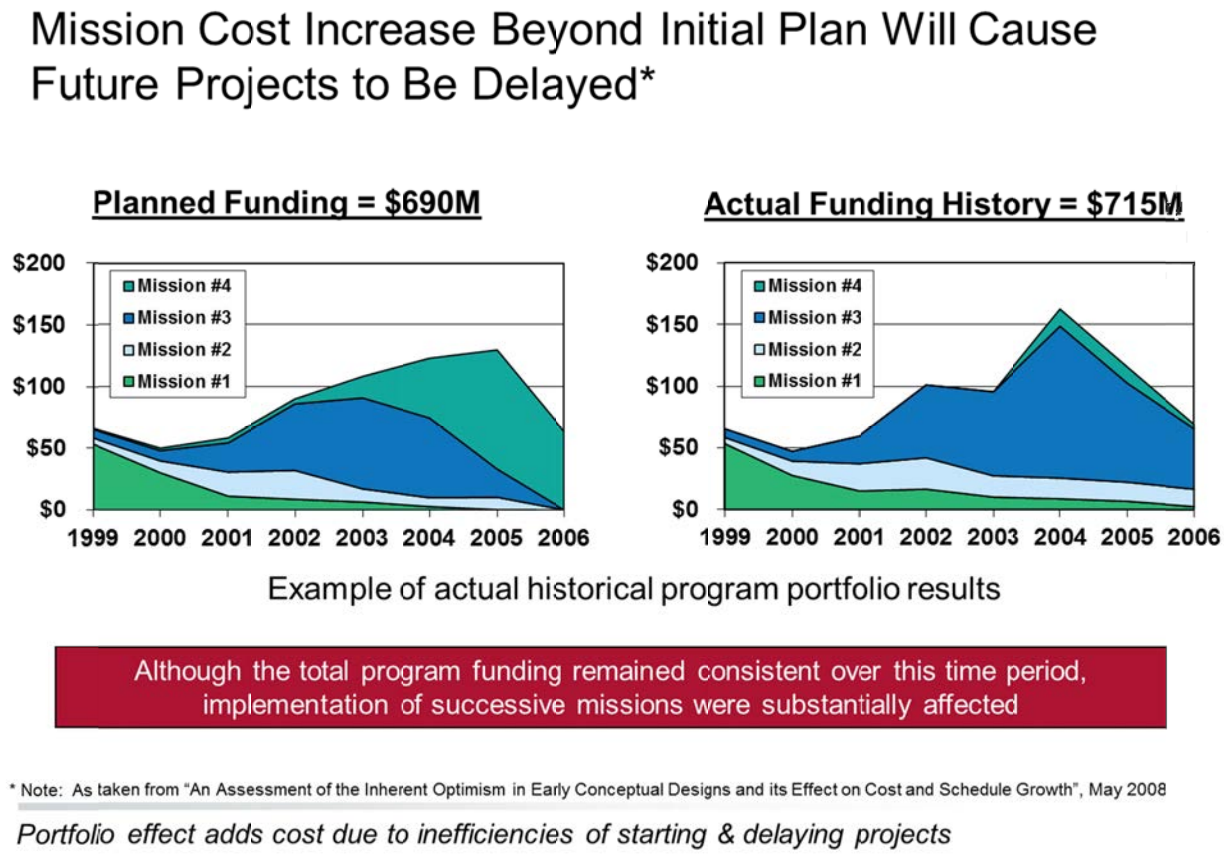

FIGURE 3.6 Example of how a major cost increase for a single large strategic mission (mission #3 in both graphs) can have a dramatic effect on the overall program. The data conveys the collateral effects of cost growth of a single mission to the entire portfolio. When mission #3 experiences cost growth around 2003, it not only delays delivery of mission #3 (planned to complete in 2006) but also dramatically curtails the progress of mission #4. The planned funding of $690M versus the actual funding of $715 million indicates a relatively fixed budget that constrains progress on mission #3 and delays start of mission #4. This is representative of what can happen to create imbalance within a portfolio and underscores the importance of conservative cost estimation and sound cost management and controls for large strategic missions. This example also suggests that cost estimating methods should place high emphasis on program phasing profiles as well as total program life cycle. SOURCE: The Aerospace Corporation.

Cost growth on large strategic missions can be particularly challenging because of the large, sometimes multibillion-dollar base estimates, where even a small percentage cost growth during development can present budget pressure within the division, affecting its overall portfolio balance. Furthermore, the large strategic missions typically have a larger number of stakeholders (perhaps an international partner), high complexity, and often a larger dependence on new technology. While science missions being developed within a science theme—for example, astrophysics—typically do not have large technical interdependencies, they are often related programmatically through budget, or might be in line to use the same launch vehicle or some other infrastructure or vendor that links them in a cost or schedule sense. When cost growth or schedule slip occurs within a fixed budget profile, collateral adverse effects on missions that are adjacent to the large strategic mission may be significant.

FINDING: Cost control of large strategic missions remains vital in order to preserve overall programmatic balance.

REFORMS IN HOW NASA ESTIMATES COSTS

The 109th Congress Public Law 155 was implemented in December 2005 to address cost growth in NASA missions with Section 103, "Baseline and Cost Controls" stating:

- The Administrator shall determine whether the development cost of the program is likely to exceed the estimate provided in the Baseline Report of the program by 15 percent or more, or whether a milestone is likely to be delayed by 6 months or more.
- If the determination is affirmative, the Administrator shall transmit to the Committee on Science of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate, not later than 15 days after making the determination, a report that includes
  - A description of the increase in cost or delay in schedule and a detailed explanation for the increase or delay;
  - A description of actions taken or proposed to be taken in response to the cost increase or delay; and
  - A description of any impacts the cost increase or schedule delay, or the actions described under subparagraph (B), will have on any other program within NASA.

In March 2006 NASA set forth policy changes to reduce cost growth in its projects. The agency implemented these changes in three steps:

1. Budgeting to the 70 percent probabilistic confidence level for both cost and schedule.
2. Establishing unallocated future expenses (UFE) at the NASA Headquarters level by funding the project at no less than the 50 percent confidence level.
3. Establishing an estimate range at KDP-B (after conceptual design but prior to preliminary design) to account for any potential design or schedule growth.

The initial policy was set forth by then NASA Administrator Mike Griffin in March 2006 stating: "NASA's standard practices will be to budget projects at a 70% confidence level based on the independent cost estimate."[4] The policy was further formalized in a NASA Interim Directive to NASA Procedural Requirement (NPR) 7120.5D and then fully formalized in NPR 7120.5E in 2009 with the intent that: "All space flight and information technology programs shall develop a joint cost and schedule probabilistic analysis and be baselined or rebaselined and budgeted such that there is a 70 percent probability of achieving the stated life cycle cost and launch schedule."[5]

Despite the establishment of these cost-estimating policies in 2006, JWST had already experienced cost growth in 2005. By 2010 the program required additional funding, which was not provided. The special Independent Comprehensive Review Panel investigation found that the baseline funding did not reflect the most probable cost with adequate reserves in each year of project execution. The replanning exercise prompted by that report resulted in an $8.8 billion life cycle cost, which is the current baseline.

It has now been eleven years since the implementation of these reforms, and a number of new space science missions—including large strategic missions—have been started and have proceeded through KDP-C to launch and initial operations. This has enabled independent assessments of the success of NASA's reforms. (See Figure 3.7.)

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[4] Tom Coonce, Joint Cost and Schedule Probabilistic Estimating and Budgeting Policy at NASA, February 2009.

[5] Ibid.

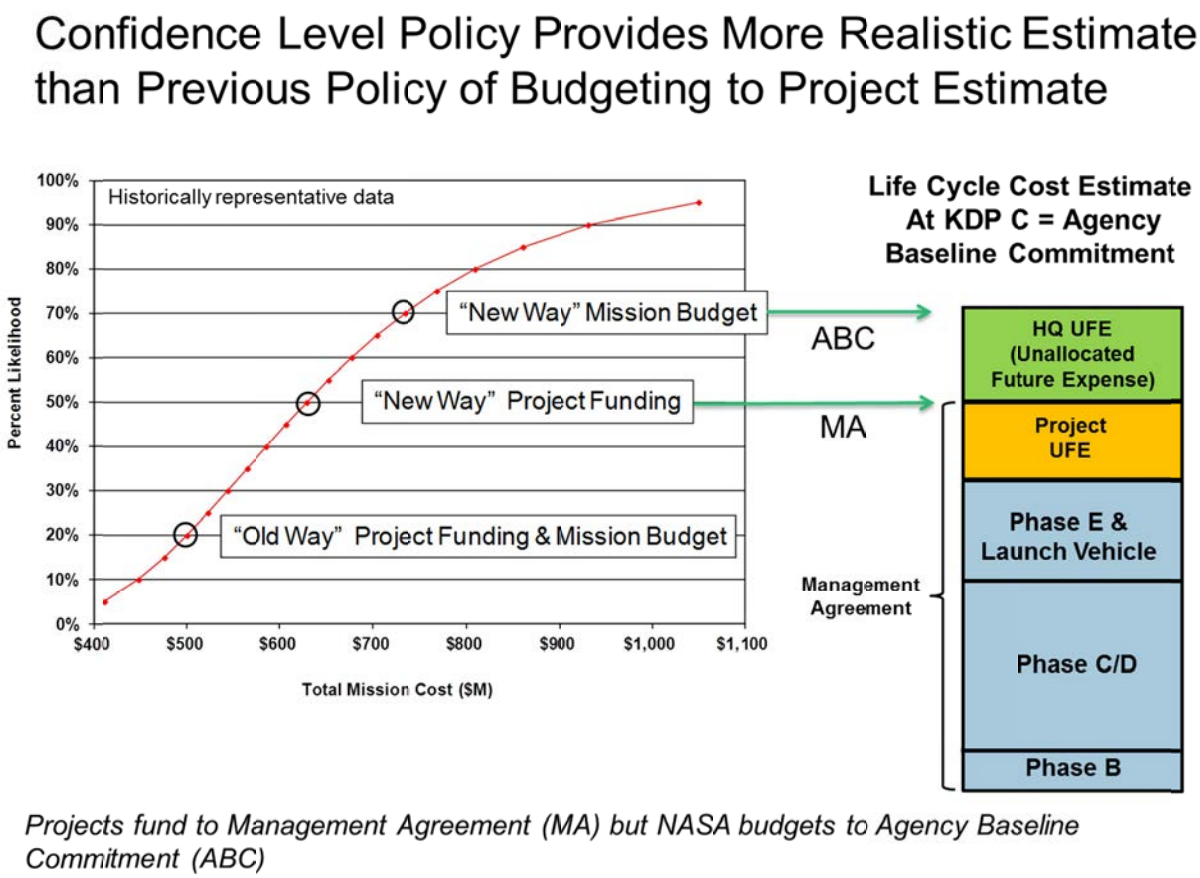

FIGURE 3.7 Graph showing the adoption of the policy implemented in 2006 requiring a higher confidence level when preparing independent cost estimates for missions. SOURCE: The Aerospace Corporation.

According to The Aerospace Corporation's Robert Bitten, The Aerospace Corporation looked at the cost increase from KDP-B and KDP-C for 42 missions in three distinct periods for projects having undergone a Preliminary Design Review (see Figure 3.8):

- FY1999 or prior (also known as the Faster, Better, Cheaper era);
- from FY2000 to FY2005, after FBC but before new confidence level policy; and
- after FY2006, when new confidence level policy was introduced.

Bitten informed the committee that the results show that the new policy is making a difference in terms of cost increase as measured from both KDP-B and KDP-C.

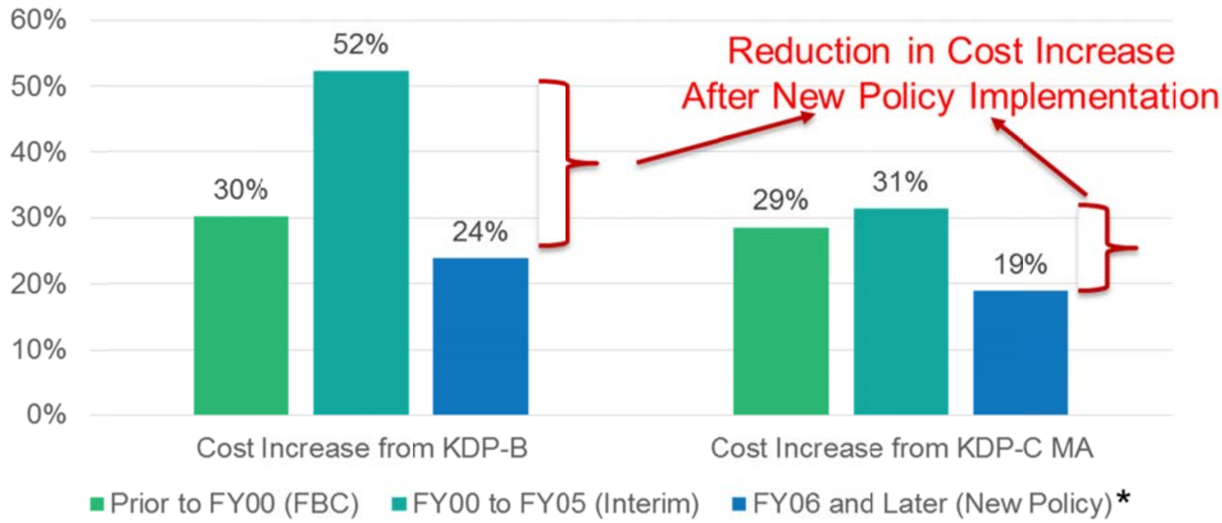

FIGURE 3.8 Example of the reduction in cost growth following KDP-B and KDP-C. One factor in cost prediction and control is how budget reserves are managed. Prior to the instigation of the new policy, limited budget reserves were maintained at NASA Headquarters and the majority of funding flowed down to the implementing center or lead organization. The policy of maintaining reserves in the form of unallocated future expenses—shown here as the difference between the 50-percentile and the 70-percentile estimates—resulted in flexibility with resources held at different levels within the agency. For example, if one project team was successful in delivering the system at or below the 50-percentile estimated budget, then the UFE remained unallocated at the directorate level and could be applied to other missions that were experiencing a larger amount of cost growth. By budgeting at the 70-percentile and holding reserves at higher levels, funds were essentially fungible and cost performance improved at the portfolio level. Furthermore, the policy resulted in a significant reduction in breach of the Nunn-McCurdy Amendment and thus less disruption to the development team. SOURCE: The Aerospace Corporation.

The Aerospace Corporation's conclusions have been supported by the Government Accountability Office (GAO) in its March 2016 report, "Assessments of Major Projects."[6] The GAO found that NASA is generally on track with its major space projects and had been successful at limiting cost growth. The GAO cautioned that several challenges may arise that affect the ability of NASA to manage its portfolio in the near future.[7]

The GAO noted that in 8 of the previous 9 years, NASA experienced at least one large-scale project with substantial budget and/or timetable growth. This form of growth usually occurred when the program reached the system assembly and integration phase. The GAO noted that there were nine projects that were reaching this critical development phase in 2016; thus, the agency is currently in a period of higher risk for cost overruns.[8] The GAO report stated that while NASA's overall performance has improved, there is a continued requirement to remain vigilant. (See Figure 3.9.)

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[6] Available at www.gao.gov/assets/680/676179.pdf. Although the committee refers to the 2016 report, the GAO produced a report in 2017 while this committee's report was in review. The GAO's 2017 report is consistent with its 2016 report. NASA Assessment of Major Projects, GAO-17-303SP, Government Accountability Office, May 2017.

[7] The GAO report included assessments of human spaceflight programs, which are beyond the scope of this study.

[8] Those projects are Parker Solar Probe; Ionospheric Connection; Ice, Cloud, and land Elevation Satellite-2; Transiting Exoplanet Survey Satellite; Exploration Ground Systems; James Webb Space Telescope; Space Network Ground Segment Sustainment; Space Launch System; and Orion Multi-Purpose Crew Vehicle.

Technology maturity and design stability aspects of NASA's large-scale projects were a common theme identified by GAO for 9 of the 11 major projects that passed the standards set by GAO best practices. The 2016 GAO report measured the overall costs for 12 projects in development at the time. The report found that the cost growth for development (excluding the James Webb Space Telescope)[9] decreased to approximately 1.3 percent, and launch delays were typically decreased to an average of 4 months.

The GAO report also noted that a major factor in past cost growth was the introduction of new technology. The average number of critical technologies used in the NASA projects that GAO assessed decreased from 4.9 in 2009 to 2.3 in 2016, which also had an impact on reducing cost growth. The report cautioned that in the future, planned projects will more likely use more technology development.

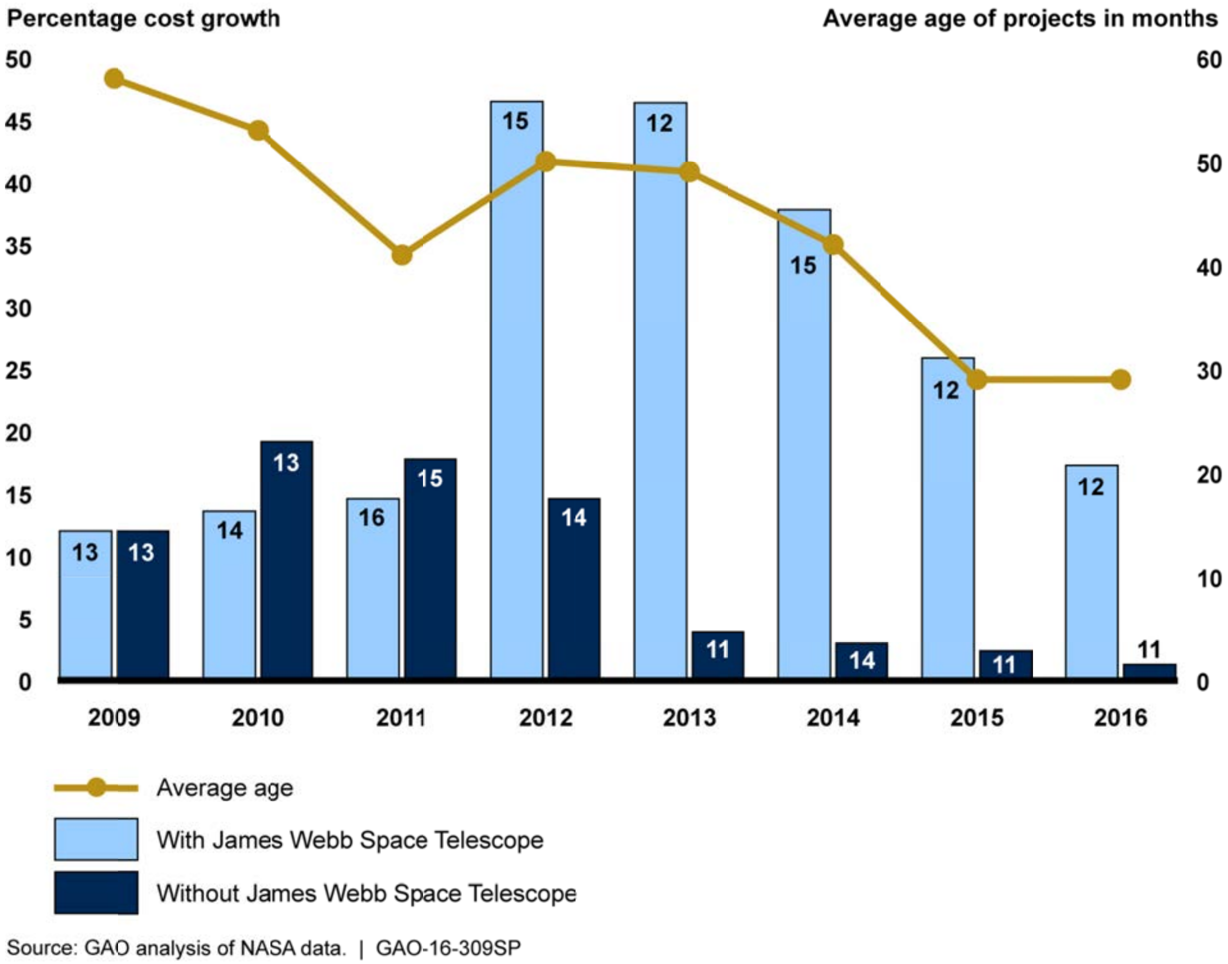

FIGURE 3.9 Percentage of cost growth for a range of NASA missions from 2009 to 2016. The data, when the James Webb Space Telescope is excluded, show a steady decrease in cost growth since 2010. This is consistent with other analyses such as that conducted by The Aerospace Corporation. SOURCE: Government Accountability Office.

[9] The JWST was not included in this report because its increase in schedule and cost was much larger than the other programs in development.

Both the Aerospace Corporation's assessment and the 2016 Government Accountability Office report are consistent and conclude that NASA has made significant strides in better estimating costs and limiting cost growth to its programs. The committee concluded that this has been an important NASA accomplishment in the past decade that has led to greater programmatic stability and allowed the divisions to better achieve their goals for balance. However, the committee also notes that there are additional methods that NASA can and has used to limit the impact of cost overruns, particularly of large strategic missions.

Over the past decade NASA has put in place a number of new approaches to cost control including establishment of independent cost estimates, periodic (up to monthly) project monitoring using earned value, major milestone cost/schedule reviews and increased allocation of reserves, among other approaches, to estimate and control cost throughout the project life cycle. These approaches, as explained in the GAO and The Aerospace Corporation reports, appear to be working and improving cost and schedule performance. Breach reports have become unusual events.[10] These approaches represent the kind of monitoring that has resulted in JWST staying on budget and schedule, and meeting milestones, since the program was restructured.

The 2005 "Baseline and Cost Controls" legislation included language similar to the Nunn-McCurdy-type controls for NASA projects. Thresholds were established for congressional notification for 15 percent cost growth over approved baseline or a 6-month launch slip beyond approved baseline. If cost growth exceeds 30 percent over the baseline, an 18-month timeline starts, after which specific congressional approval is required to continue the project. The fact that a project commits to a budget at KDP-C (confirmation) allows the concept to mature, technology to be advanced, and risks to be retired *before* the agency commits to the Office of Management and Budget to execute the program.

The committee notes that program cost overruns are directly related to the program's ability to accurately capture and mitigate risks, establish realism in the technical baseline, implement a method to introduce new technology and mature technology, and manage external factors that would lead to schedule and management issues. The ability to develop an accurate cost estimate does not lie solely in the hands of the cost estimating tools, techniques, and data, but in the program's ability to accurately reflect the program scope and risk.

FINDING: In the last decade, NASA has introduced numerous cost control and cost evaluation mechanisms. These mechanisms have been effective at limiting unexpected overruns and impacts on programmatic balance.

BOX 3.1
Case Study—The 2011 Planetary Science Decadal Survey

The past decade provides an example of how flexibility in implementing large strategic missions can assist NASA in accomplishing goals established by a decadal survey without creating major imbalance within the overall portfolio of missions. During the planetary sciences decadal survey the steering committee was given a budget projection by NASA for the Planetary Science Division for the period they were addressing (2013-2022). The budget identified run-out costs for current projects that were considered fixed and outside the scope of the committee. The committee referred to this as "the commitment." The committee was charged with prioritizing spending of the difference between the total budget projection and the commitment.

The decadal survey committee's highest priority large strategic mission was the Mars Astrobiology Explorer-Cacher (MAX-C) sample-caching rover that was a de-scoped version of the mission originally submitted to the committee. This de-scoped version eliminated the European Space Agency (ESA)-provided rover to allow use of mature hardware already developed for the Mars Science Laboratory

[10] The Nunn-McCurdy Amendment was included in the Department of Defense Authorization Act of 1982.

(MSL)/*Curiosity* rover mission. The resulting Mars 2020 mission is heavily based on the proven MSL/*Curiosity* mission.

The committee's second highest priority large mission was the Jupiter Europa Orbiter. The cost and technical evaluation (CATE) of the cost for the Jupiter Europa Orbiter mission was too high for the committee to recommend the mission as its first choice within the expected budget and also based on the "science per dollar" criterion used by the committee. The decadal survey recommended the mission be developed "only if changes to both the mission and the NASA planetary budget make it affordable without eliminating any other recommended missions."

The Planetary Science Division budget has been lower in the years 2011 to 2015 than the budget projections that were provided to the decadal survey steering committee, and current projections for 2016 and beyond are also lower than the survey projections, although these projections are in flux. The total amount available is roughly $2.3 billion less from 2011 to 2021. NASA therefore had to seek to implement the recommendations of the decadal survey with significantly less money.

NASA has implemented the Mars 2020 rover project that conforms to the guidance of the decadal survey (i.e., the requirements for the MAX-C rover). The rover has significant hardware heritage from MSL/*Curiosity*, including reuse of spare hardware. It is currently estimated to cost less than $2.5 billion.[11]

NASA has also begun the development of the Europa Clipper mission, which is intended to accomplish much (but not all) of the science outlined in the decadal survey. From 2013 to 2016 Congress has appropriated funding for a Europa mission. The mission reached its Key Decision Point-B milestone in February 2017. An independent cost estimate for the Europa mission will be developed after it reaches its KDP-C ("confirmation") point. However, the Europa mission was significantly de-scoped following the decadal survey in order to lower its cost, and the mission is expected to cost significantly less than the estimate produced for the decadal survey, which the committee considered to be unaffordable.

In order to fund the top-priority large strategic mission in the planetary decadal survey—the MAX-C rover now being implemented as the Mars 2020 mission—within a lower budget profile, NASA took several actions. These included delaying the New Frontiers 4 Announcement of Opportunity significantly as compared to the decadal survey recommendation, possibly holding only one New Frontiers announcement during the decade compared to the recommended two announcements. Other aspects of the planetary program that the decadal survey recommended should be protected, such as the Research and Analysis (R&A) program, were protected from cuts. NASA has also been able to begin work on the decadal survey's second large strategic mission recommendation, the Europa mission, now known as Europa Clipper. However, the recommended cadence for both the Discovery and New Frontiers programs has been lower.

There are valuable lessons that can be learned from the planetary science experience. One lesson is that it is possible to keep costs for large strategic missions within manageable limits provided the program considers ways to de-scope them, and the decadal survey has provided guidance on how to de-scope large strategic missions.

END BOX 3.1

THE DECADAL SURVEYS AND COST EVALUATIONS

Long before a large strategic mission is adopted by NASA, it is evaluated by a decadal survey committee. In advance of a decadal survey, advocates for certain science goals may develop

[11] In May 2017 the GAO indicated that the Mars 2020 mission was projected to cost $2.44 billion in then-year dollars. NASA Assessment of Major Projects, GAO-17-303SP, Government Accountability Office, May 2017, p. 59.

representative mission concepts designed to achieve a certain set of measurements. These concepts are typically called a "point design": a specific instance or existence proof that can achieve the science goal.

The decadal surveys are iterative in nature: the scientific community provides inputs—often with the support of NASA in terms of specific mission concept studies—and the decadal surveys produce a recommended prioritized scientific program that NASA (and on occasion other agencies, depending on the survey) attempts to implement.

As the Europa orbiter and MAX-C examples have illustrated, by providing NASA a range of options at varying levels of science, complexity, and cost, a decadal survey can assist the agency in examining options within a balanced portfolio, make trades against budget constraints, or appropriately sequence mission priorities within the coming decade. The existence of trade-offs might allow large strategic missions to co-exist with a science theme with other commitments—for example, developments already under way, R&A, or missions in the operations phase. The ability to make trade-offs or have variants of a mission concept might also inform the writing of decision rules that would provide NASA additional flexibility in the wake of a decadal survey. It is important to balance the desire for a range of science, risk, cost, performance, and schedule against practical considerations of team design capabilities, study funding limitations, or sufficient time to prepare notional missions in advance of a decadal survey.

RECOMMENDATION: NASA should ensure that robust mission studies that allow for trade-offs (including science, risk, cost, performance, and schedule) on potential large strategic missions are conducted prior to the start of a decadal survey. These trade-offs should inform, but not limit, what the decadal surveys can address.

Starting with the 2010 astrophysics decadal survey, the Academies as required by law instituted a cost and technical evaluation (CATE) process to assess risk, feasibility, and affordability of representative notional science missions. This process has been used for all subsequent decadal surveys. The CATE process has become particularly important for large strategic missions. Ideally, each decadal survey has latitude to apply or tailor a cost and risk evaluation process to their specific needs and to decide a dollar threshold above which to apply that process.

A CATE is not necessary for all mission concepts. However, the fundamental questions of whether the proposed approach to achieve a certain science goal and measurement is technically feasible and affordable within the coming decade are of paramount importance.

Cost estimation tools inherently lag behind the actual programs they assess. The reason is that NASA is often conceptualizing new approaches to increasingly ambitious science missions, many of which are first-of-a-kind, or taking advantage of new architectures or technologies. NASA is expected to push the state of the scientific and technological art and adopt new approaches in order to maximize science return. Cost models, whether empirical parametric tools or analogy-based approaches, are dependent on historical data for systems that have previously flown. Furthermore, new architectures such as large deployable optics, or CubeSats, sometimes extend beyond the boundaries of the existing cost databases upon which the tools and estimates are based. (In the case of CubeSats, NASA may benefit from the substantial development work currently being done in industry, which also wants to produce accurate cost estimates for its large projects.) NASA currently invests in data capture and tool development and it is important that the agency continue to do so. Mechanisms to capture and normalize cost data such as the agency's explanation of change (EoC) studies and the Cost Analysis Data Requirement (CADRe) database are of tremendous value. Because technology and management and development procedures are always evolving, new cost models and approaches will have to be developed for new applications—cost estimation cannot be static. Innovative approaches to capture cost reduction associated with leveraging commercial or agile development approaches, or taking advantage of heritage, for example, need to be rapidly inserted into the analysis tools so that estimates are not overly conservative. As manufacturing approaches change (for example, the industry moves to larger production runs on components, subsystems or complete satellites), the tools and databases will need to be evolved rapidly to remain relevant.

RECOMMENDATION: NASA should continue to use its various cost estimation and cost management tools to assess and control the costs and risks of large strategic missions to ensure that they remain a viable option. As new technologies and new missions arise, new cost estimation tools will be required to enable NASA to determine their likely costs. NASA should support the development of new tools to perform robust cost estimates and risk assessment. These new cost estimation tools will also be helpful in support of the National Academies' decadal surveys.

CONCLUSION

NASA's Science Mission Directorate has achieved great success since 2010 at better estimating the costs of its missions and controlling cost overruns. Although cost overruns for missions garner headlines, a number of NASA missions have actually been developed below cost. In addition, many NASA spacecraft have lasted significantly longer than their design life, providing tremendous overall benefit compared to their development costs. These success stories have received relatively little attention, but they were not accidental. They resulted from significant work and oversight by agency personnel, contractors, and advisory bodies.

The risk of cost overruns for large strategic missions is much greater simply because of their size and complexity. They can threaten the rest of a division's portfolio if they overrun by any substantial amount. For this reason, they receive substantial attention from agency leadership.

4

Comparing Large Strategic Missions and Smaller Missions

The statement of task charged the committee to:

> Assess the impact of current and recent SMD missions with a range of life cycle costs. A representative subset of missions within each of SMD's four science theme areas may be selected for analysis. The committee's analysis of each representative mission will include a discussion of the relation between mission scientific impact and mission life cycle cost (or cost to date) in order to understand the return on expenditures for various mission classes. In describing the impact of the chosen missions the committee should consider dimensions such as:
>
> - Scientific productivity;
> - Impact on the current and future health of the relevant scientific community; and
> - Contribution to development and demonstration of technology applicable to future missions.

In 2012 the Jet Propulsion Laboratory (JPL) led a study to try to adequately assess the impact of large strategic missions compared to competed missions for planetary sciences. The study team concluded that there are many rules that need to be followed in order to make an assessment. First, the approach needs to be quantitative and applied in a consistent manner throughout both classes of missions. Second, the information needs to be clearly identifiable and available to the public. Third, the study should be conducted by a group of people with viewpoints that are diverse and across the spectrum of competed and strategic planetary missions. The approach to these evaluations should include (1) the scientific impact; (2) the impact on the number of scientists directly supported; and (3) the impact on the number of mission instruments.

The scientific impact refers to the utilization of already existent data, which may include publications, citations, and *h*-index information taken from the Web of Science on a mission-by-mission basis. The *h*-index is defined as the number of papers cited at least *h* times each for a given mission (rather than for a given scientist).[1] The JPL study concluded that the citation peak for most publications is reached at the 5- to 6-year mark.

According to the JPL study's analysis of the *h*-index and other publication statistics, both large and smaller planetary missions have a significant scientific impact. If larger or smaller missions were eliminated in the future it would have a negative effect upon the program. For instance, eliminating large strategic missions would make it difficult to access challenging locations, and eliminating smaller missions would limit the ability to respond quickly to new discoveries. For the scientific community, eliminating either large or smaller missions could lead to major funding gaps that would place strain on the research and analysis program. For the engineering community specifically, there could be a loss of opportunity to produce unique classes of instruments required by planetary science, and loss of entry, descent and landing, and deep-space navigation capabilities. The JPL data are retrospective and aggregate

[1] J.E. Hirsch, 2005, An index to quantify an individual's scientific research output, *Proceedings of the National Academies of Science* 102(46): 16569-16572.

over four decades with a variety of political and fiscal environments. The JPL method is not predictive but is informative.

To seek to address the charge regarding comparing the impact of a range of missions, this committee requested data from NASA's Science Mission Directorate (SMD). The data were sought to inform the committee's analysis of scientific productivity, impact of missions and mission size on the current and future health of the relevant scientific community, the use of past technology, and the potential feed-forward of technology developed and demonstrated in current missions. Because the committee expected that data on a number of missions might be incomplete or nonexistent due to incomplete historical databases of program costs, it asked for data on more missions than it required for its analysis with the hope of obtaining sufficient information to accomplish the task.

NASA's SMD expended considerable effort to provide the committee with the requested data. Nevertheless and unfortunately, the data the four science divisions were able to provide are uneven and, in some cases, entirely missing. This affected the committee's ability to properly and thoroughly address the statement of task. In part, missing data is due to the change in accounting practices at NASA in the early 2000s and the switch to full cost accounting. Missions started before the implementation of full cost accounting, which includes many of the currently operating large strategic missions, have less complete cost data than more recent missions. A greater ability to rapidly provide public data of this kind, however, would have broader implications for the ability of SMD to present their story and successes to Congress, the executive branch (e.g., the Office of Science and Technology Policy [OSTP] and the Office of Management and Budget [OMB]), the NASA administrator, the scientific community, and the public.

The committee attempted to make some comparisons of the outputs of different-size missions for NASA's science divisions. The committee cautions, however, that any comparisons of such data are best made *within* their respective disciplines, not *across* the disciplines. For example, trying to compare scientific productivity of a heliophysics mission to an astrophysics mission would be highly dubious, because their value cannot be understood without the context of how they fit within their disciplines. Furthermore, publication data alone is not a perfect indicator of importance. The generation of thousands of peer-reviewed scientific papers from a single mission is impressive, but a single observation could significantly change an entire scientific field.

This committee was unable to draw many conclusions from the data on the various space science missions, other than some obvious ones such as larger missions result in funding more full-time equivalent personnel and higher numbers of publications. In general, the data confirmed information and comments that the committee heard from various speakers:

- Large strategic missions are inherently designed to conduct transformative science with order of magnitude increases in discovery space.
- Many large strategic missions are managed to engage a broad segment of the community, ranging from guest observer grants in the case of astrophysics to access to large layered data bases in the case of Earth science.
- Many large strategic missions address fundamental questions at the frontiers of the space sciences that are of great interest to the broader scientific community, to policy makers, and to the public.
- Technology development occurs in large strategic missions, as well as dedicated technology development programs. Technology can flow in multiple directions, from large missions to small and from small missions to large.

What several of the missions discussed in the following appendixes demonstrate is that technology development is different for each division, and there is no inherent path for technology flow. Currently small spacecraft such as CubeSats are generating technology that is migrating to larger missions. Larger missions have developed their own technology, some of which has been adopted by smaller missions and some of which is unique to those missions that develop it. Finally, separate technology development programs in the divisions, as well as the Space Technology Mission Directorate, have also been important incubators.

FINDING: Large strategic science missions support large teams of scientists and graduate students and therefore support the development and the health of their respective scientific communities in ways that smaller missions cannot.

FINDING: Smaller missions are often necessary to provide new insights, respond to recent discoveries, and refine the scientific goals of less frequent large strategic missions.

FINDING: Technology development occurs at many levels: large strategic missions, medium-size and even small missions, and separate technology developments programs.

The limitations of the data across various space science missions are in some cases a result of when these missions were in development. For example, the implementation of full cost accounting at NASA in the early 2000s has made cost comparisons between missions before and after this date—such as Hubble, Chandra, and Cassini—difficult except in broad terms. But now that full cost accounting has become the standard at NASA, it is easier for the agency to acquire and compare these data. In addition, the agency already uses its senior review process to gather data on the scientific productivity of its missions. The senior review data is publicly releasable and NASA has released it, although not consistently across divisions or always easily accessible. The committee concluded that there would be great value to the agency and its programs if the SMD made these data as well as its other programmatic data more publicly available and standardized. If, in the future, the SMD faces questions about the productivity and value of its large strategic missions, then having the data compiled and made public to respond to these questions would be vital.

RECOMMENDATION: In order to demonstrate the role and scientific productivity of large strategic missions in advancing science, technology, and the long-term health of the field, NASA's Science Mission Directorate should develop a publicly accessible database, updated at least annually, that tracks basic data related to all confirmed missions in development as well as operational and past missions from each of the SMD divisions. These data should include development costs; publication numbers and other bibliographic data; outreach data (number of press releases and so on should be tracked); science, engineering, and other full-time equivalents (FTEs); and other routine data typically sought in senior review proposal submittals once prime missions have been completed. These data should be of sufficient detail and quality to enable basic analyses related to scientific productivity and contributions to the health of the respective fields.

Although the committee acknowledges that establishing such a public database will require effort by NASA, it concluded that this would be useful to the agency in communicating the value and output of its missions as a whole, as opposed to via periodic press releases or at scientific conferences. The agency is in a better position today than it was only a decade ago to accurately report on its mission costs and performance across the entire Science Mission Directorate, and the committee concluded it can and should do so.

This study was initiated in part to evaluate the value and role of large strategic missions and concluded that they are highly valuable, to the scientific endeavor, to NASA, and to the United States. The committee concluded that NASA has substantial information to make that case and can continue to do so provided that it prepares the information in a coherent manner.

Appendixes

A

Astrophysics Science Division Missions

The committee requested data on several NASA astrophysics missions. These included the Astro-H (now the Hitomi), Kepler/K2, Nuclear Spectroscopic Telescope Array (NuSTAR), Wide-field Infrared Survey Explorer (WISE), Galaxy Evolution Explorer (GALEX), Swift Gamma-ray Burst (Swift), James Webb Space Telescope (JWST), and Fermi Gamma-ray Space Telescope (Fermi).

ASTRO-H

The Hitomi mission (formerly Astro-H) is a joint program between NASA and the Japan Aerospace Exploration Agency (JAXA). Launched in February 2016, the new Hitomi program's goal was to seek insights on evolutionary characteristics of some of the universe's largest structures, behavior of matter in gravity fields, black hole spins, internal structures of neutron stars, and the physics of particle jets. For Astro-H, Key Decision Point (KDP)-C was in June 2010 and launch was in February 2016. Astro-H was lost before it completed commissioning.

Scientific Productivity

The Astro-H Soft X-ray Spectrometer (SXS) was a cryogenic instrument, operating at 0.05 Kelvin (K). Achieving this temperature requires feed-forward technology. There are many future missions that will require sub-K technology. These include cryocoolers, to get down to 1 to 4 K, and solid-state magnetic refrigerators, to get to < 0.1 K.

The Astro-H microcalorimeter array works by sensing electromagnetic radiation as heat, similar to infrared (IR) detector technology. In fact, the X-ray calorimeter array on Astro-H would have made a very sensitive IR bolometer if it were configured for this application. The spacecraft also used very thin-film optical blocking filters, which have general applicability throughout X-ray and ultraviolet (UV) astronomy.

Impact on the Current and Future Health of the Relevant Scientific Communities

The spacecraft flew a detector array that was developed for the Astro-E2 (Suzaku) mission. The spacecraft also used spare electrical components. Critical capabilities were created and maintained at Goddard Space Flight Center (GSFC) in the areas of microcalorimeter fabrication and applications, low temperature systems technology, high spectral resolution X-ray calibration technology, and atomic physics as applied to X-ray astronomy.

Astro-H was a JAXA-led mission, with JAXA providing the project, spacecraft, launch, operations, three instruments, and part of the SXS. NASA provided key elements of the SXS (detector array, adiabatic demagnetization refrigerators [ADRs], aperture, electronics) and soft X-ray telescopes for two missions, as well as the science pipeline for the SXS.

Astro-H technology will enable future international missions including the Astro-H recovery mission and the European Space Agency (ESA) Advanced Telescope for High-Energy Astrophysics (ATHENA) mission, utilizing the X-ray Integral Field Unit instrument.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Astro-H carried the first calorimeter detector that accumulated scientific data of astronomical objects, such as the Perseus cluster of galaxies. These calorimeters are the detectors of the future, and more advanced versions will be key elements of any major mission. They are in the baseline instrument package (to which NASA is contributing) for ATHENA, an ESA L1 ("Large" class) mission. A calorimeter is also in the baseline design for a large strategic NASA X-ray mission, X-ray Surveyor. The development of the Astro-H calorimeter, funded by NASA, has created a team that leads the field in this technology.

Conclusions

Hitomi was a short-lived mission that demonstrated the power of an X-ray calorimeter for addressing astrophysical problems. The construction of the calorimeter detector helped NASA to advance this critical technology, which will be a vital instrument on any large X-ray mission of the future.

KEPLER/K2

Kepler is a mission that uses the transit method to find Earth-like planets around Sun-like stars. When the Earth passes in front of the Sun, as seen by a distant observer located in the plane of the ecliptic, a reduction in flux by 80 parts per million would be seen. This dip lasts for several hours and recurs every year. At least three, and preferably four, such transits must be seen to be sure one is seeing a planet instead of random glitches. In addition, less than 1 percent of distant observers will be situated where these transits can be seen. Thus, Kepler set out to obtain simultaneous photometry with 10 parts per million accuracy on more than 150,000 stars with continuous coverage for 4 years. It succeeded in this prime mission but then experienced a second reaction wheel failure, leading to a degraded attitude control capability. An extended mission, known as K2, is currently ongoing and is working around this difficulty by observing a field for about 80 days and then moving on to a new field. While this mission is unable to detect orbital periods longer than about 30 days, it can still find planets in the habitable zone around low luminosity stars. Since the number of stars observed by K2 is larger than the number observed by the prime Kepler mission, a larger variety of stellar types can be targeted, including red dwarfs and X-ray binaries like Sco X-1.

Scientific Productivity

Kepler has been an extremely productive mission. Through 2016, over 2000 papers using Kepler or K2 data have been published.

Impact on the Current and Future Health of the Relevant Scientific Communities

The Kepler mission has contributed to an explosion of the exoplanet community in astrophysics, to the point that it seems like astrophysics has become "all exoplanets all the time." Public interest in exoplanet research is very high, which encourages students to study science, technology, engineering, and mathematics (STEM) fields and Congress to continue to fund NASA. The techniques developed for Kepler that allow highly precise wide-field photometry have been widely adopted throughout the exoplanet community and will certainly be used in the upcoming Transiting Exoplanet Survey Satellite, which will extend K2-like observing cadences to the entire sky.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

There was, intentionally, little new technology developed for the Kepler mission. Off-the-shelf technology was used to the greatest extent possible to keep costs low. The only exception was in the development of the focal plane. While all the parts were essentially off-the-shelf, or built using existing processes, there was a need to extend certain practices: the coating of the sapphire field-flattener lenses required a complex custom technique to provide the consistent, required bandpass.

Although the Kepler mission did not use existing flight spares from other missions, it took significant advantage of technology and designs that already existed. The list includes fully off-the-shelf components and software (e.g., thrusters, star trackers, solid-state recorders) as well as system designs that needed only marginal Kepler-specific alterations (e.g., spacecraft bus, spacecraft operating system software).

Conclusions

Kepler has been a highly successful mission that has contributed substantially to the development of the field of exoplanets.

NUCLEAR SPECTROSCOPIC TELESCOPE ARRAY

The Nuclear Spectroscopic Telescope Array (NuSTAR) is the first orbiting telescope with focusing optics for a hard X-ray light (3 to 80 kiloelectron volts [keV]). First launched in March 2012, the prime mission was originally scheduled for 2 years but is now operating in extended phase. The current extended phase also includes a guest investigator program, and the spacecraft and instruments continue to operate nominally. The Senior Review of Astrophysics panel highly regarded the program in their 2014 and 2016 reviews.

The NuSTAR telescope also includes hybrid X-ray detectors that utilize CdZnTe sensors, which are segmented into 32 × 32 pixels with a 13 × 13 field of view. In addition to its positional sensitivity, it records the energy and arrival times of photons.

Scientific Productivity

NuSTAR has investigated a variety of high-energy astrophysical issues, such as detecting nuclear line emission from Ti in young supernova remnants; revealing supermassive black holes (active galactic nuclei) that are mostly hidden by large quantities of absorbing gas; showing the emission from the halos around black holes, where the light is bent by the gravity within the system; and resolving a significant fraction of the hard X-ray background. It maintains an active community and a strong publication rate.

Impact on the Current and Future Health of the Relevant Scientific Communities

The NuSTAR mission will have a positive impact on the current and future health of the astrophysics scientific communities. Some of the primary examples include the development and maintenance of the capabilities for the X-ray detectors (Caltech), the mirror production (Columbia), and contributions to maintaining the mission operations center at University of California, Berkeley, and its Space Sciences Lab.

Also, the maturation of technology, including the imaging in the hard X-ray band, can be infused for future missions. Other developments include the extendible mast, the adjustment mechanism, and the metrology system that will be used to help develop future Small Explorer (SMEX) X-ray polarimeter missions.

The mirrors, coatings, and detectors were developed through the suborbital program. NuSTAR adapted the deployable mast from the Shuttle Radar Topography mission. It used flight spares from the Lunar Reconnaissance Orbiter (LRO) (transceiver) as well as some miscellaneous electronic flight parts. The spacecraft was commercial-off-the-shelf.

The NuSTAR mission was also an international collaborative effort with Denmark's contribution of optics coatings and pipeline software and the Italian Space Agency's contribution of the Malindi ground station.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

This was the first hard X-ray telescope with focusing optics, a technology developed in part for this mission. Another contribution is the development of multilayer technologies for the optics, which extend the reflectivity to higher energies. The improvement in optics has led to an enormous improvement in sensitivity. The successful demonstration of this technology can naturally lead to higher quality optics with greater collecting area for future missions.

Conclusions

This Explorer-class mission demonstrated the exciting science possible with focusing hard X-ray optics and efficient detectors. There is considerable room for improvement in somewhat larger missions, given the relatively modest collecting area of NuSTAR, as well as improvement in multi-layer technology. The user base is significant and active and should increase if a subsequent mission is developed.

WIDE-FIELD INFRARED SURVEY EXPLORER

The Wide-field Infrared Survey Explorer (WISE) was launched on December 14, 2009, to scan the entire sky in infrared bands. The three primary goals were to find the most luminous galaxies in the Universe, to locate the closest stars to the Sun, and to discover and characterize asteroids. The Planetary Science Division of NASA funded a Near-Earth Object WISE (NEOWISE) add-on, which ran a special data processing pipeline. The WISE astrometric data on asteroids became available within a few days of observation and enabled ground-based follow-up. The project was then temporarily decommissioned in February 2011 and reactivated in September 2013 as NEOWISE-Reactivation (NEOWISE-R) with Planetary Division funding. This new mission focused its attention on scanning for near-Earth objects, producing only the single frame images and source detections useful for moving objects. NEOWISE-R continues to survey the sky in 2017.

Scientific Productivity

The scientific productivity of the WISE mission was substantial and provides many opportunities for development and research in the future. With over 7 years of flight, the returned science was vast and beneficial for researchers. The results of the mission included photographs taken of over 750 million objects, such as remote hyper-luminous infrared galaxies, nearby low luminosity cool brown dwarfs, and over 150,000 asteroids during the first year of the mission. Over 2000 refereed publications have used WISE data.

The WISE mission provided a critical platform for the development of new technologies. These new technological developments for the WISE spacecraft include the following: a 96 gigabyte (GB) flash memory card by SEAKR, the WISE Ku-band transmitter that was based on Fermi and supports a much higher data rate at 100 megabits per second, and the WISE Ku-band high-grain antenna that provides an evolved design from the model used in many commercial satellites. The technology development conducted for the WISE payload includes the following: the cryogenic readout for the WISE 1024 × 1024 Si:As detector arrays that provides more resources to detect longwave IR, which maintains competition and potentially lowers the cost of future missions; the 5 micron 1024 × 1024 HgCde detectors, which could also benefit future Near-Earth Object Camera (NEOCam) missions; and the WISE advanced telescope design developed by L-3 SSG-Tinsley, which utilizes lower cost materials such as aluminum diamond-turned mirrors that could benefit future mission proposals like NEOCam and Field Investigations to Enable Solar System Science and Exploration.

Impact on the Current and Future Health of the Relevant Scientific Communities

The WISE mission will have a positive impact on future missions through continual technology development and by providing a “heritage” of instruments used. This includes the WISE spacecraft, which was originally based on Ball Aerospace’s RS200-bus and software package. This package originated from the 2005 Deep Impact mission’s Impactor spacecraft and the 2007 Orbital Express mission’s NEXTSat spacecraft.

The payload component of the WISE mission will also be used as part of a larger line of payload technology development. The current system was developed and evolved from the Space Dynamic Laboratory for the Wide-field Infrared Explorer (WIRE) satellite. Before the WISE mission, WIRE was developed with a solid hydrogen cryostat under Lockheed Martin. The two short-wavelength detectors were also developed from a model used under the JWST (built by Teledyne). In addition to the shortwave detectors, the long-wavelength detectors originated from a smaller format used in Spitzer’s Multiband Imaging Photometer and Infrared Spectrograph instruments. These heritage developments decrease the risks and vulnerabilities that may come with testing new technology.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

WISE played a critical role in continuing many mission capabilities from other programs. This includes, but is not limited to, maintaining the Earth-orbiting mission operations capabilities from JPL; the science data processing and archiving capabilities from the Infrared Processing and Analysis Center at Caltech; and the expertise on solar system small bodies, brown dwarfs, galaxy clusters, and active galactic nuclei from both institutions.

Conclusions

WISE provided orders of magnitude improvements in the sensitivity of all-sky surveys in the mid-infrared, being hundreds of times more sensitive than the Infrared Astronomical Satellite at 12 and 22 microns, and hundreds of thousands times more sensitive than the Diffuse Infrared Background Experiment at 3.4 and 4.6 microns. By observing the whole sky, WISE automatically provided data for almost all astronomical research programs, leading to a large number of papers using WISE data.

WISE achieved its prime objectives. It discovered the third and fourth closest star systems to the Sun, a brown dwarf binary at 2 parsec (pc) distance, and the coldest known brown dwarf at 2.3 pc distance. WISE discovered a class of hot dust obscured galaxies with luminosities up to 400 trillion solar luminosities.

GALAXY EVOLUTION EXPLORER

Launched in 2003, the Galaxy Evolution Explorer (GALEX) is a small explorer (SMEX)-class mission with the purpose of studying the origins of star formation in galaxies. By observing low redshift galaxies in the ultraviolet, GALEX provided an important reference set for studies of high redshift galaxies where the rest frame ultraviolet (UV) was redshifted in the visible. GALEX had two wide-field ultraviolet detectors: the near ultraviolet (NUV) and the far ultraviolet (FUV). The planned program for the 29-month prime mission included a targeted Nearby Galaxy Survey and three levels of untargeted surveys: a Deep Imaging Survey (DIS), a Medium Imaging Survey (MIS), and an All-Sky Imaging Survey (AIS). GALEX was extended by more than one NASA Senior Review panel but was finally decommissioned on June 28, 2013. The FUV detector failed 6 years after launch. The UV detectors could be damaged by looking at bright stars, so the AIS was not actually all-sky, avoiding the galactic plane and bright stars at higher galactic latitudes. During the latter part of the extended mission, observations of the galactic plane and brighter stars were undertaken.

Scientific Productivity

GALEX data have been used in at least 750 papers. In addition, the data archive is available at the Barbara A. Mikulski Archive for Space Telescopes and can provide data on sources discovered at other wavelengths. The untargeted GALEX surveys have led to serendipitous discoveries like the long "comet" tail nebulosity being shed by Mira Ceti.

Impact on the Current and Future Health of the Relevant Scientific Communities

GALEX was a SMEX mission that ran on a very constrained budget. Thus, grants for guest investigators did not have a significant impact on the community. However, GALEX collected a large amount of data that still has value, and proposals to mine this archive can be submitted through the Astrophysical Data Program.

Conclusions

GALEX was a very productive SMEX mission. It was fully operational for more than twice its design lifetime and continued to provide useful NUV data for 4 additional years. Its archive covers most of the sky (except when limited by bright stars) and is the UV-equivalent of the Palomar Sky Survey.

SWIFT GAMMA-RAY BURST

Launched in 2004, the Swift Gamma-ray Burst mission (Swift) is classified as a medium explorer (MIDEX) mission. Swift includes a hard X-ray and gamma-ray burst detector (large field of view), a pointed soft X-ray telescope, and a pointed UV-optical telescope (larger field of view than the Hubble Space Telescope [HST] by approximately 20). The primary goals of the Swift missions were to determine the origin of gamma-ray bursts, to classify gamma-ray bursts and search for new types, to determine how the burst evolves and interacts with the surroundings, to use gamma-ray bursts to study the early universe, and to perform the first sensitive hard X-ray survey of the sky.

Scientific Productivity

The team rewrote the control software so that it could easily accept targets of opportunity from the outside (rather than being triggered internally). This allowed the team to interface with other ground- and space-based observatories. This leads to a natural synergy with other observatories when investigating astrophysical phenomena.

The team also opened up the telescope to a user community to perform any observations that the satellite was capable of. During the past 12 years, observations of transient objects have gained in importance, so these modifications transformed the telescope from a narrow focus to a much broader set of science.

Its ranking has been #1 of 11 in the 2008 Senior Review (SR), #4 of 11 in the 2010 SR, the best Explorer mission in the 2012 SR, #1 of 9 in the 2014 SR, and #1-2 of 6 in the 2016 SR. The high rankings reflect the adaptability to new science, which has led to an impressive set of discoveries. The budget has decreased from approximately $10 million per year to approximately $6 million per year. This is less than the team needs to run the observatory without risk, for which it has been criticized. Most of the cost is in full-time equivalents (FTEs), and the team has sold guaranteed time for cash in order to hire FTEs, a mutually beneficial arrangement.

Impact on the Current and Future Health of the Relevant Scientific Communities

Swift has made significant strides in the field of gamma-ray bursters, but its primary mission has become much broader. It responds to outbursts of many different types of astronomical objects (e.g., tidal disruption events) and is the leading space observatory for time domain astronomy. Its importance in the area of time domain astronomy will continue, even with significant new ground-based efforts. Swift covers wavebands not possible from the ground, and it responds extremely rapidly from its own triggers. In addition, the UV telescope is the best operating wide field of view UV telescope, with a field of view 6 times that of the Wide-field Camera (WFC) 3 on the Hubble. Overall, it offers a unique set of capabilities.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Swift was the first operating mission to employ CdZnTe detectors in an orbiting mission. This detector technology was used for the burst alert telescope, and it offered some significant advantages over previous detectors. It has demonstrated both excellent performance and longevity without significant degradation. The other new aspect of this mission was its rapid response time, about 1 minute from the time of the burst alert to the pointing of its X-ray and UV-optical telescope. This high-speed repointing and stabilization system has proven to be extremely reliable and of low risk. A third contribution is by flight software redevelopment after launch, which greatly improved flexibility for target acquisition and reduced costs. This shows that critical software can be modified on a large scale.

Conclusions

This Explorer mission delivered on its original scientific promise, unraveling the mysteries of gamma-ray bursts (GRBs) and, in the process, demonstrating the viability of a new detector and a fast response pointing system. Several years after the launch, the Swift team rewrote the flight software, allowing it to better respond to transient events, including targets of opportunity that are triggered by ground requests. These capabilities have transformed the mission, giving it greatly improved scientific breadth, from which it continues to be a high-value NASA asset, as judged from several NASA Astrophysics Senior Reviews.

JAMES WEBB SPACE TELESCOPE

The 2000 astronomy and astrophysics decadal survey ranked the James Webb Space Telescope (JWST) as the highest priority space astronomy recommendation. It was recognized as the successor to the HST and a continuation of the Great Observatories program.

JWST undertook an intensive technology development period following the selection of the prime contractor in 2002. According to the Independent Comprehensive Review Panel (ICRP) called for by Congress, these developments took longer and consequently cost more than forecast during formulation. The ICRP found, “The problems causing cost growth and schedule delays on the JWST project are associated with budgeting and program management, not technical performance. The technical performance on the project has been commendable and often excellent. However, the budget baseline accepted at the confirmation review did not reflect the most probable cost with adequate reserves in each year of project execution. This resulted in a project that was simply not executable within the budgeted resources.”

Following a rebaselining of the program in 2011, the program has met its technical milestones, schedule, and budget. Although it is widely recognized that the final testing and integration phase of the project is a major challenge, the project remains on track for launch in 2018.

Scientific Productivity

JWST has not yet been commissioned. The confirmation date was March 9, 2009.

Impact on the Current and Future Health of the Relevant Scientific Communities

JWST did not use any flight spares from previous missions. No specific hardware technology from prior astrophysics missions was used.

JWST is a partnership among NASA, ESA, and the Canadian Space Agency (CSA). ESA is providing the design, optical benches, filters, and dispersive optical elements for two science instruments (Near Infrared Spectrograph and Mid-Infrared Instrument); an Ariane 5 launch from Kourou with standard launch services; and 15 FTEs at the Space Telescope Science Institute (STScI) during mission operations. CSA is providing the Fine Guidance Sensor, one science instrument (they share opposite sides of one optical bench), and 5 FTEs at the STScI during operations.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Detector technology developed for JWST is being used in the NASA contribution to the Euclid mission. The Wide-field Infrared Survey Telescope (WFIRST) mission is studying whether components of the cryocooler system would be applicable for that mission. The cryogenic Application-Specific Integrated Circuit developed by JWST was actually used in the final servicing mission of Hubble. Also, several components of the community-facing software developed by the STScI for JWST are now being used for Hubble.

JWST developed numerous facilities for its construction and testing. The most significant and long lasting of these were the improvements at the GSFC Space Environment Simulator (SES) and the Johnson Space Center Chamber A facility. Smaller improvements were made at the Marshall Space Flight Center's X-ray and Cryogenic Facility. Most of these improvements were related to the mission's cryogenic and cleanliness requirements. Additionally, GSFC acquired two very large shaker table systems that could be useful for ambient testing of future missions. NASA does not track whether its industry partners maintained their JWST-specific facilities and hardware after they had finished using them. With the selection of STScI as the operations center for JWST, NASA has ensured that that capability, developed initially for Hubble, will exist should Hubble cease operations.

Conclusions

There have been many lessons learned from the JWST experience. The ICRP report stressed that agency managers plan for project reserves in the years needed and that inadequacy of reserves early in the program was a major factor in the bow wave of cost increases. The ICRP also highlighted the need for unimpeded, transparent communications at all levels to ensure that risks and budget problems are well understood.

FERMI GAMMA-RAY SPACE TELESCOPE

The Fermi Gamma-ray Space Telescope (Fermi) is the only observatory sensitive to cosmic gamma-rays that employs two instruments. The primary instrument is the Large-Area Telescope (LAT), which has a wide field-of-view pair conversion device and is sensitive to gamma-rays with energies between 20 megaelectron volts (MeV) and > 300 gigaelectron volts (GeV); photon energies, arrival times, and directions are recorded. The other instrument is a Gamma-ray Burst Monitor, operating in the energy range between 8 keV and 40 MeV. These two instruments have modest angular resolution but observe most of the visible sky continuously. This makes it different from most observatories, which operate in "pointed" mode. For point sources, it measures spectral properties as a function of time, making it the premier time domain observatory at these high energies. For extended sources that do not vary (e.g., Fermi bubbles), it accumulates photons in every orbit.

Fermi was a joint NASA and Department of Energy (DOE) collaboration, along with institutions in France, Germany, Japan, Italy, and Sweden. It was launched June 11, 2008, and has been working without degradation since full science deployment in August 2008. The 5-year prime phase ended in 2013, and it continues to operate in extended phase, following successful evaluations by the Senior Review (SR) panels.

Fermi is the highest energy orbiting observatory, with the photons detected coming from compact objects (active galactic nuclei, pulsars, neutron stars), explosive events (supernova remnants, gamma-ray bursters), and a few other potential or observed phenomena (dark matter decay, pulsar wind nebulae, terrestrial gamma-ray flashes). It has surveyed the sky, addressing the nature of the gamma-ray background and making the surprise discovery of giant bubbles of plasma extending from the center of the Galaxy, which probably were created by the supermassive black hole at the center.

Fermi has significant synergies with other missions and ground-based observatories, most prominently at high energies in the radio regime, and with optical ground-based efforts, such as surveys. It may contribute to the Laser Interferometer Gravitational-Wave Observatory detections. There is an active ground-based community involved in the data (mainly from the LAT) and publishing at a rate of about 300 to 350 papers per year. It has led to more than 200 Ph.D. theses.

Impact on the Current and Future Health of the Relevant Scientific Communities

The overall concept of the Fermi-LAT pair conversion telescope was directly derived from previous pair conversion telescopes (Energetic Gamma Ray Experiment Telescope [EGRET], Cosmic Origins Spectrograph [COS]-B, etc.). The optimization of the Fermi-LAT design was based on lessons learned from EGRET. Design of the micrometeoroid shield on Fermi-LAT was directly derived from the design developed for EGRET onboard the Compton Gamma-Ray Observatory (CGRO). The LAT benefitted enormously from the efforts in particle physics to develop silicon strip detectors at an affordable cost and in a manner that allows large-scale integration.

Fermi is an international and interagency partnership, supported by NASA and DOE in the United States and by agencies in France, Germany, Italy, Japan, and Sweden.

International hardware contributions and roles include the following:

- Sweden provides and acceptance tests the CsI crystals for the Fermi-LAT calorimeter.
- France designs and fabricates the calorimeter mechanical housing.
- Italy assembles and tests the Fermi-LAT tracker towers.
- Japan purchases and acceptance tests Si-strip detectors for the Fermi-LAT tracker.
- Germany provides Fermi Gamma-ray Burst Monitor detectors.

Fermi uses DOE (Stanford Linear Accelerator Center [SLAC]), French (Lyon), and Italian (Bologna) computing resources. The bulk of the processing is done on the High Throughput Computing facility at SLAC. Additional high throughput resources from the Computing Center of the National Institute of Nuclear Physics and Particle Physics in France and GRID-based supercomputers in Italy are used as needed.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Fermi pioneered the use of Mock Data Challenges and detailed detector simulations in NASA missions. These techniques have been adopted by missions such as the Laser Interferometer Space Antenna.

The Fermi-LAT tracker was the first large-scale silicon detector placed on a space mission. The technology development and lessons learned from the Fermi-LAT silicon tracker design and construction have a direct impact on reducing risk for future medium-energy gamma-ray mission concepts such as the All-Sky Medium Energy Gamma-Ray Observatory (United States) and eASTROGAM (ESA), both of which include large silicon strip trackers.

Science data processing for Fermi-LAT is complex and computer-intensive, and it requires handling of large data sets (5 terabytes per week). The pipeline infrastructure developed for Fermi-LAT to process data using approximately 1000 CPUs, track all data products and processes, and seamlessly utilize international supercomputing resources has been adapted for use on the Large Synoptic Survey Telescope. Since launch, there have been a number of improvements in the data processing software that have led to considerable noise reduction and improved sensitivity.

Conclusions

Fermi is unusual for the astrophysics division in that it was a joint project, mainly with the DOE, at a cost that would be in the range of a probe ($500 million to $1 billion). It was not competed in the same way as an established Announcement of Opportunity line (e.g., Explorer), so it may be considered a strategic mission. The LAT on Fermi is the only orbiting instrument capable of detecting photons at energies up to about 100 GeV with good sensitivity (GRB detectors have much lower sensitivity). It has made a variety of unique scientific contributions, carried forward by an active scientific community, with most publications from guest observers.

B

Earth Science Division Missions

The committee requested data on several NASA Earth science missions. These included Landsat 8; the large strategic Earth Observing System (EOS) missions Terra, Aura, and Aqua; and the small mission Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) and Gravity Recovery and Climate Experiment (GRACE). In addition, because these missions serve different purposes, it is difficult to make equal comparisons among them. In contrast, the Terra, Aqua, and Aura missions are more science-oriented in their goals, contributing to an understanding of the Earth as a system.

EARTH OBSERVING SYSTEM LARGE STRATEGIC MISSIONS

In the late 1980s, the Earth Observing System (EOS) was initiated to promote the concept of Earth system science supported by a large database of observations from satellites. The EOS concept spent many years in development and revision due to changes in the external science requirements, technological advancements, and budget environment. Officially initiated in FY1991, EOS was proposed as a series of spacecraft with an operational data collection period of 15 years. The platforms (at 10,000 to 11,000 kilograms each) were the largest ever flown, and they included a larger number of major instruments than previously hosted on a single spacecraft. After recommendations from the National Research Council and the Advisory Committee on the Future of the U.S. Space Program, and in recognition of the constrained fiscal environment, the program revised the payloads to make greater use of smaller platforms and shifted focus to concentrate on global climate change. As a result, the EOS mission set was divided into three large “flagship” missions supported by a state-of-the-art Data Information System (EOSDIS). Terra (initially EOS-AM1) was launched in 1999, followed by Aqua (initially EOS-PM1) in 2002, and Aura (initially CHEM) in 2004. These three missions are described in the following sections. Descriptions across the Terra, Aqua, and Aura entries are not necessarily equal; because Terra was the first in the series, there is more information available about that mission.

Terra

Terra was first of the EOS platforms built and is still operating. It is a large directed mission run out of NASA’s Goddard Space Flight Center (GSFC) and includes both facility and principal investigator-class instruments from three NASA centers, the National Center for Atmospheric Research (NCAR), and Japanese and Canadian partners. With an orbit collecting daytime data in the AM (local time), Terra carries a suite of five complementary instruments:

1. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), contributed by the Japanese Ministry of Economy, Trade, and Industry with a U.S.-led science team at the Jet Propulsion Laboratory (JPL), provides a unique benefit to Terra’s mission as a stereoscopic and high-resolution instrument required to measure and verify processes at fine spatial scales.

2. Clouds and the Earth's Radiant Energy System (CERES), originally a principal investigator (PI) instrument led out of Langley Research Center and now a facility-class instrument with similar sensors on several platforms (a copy of CERES is also flying on Aqua for the PM constellation), investigates the critical role clouds, aerosols, water vapor, and surface properties play in modulating the radiative energy flow within the Earth-atmosphere system.
3. The Multi-Angle Imaging Spectroradiometer (MISR), a PI-led instrument out of JPL, characterizes physical structure from microscopic scales (aerosol particle sizes and shapes), to the landscape (ice and vegetation roughness and texture), to the mesoscale (cloud and plume heights and 3-D morphologies).
4. The Moderate Resolution Imaging Spectroradiometer (MODIS), a facility-class instrument directed out of GSFC, acquires daily, global, and comprehensive measurements of a broad spectrum of atmospheric, ocean, and land properties, improving and supplementing heritage measurements needed for processes and climate change studies (a copy of the MODIS instrument was also included on the Aqua platform as part of the PM formation).
5. The Measurements of Pollution in the Troposphere (MOPITT) instrument, sponsored by the Canadian Space Agency (CSA) with a science team at the University Corporation for Atmospheric Research (UCAR), retrieves carbon monoxide total column amounts as well as mixing ratios for seven pressure levels, and its gas correlation approach still produces the best data for studies of horizontal and vertical transport of this important trace gas.

As an individual mission, Terra did not incur serious cost overruns, despite its size. Terra's phase B/C/D costs were $1.3 billion, distributed over nearly a decade. Terra expended about 30 percent of its funding and schedule prior to the preliminary design review and experienced only limited cost growth (less than 10 percent). Terra launched successfully, and all five of its instruments operated nominally on-orbit and collected data in its prime mission period from December 1999 through 2004. Terra had its first extended mission review (Senior Review) in 2005. In extended mission phase, costs changed over time as some of the R&D associated with Terra was stripped from the mission core-operating budget (prior to the 2007 Senior Review) and returned to the Earth Science Division general research pool supporting the broader community. By the 2007 Senior Review, the baseline operating budget for Terra was $38 million per year, distributed across three NASA centers and NCAR. Approximately 45 percent of those funds supported mission operations, mostly at NASA's GSFC; 51 percent was allocated for science—primarily data analysis for PI instruments; and the remainder was split between Education and Public Outreach and management. By 2012 the baseline operating budget of Terra was reduced to $30.6 million, with cuts to both the data analysis and mission operations components. Since the Terra platform is aging, and all five instruments rely on mission operations, further reductions in the mission operations budget were becoming problematic. In 2012 the data analysis and mission operations funding split was even. In extended mission phase (FY2012), the Terra core mission funded approximately 155 WTEs per year, spread across three NASA Centers, NCAR, and academic institutions.

Aqua

Aqua, the second of the EOS missions, obtains information on the Earth's water cycle, including evaporation from the oceans, water vapor in the atmosphere, clouds, precipitation, soil moisture, sea ice, land ice, and snow cover on the land and ice. Aqua instruments also observe radiative energy fluxes, aerosols, vegetation cover on the land, phytoplankton and dissolved organic matter in the oceans, and temperatures of air, land, and water. Aqua carries six instruments on board and, like Terra, has far exceeded its 6-year design life. Four of the Aqua instruments (Atmospheric Infrared Sounder [AIRS], Advanced Microwave Sounding Unit (AMSU), CERES, and MODIS) continue to operate well. The

Advanced Microwave Scanning Radiometer (AMSR-E) for EOS was turned off in May 2016, and the Humidity Sounder for Brazil instrument failed in February 2003.

Aura

Aura, the third of the EOS missions, was designed to provide observations of atmospheric composition from the near surface through the troposphere, stratosphere, and mesosphere in order to address three broad areas of scientific inquiry related to atmospheric composition: (1) recovery of the stratospheric ozone layer as the man-made ozone depleting substances, including chlorofluorocarbons, decline as a result of the Montreal Protocol and its amendments; (2) emission, transport, and chemical transformation of tropospheric pollutants; and (3) the roles of constituents including aerosols, water vapor, and ozone in climate change. Aura carries four principal investigator (PI)-led instruments. Two of Aura's instruments (Microwave Limb Sounder [MLS] and Ozone Measuring Instrument [OMI]) are operating well, and the Tropospheric Emission Spectrometer (TES) is making limited observations at the time of this writing. The High Resolution Dynamics Limb Sounder (HIRDLS) was compromised at launch but obtained a 3-year data set for most of its constituents. HIRDLS ceased operations in 2008.

Scientific Productivity

Understanding Earth's interdependent planetary-scale physical, biogeochemical, and climate systems requires that a broad set of measurements be made over long time periods—decadal or longer. At 17 years after the launch of the first EOS platform Terra, 15 years after Aqua, and over a decade since the launch of Aura, these large strategic EOS missions have had an enormous impact on the global Earth science community by providing over a decade of observations to the user community spanning all of NASA Earth Science Division's designated science focus areas. Where relatively little data existed supporting Earth system science prior to EOS, there is now an extensive library of well-calibrated, validated data with the spatial and temporal acquisition characteristics required to make significant advances in Earth system science. The data generated by EOS have been widely used by the global scientific community to garner its own funding for support outside of NASA. In aggregate, by 2016, Terra, Aqua, and Aura produced over 33,000 publications in the refereed literature from over 100 countries, and downloads from the three missions are in the millions of data files per year.

Terra

As of the 2016 Senior Review, Terra produced 81 community-defined, well-calibrated, validated, temporally and geospatially overlapping Earth observations supporting studies in climate variability and change; atmospheric composition; the carbon cycle and ecosystems; the water and energy cycle; weather; Earth's surface and interior; and applications in agriculture, disaster mitigation, and environmental studies. By the end of 2016, an estimated 14,400 publications using Terra data appeared in the refereed literature from 6480 unique institutions in 167 countries, with more than 285,000 total citations. More than 3000 of these publications were from the People's Republic of China, and over 3800 were from the European Union.

Aqua

Aqua continues to produce 78 data products supporting almost all fields of Earth science, from trace gases and aerosols in the atmosphere, to chlorophyll in the oceans, to fires on land, to the global ice cover, and numerous other geophysical variables. Year-over-year increases in publications and data downloads attest to Aqua's scientific productivity. By the end of 2016 an estimated 14,400 publications using Aqua data appear in the refereed literature. These are from 6184 unique institutions in 143 countries, with more than 275,000 total citations. More than 3000 of these publications were from the People's Republic of China, and over 3700 were from the European Union. There are many users of Aqua data beyond those supported by NASA-funded investigations (through either core mission or Research Opportunities in Space and Earth Sciences [ROSES]). Download statistics for 2016 show about 23,000 users in the United States, with 222,000 additional users worldwide. The committee did not obtain end-to-end mission cost data for Aqua. Ongoing funding for the extended mission in the 2015 Senior Review proposal cost about $28 million per year, with about 60 percent going to mission operations at GSFC and the remainder supporting science at JPL and GSFC. ROSES solicitations in 2014 (The Science of Terra and Aqua; Terra and Aqua—Algorithms—Existing Data Products) provided opportunities to the broad community interested in atmospheric composition research and also for targeted algorithm development.

Aura

Year-over-year increases in publications and data downloads attest to Aura's scientific productivity. Operational uses of Aura data have grown rapidly during the past few years, especially for air quality applications. Aura completed prime mission (6-year operations) in July 2006 and has participated in Senior Review every 2 years, beginning in 2009. To date, the 2330 Aura publications from 1151 unique institutions in 71 countries have been cited more than 36,000 times.

There are many users of Aura data beyond those supported by NASA-funded investigations (through either core mission or ROSES). Download statistics for 2016 show about 4000 users in the United States and 37,000 additional users worldwide. The committee did not obtain end-to-end mission cost data. Ongoing funding for the extended mission in the present Senior Review proposal cost about $25 million per year, with about half going to mission operations at GSFC and the remainder to the TES and MLS instruments teams at JPL and to the U.S. OMI science team. A recent ROSES solicitation included the Aura Science team along with the Atmospheric Composition Modeling and Analysis Program (ACMAP), providing a funding opportunity to the broad community interested in atmospheric composition research.

Impact on the Current and Future Health of the Relevant Scientific Community

As described earlier, the EOS missions Terra, Aqua, and Aura provide the basic library of science data needed by the Earth science community. The importance of these data to the science community can be seen by the request in the 2007 decadal survey that these missions continue to operate for as long as possible. The EOS missions have contributed directly to the health of the science community as well. In 2001, Terra and the EOS missions were directly supporting 159 graduate students and 112 postdoctoral studies, and by 2005, EOS funded more than 770 science investigators in over 330 separate investigations.

Terra

Terra continues to have a robust and positive impact on the current and future health of the Earth science community. Breakthroughs in Earth science not only require specific measurements, but they also require a long baseline over time to detect trends and tease out links between processes. This was recognized in the 2007 decadal survey with the recommendation that "every effort should be made to extend the life of Terra, Aqua, Aura, the Solar Radiation and Climate Experiment (SORCE), and Glory to ensure the longest possible data records and to minimize or eliminate critical data gaps." Because of the need for multidecadal records, data from Terra and the other EOS missions become more useful over time. This can be shown in the demand records for Terra data. In the first year of full operation (FY2001), the user community downloaded over 2.6 million Terra data files (not including metadata). This steadily grew, and in 2016 more than 284 million files were downloaded, with a mission total of over 1 billion data files being distributed to a growing international user community. In 2016 about half of the downloads were from foreign research organizations, with the rest divided up among U.S. federal, state, and local government agencies; businesses; and educational institutions. In Terra's post-launch lifetime (up through FY2016), of the more than 1 billion data files downloaded, about 40 percent of those were downloaded by foreign institutions, another 40 percent roughly split equally between U.S. government agencies (federal, state, local) and U.S. educational institutions, and about 8 percent by U.S. commercial enterprises (the remainder by users outside the tracked domains).

Terra's impact is also documented in the broader research and applications communities. Besides downloads from archives, Terra data pass through 143 direct broadcast sites with over 1000 users from these stations. More than 86 million Near Realtime files were delivered to the National Oceanic and Atmospheric Administration (NOAA), the U.S. Department of Defense (DOD), the U.S. Department of Agriculture, and other national operational users in FY2013 and FY2014. In 2014, the Office of Science and Technology Policy (OSTP) Committee on the Environment, Natural Resources, and Sustainability rated the Terra satellite among the top 10 of the nation's high impact observation systems for its impact on societal benefit areas, which include the following: agriculture and forestry, biodiversity, climate, disasters, ecosystems, energy and mineral resources, human health, ocean and coastal resources and ecosystems, space weather, transportation, water resources, weather, and reference measurements.

Aura

Aura data contribute substantially to several groups within the scientific community. Many MLS stratospheric measurements are unique (since the 2012 demise of European Envisat), and MLS ozone profiles (along with other MLS measurements of other constituents) are necessary to identify and quantify ozone increases that are expected as ozone depleting substances decrease, as mandated by the Montreal Protocol and its amendments. MLS and OMI together provide information needed to detect recovery of the Antarctic ozone hole. These data are critical input to the quadrennial World Meteorological Organization ozone assessments required by the Montreal Protocol. Measurements of ozone and water vapor in the upper troposphere and lower stratosphere are necessary for understanding their contributions to climate change and feedbacks in the climate system. TES data provide insight into the long-range transport of pollutants and the impact of such pollution on air quality worldwide. Health community use of Aura data has grown dramatically since 2015. Applications include exposure to ultraviolet radiation (controlled by stratospheric ozone levels) and exposure to nitrogen dioxide (an industrial pollutant and component of automobile exhaust). Data from Aura and various A-train sensors are in use to quantify interactions between composition and clouds, chemical compounds and aerosols, upper tropospheric composition and convective processes, and other topics too numerous to list here.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

The large size and cross-disciplinary nature of the EOS missions served as a test bed for demonstrating and testing different technologies and approaches for meeting Earth science goals. As a result, many of the instruments on the EOS platforms were state of the art in the development phase and became predecessors for follow-on missions. With 15 instruments on three platforms, describing each one here is not practical. Instead, in this section the committee cites some examples, which are not meant to be ranked or exhaustive.

Terra and Aqua

Terra and Aqua carry versions of two instruments deemed to be of such primary importance that it was desirable to have data collected twice during daylight hours (locally)—CERES and MODIS.

The CERES instrument was a significant advancement over its predecessor, the Earth Radiation Budget Experiment. Advances in the time response of thermistor bolometers increased spatial resolution by a factor of 2 and increased instrument lifetime by a factor of 3 (and counting). The CERES ground calibration facility enabled a factor of 2 improvement in absolute calibration accuracy. The CERES instrument's innovative azimuthal axis drive system provided the ability to rotate in azimuth as it scans in elevation, which greatly improved the angular sampling needed to convert measured radiances to radiative fluxes. The azimuth axis drive system also enabled CERES to be placed in a programmable mode for intercalibration with other instruments and sample optimization to support field campaigns. CERES demonstrated how multiple instruments (CERES, MODIS, geostationary imagers) can be used synergistically to provide a diurnally complete representation of Earth's radiation budget from the top-of-atmosphere to the surface with unprecedented accuracy. The many advances in CERES technology and data processing, and the important lessons learned gained during over 17 years in orbit, are now being incorporated in the successor to CERES, the Radiation Budget Instrument (RBI).

The closest predecessor to MODIS was the Advanced Very High Resolution Radiometer (AVHRR) that operated on NOAA polar platforms for more than two decades. MODIS improved on the spectral sampling and signal-to-noise ratio over the heritage AVHRR. The prelaunch and onboard calibration of MODIS vastly improved that of AVHRR, which did not have a means of monitoring its absolute calibration. Aqua MODIS is now used by the Global Space-based Inter-Calibration System (GSICS) as its standard for intercalibration of operational geostationary and low-earth-orbit imagers. MODIS was designed with what is still the most comprehensive onboard calibration systems, including a Spectralon-based solar diffuser approach with a solar diffuser stability monitor (SDSM), a new V-groove blackbody, lamp-based source coupled with a spherical integrator, and spectroradiometric calibration assembly (or SRCA). The many advances in MODIS technology and data processing have impacted the design and operation of the Visible Infrared Imaging Radiometer Suite (VIIRS); Operational Land Imager (OLI); Thermal Infrared Sensor (TIRS); Climate Absolute Radiance and Refractivity Observatory (CLARREO); Plankton, Aerosol, Cloud, and Ocean Ecosystem (PACE); and Advanced Baseline Imager (ABI). The overall success of MODIS led to its design being the basis for the VIIRS sensor on the NOAA polar orbiting platforms. The SRCA gave confidence that new designs of spectral filters were not susceptible to degradation on orbit, meaning that future sensors would not need to include an SRCA and could rely on simplified prelaunch characterization leading to shorter development times, lower sensor weight, and associated cost savings. The success of the design of the MODIS onboard blackbody was implemented for TIRS, simplifying the design and shortening the development time of the onboard calibrator for that mission. The SDSM provided a clear understanding of how the MODIS solar diffuser changed on orbit and how processing of the SDSM data led to a model of the behavior of Spectralon as a function of solar illumination. The Spectralon solar diffuser demonstrated that this material was suitable for use in both operational and research sensors and what manufacturing processes are needed to mitigate changes on orbit. The OLI project used the SDSM data to define an on-orbit operational approach with three diffusers, rather than requiring an SDSM. The CLARREO project used the MODIS results to verify that a diffuser approach would not satisfy requirements leading to a lower weight, solar irradiance ratio approach for on-orbit calibration. The VIIRS mission required a monitoring system similar to SDSM to achieve their requirements and relied on the SDSM design to shorten development times and define prelaunch characterization. The science from MODIS defined the spectral bands needed for the operational VIIRS and ABI missions. The use of the moon and terrestrial desert scenes for monitoring sensor health has led to the definition of protocols and methods for multiple other missions, allowing the moon and deserts to be lower cost options for on-orbit radiometric calibration. Similarly, the algorithms to process MODIS data to retrieve aerosol properties, locate fires, assess snow/ice, track vegetation changes, and retrieve cloud parameters have been used for the VIIRS project and are being considered for

ABI, leading to high quality data products while leveraging the development time and costs through the Terra and Aqua missions.

Terra: Advanced Spaceborne Thermal Emission and Reflection Radiometer

Composed of three separate instrument subsystems (the visible and near infrared [VNIR], the shortwave infrared [SWIR], and the thermal infrared [TIR]), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) pushed the state of the art in multispectral imaging, especially in space-based multispectral stereoscopic imaging and high-resolution multispectral remote sensing in SWIR and TIR. ASTER is the only instrument with high-resolution (90 meters) multispectral TIR imaging bands, and it remains an important contributor to the development of future TIR missions. Throughout its lifetime, researchers demonstrated how the unique information from the TIR benefits many disciplines. Several initiatives have built on ASTER's technology, data processing, and acquisition strategy. The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), a multispectral TIR instrument heavily reliant on ASTER's heritage, is scheduled to go on the International Space Station in 2018. The Hyper Spectral InfraRed Imager, a Decadal Survey Tier 2 mission, is planned as the natural follow-on to ASTER.

Terra: Multi-Angle Imaging Spectroradiometer

The Multi-Angle Imaging Spectroradiometer (MISR) demonstrated the use of miniaturized focal plane "butcher block" pushbroom stripe filters; automated photogrammetric image geolocation and co-registration data processing algorithms; and advanced multi-angle, multispectral data processing algorithms to improve the ability to measure and map the abundance of different types of airborne particulates. These technologies were subsequently used by the Multi-Angle Imager for Aerosols investigation of the human health impacts of airborne particulate pollution, which was selected in 2016 under the Earth Venture Instruments-3 program and will fly as a hosted payload on a commercial satellite platform. MISR technology was also used to demonstrate a novel, automated multi-angle stereophotogrammetric remote sensing and data processing approach for the measurement of accurate, height-resolved atmospheric winds. When combined with recent advances in complementary metal-oxide-semiconductor array detectors flown commercially on SkySat-1 and SkySat-2, this approach will enable the design of a low-cost, compact cloud-tracking wind sensor that can be used to provide global winds from a future low-Earth orbit satellite constellation.

Terra: Measurements of Pollution in the Troposphere

The Measurements of Pollution in the Troposphere (MOPITT) instrument makes use of the principle of correlation spectroscopy whereby a cell of the gas to be measured is used as an optical filter in the infrared to measure the signal from the same gas in the atmosphere. Using this approach, MOPITT first demonstrated the ability of satellites to continuously monitor global sources and transport of carbon monoxide in the troposphere. Retrieval techniques, model evaluation, and data assimilation for remotely sensed trace gas data have all been greatly enhanced through experience with MOPITT data. MOPITT was also the first satellite instrument to demonstrate the use of radiance observations from separate wavelength regions simultaneously for the determination of both near surface and free troposphere trace gas concentrations. These advances have been applied to later instruments such as AIRS on Aqua, the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography on Envisat, TES on Aura, Infrared Atmospheric Sounding Interferometer on MetOp, and future instruments such as the upcoming Tropospheric Monitoring Instrument on Sentinel-5p.

Aura

Aura provided the opportunity for advancements in technology over predecessor missions. The Aura MLS obtains a more comprehensive suite of constituents with improved vertical range and resolution compared to the MLS instrument that was flown on the Upper Atmosphere Research Satellite (UARS) and included a novel terahertz radiometer to obtain a near daily global 5-year data set for the hydroxyl radical. TES obtained the first simultaneous profile information for tropospheric ozone and precursor gases. HIRDLS obtained profiles of temperature and ozone with about 0.5 kilometers (km) vertical resolution, the best ever achieved with remote sensing. The OMI observed total column ozone and near surface pollutants, including nitrogen dioxide and sulfur dioxide, with unprecedented horizontal resolution (13 km × 25 km) with a wide swath, obtaining daily global coverage for the first few years of operations and within 2 days at present. Improved algorithms make it possible to estimate emissions of nitrogen dioxide and sulfur dioxide directly from OMI data. The Aura team has combined information from several sensors to improve vertical resolution or horizontal coverage. This includes using more than one Aura sensor (e.g., MLS/TES carbon monoxide, OMI/TES ozone) or including an A-train sensor (OMI/[Aqua]AIRS ozone).

Conclusions: Terra, Aqua, and Alta

Terra (and the other EOS missions) clearly demonstrates that large strategic missions can successfully serve to focus and galvanize the science community around new and emerging scientific perspectives. As the first of the Earth Observing System (EOS) missions, Terra was referred to as a "flagship mission" in Earth science because it was the first in a series demonstrating the value of a "great observatory" approach for collecting the vast amount of data required to advance Earth system science. At the time of its conception, there was a sense of urgency in the community to begin collecting the vast amount of daily, global observations needed to test and advance the state-of-the-art physical, biogeochemical, and climate models and better understand the magnitude and direction of critical processes and their linkages. Terra and the other EOS missions did this very well. As large missions, they not only provided the basic data to advance Earth system science in its early phase, but they also continue to provide needed baseline data and the continuity required by the science community to fully realize science goals. Terra also sustained the community by providing a test bed for technological development and financial support with durations that provide stability for learning and career development. The mission funds for Terra (and other EOS missions) were widely distributed across sectors (government, commercial, and educational) and supported personnel in science, engineering, and management of a duration (decadal timeline) sufficient to establish and maintain a national capability. Educational timelines, for example, are getting longer, and the average Ph.D. in the sciences takes over 6 years of postgraduate work.[1] The Terra mission alone supported the education of a generation of scientists and engineers for nearly 10 years in formulation and another 4 in prime mission, contributing significantly to making the United States a leader in Earth observation science and technology. The large strategic nature of Terra also enabled international cooperation and fostered U.S. leadership. Funding and schedule duration for a large mission better facilitates international collaboration through the availability of personnel and cross-administration stability. Terra (and Aqua and Aura) had broad and deep national and international support including international partners. EOS stimulated the development and formation of numerous Earth system science research centers and enterprises worldwide, and the instruments flown on these missions are emulated by other countries. Data from the EOS series of missions are used globally by many thousands of scientific researchers, investors, policy makers, and commercial enterprises. Also important in the success of Terra

[1] National Center for Science and Engineering Statistics Directorate for Social, Behavioral, and Economic Sciences, National Science Foundation, December 2015 NSF 16-300, https://www.nsf.gov/statistics/2016/nsf16300/digest/nsf16300.pdf.

and the other EOS missions is the EOSDIS. EOSDIS is the world's largest Earth satellite data distribution system and has been responsible for making data from NASA's EOS fleet available to scientists and users worldwide. EOSDIS was built within the concept of large strategic missions and has subsequently benefitted missions of all sizes.

Earth science missions have a unique position within NASA, responding to both immediate and long-term societal needs. The current Earth science decadal survey will define balance for the recommended program in the future.

CLOUD-AEROSOL LIDAR AND INFRARED PATHFINDER SATELLITE OBSERVATION

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission is an international partnership between NASA and the French Space Agency (CNES). Launched on April 28, 2006, CALIPSO measurements fill a crucial, well-recognized need for high-resolution atmospheric profiling and are proving essential in reducing the uncertainties that limit our understanding of the role of aerosols and clouds in the global climate system. The 3-year nominal mission was completed in April 2009. It was subsequently extended during Earth Science Division Senior Reviews in 2009, 2011, 2013, and 2015. CNES participated in and concurred with all mission extension decisions.

The CALIPSO instrument suite consists of a two-wavelength polarization-sensitive lidar, a three-channel infrared imaging radiometer, and a single-channel wide field-of-view camera.

Since launch, CALIPSO has been acquiring near-continuous observations of the vertical distributions of clouds and aerosols in the Earth's atmosphere. The new information provided by these unique measurements is substantially advancing human understanding of the spatial structures and optical properties of clouds and aerosols, and markedly improving the performance of a variety of models ranging from regional chemical transport and weather forecast models to global circulation models used for climate prediction.

CALIPSO orbits in formation with five other spacecraft in the A-Train satellite constellation and provides complementary, near-simultaneous observations with CloudSat and the many passive sensors in the A-Train.

Scientific Productivity

CALIPSO observations and data products are widely used throughout the international scientific community. CALIPSO measurements, accumulated over 10+ years of near-continuous global observations, provide new and valuable insights into the distributions and properties of aerosols and clouds and the processes that control them. CALIPSO observations are greatly improving our understanding of radiative forcings and feedbacks, allowing for more powerful evaluations of cloud and aerosol parameterizations in a variety of models, and providing comprehensive validation of other remote sensing techniques. The CALIPSO observational record now captures significant interannual modes of variability, which influence climate on seasonal to decadal scales.

CALIPSO data are used in increasingly sophisticated ways, and there is increasing use of merged data products that combine CALIPSO and CloudSat measurements with A-Train passive sensor data, such as 2B-FLXHR-Lidar and C3M. CALIPSO observations have been widely adopted by the modeling community, particularly by the Cloud Feedback Model Intercomparison Project. CALIPSO observations and data products produced by the CALIPSO project are highly valued by the international scientific community and are used in more than 1800 publications.[2] (See Figures B.1 and B.2.)

[2] A complete bibliography of peer-reviewed CALIPSO publications can be found at https://www.calipso.larc.nasa.gov/resources/bibliographies.php.

Benefits to Operational Agencies

CALIPSO profile observations provide a valuable source of information for operational forecast centers and application-focused researchers. Expedited products, with a latency of 24 hours or less, are produced for users with time-sensitive applications. Standard products have a latency of several weeks and can be used for off-line evaluations. Additionally, CALIPSO provides a near-real-time expedited aerosol product specifically designed for assimilation by operational centers. This mission demonstrates that science missions can have value to operating agencies that have to make predictions about weather events.

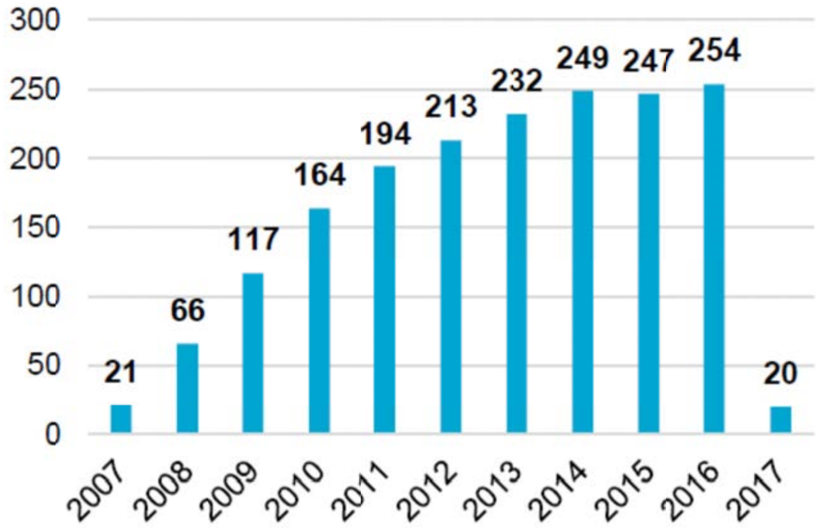

FIGURE B.1 Publications based on CALIPSO data by year. SOURCE: NASA data.

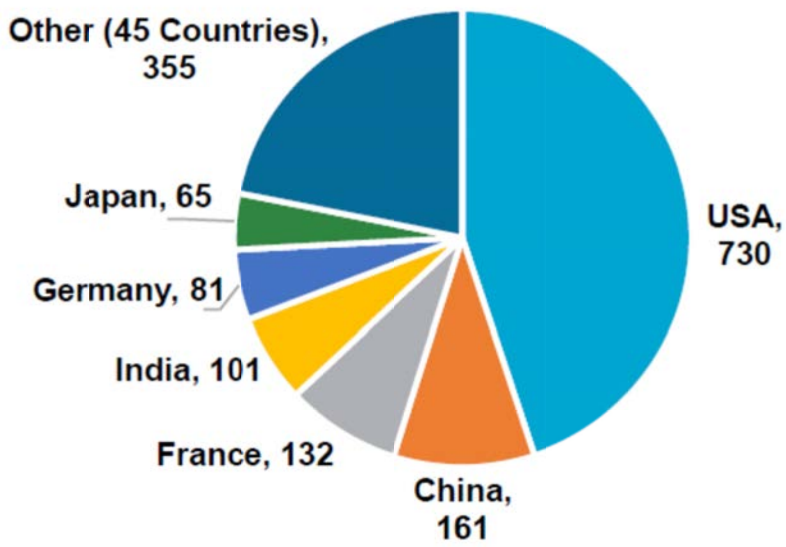

FIGURE B.2 Publications by country highlighting the location of the lead author's institution. Overall, institutions from 51 countries have sponsored CALIPSO publications, with the United States at 730 publications and France at 132. SOURCE: NASA data.

Conclusions

CALIPSO is an example of a mission that is both international and serves an operational purpose. It demonstrates that traditional metrics of evaluating the productivity of a mission, such as published papers, may not capture the full value of a mission. How can the value of a mission that produces benefits to international partners as much as the United States be judged? How can the value of a mission that may provide timely data required for forecasting and decision making be compared to the slower pace, and different impacts, of scientific publications? CALIPSO demonstrates that missions have to be evaluated on individual merit in addition to more traditional metrics such as publications produced over a longer period of time.

GRAVITY RECOVERY AND CLIMATE EXPERIMENT

The Gravity Recovery and Climate Experiment (GRACE) is a collaborative NASA and German Aeropace Agency (DLR) mission launched on March 17, 2002, as the first of the Earth System Science Pathfinder missions. The objective of the GRACE mission is to characterize the spatial and temporal variations in the Earth's mass transport, through accurate measurements of its gravity field. The GRACE mission completed its baseline 5-year mission in 2007 and has received four additional 2-year mission extensions. The GRACE extended mission provides a continuous, multiyear sequence of measurements that characterize the seasonal cycle of mass transport between the oceans, land, and atmosphere; observes its interannual variability; and measures the decadal and secular trends in mass transport.

GRACE provides new insights into the evolution of the Earth's climate system by making mass flux measurements at spatial resolution scales, from approximately 200 km to global, and time scales, from 10 days through the interannual and secular. The GRACE measurements are recognized as a key component of NASA's capability to observe the Earth system interactions. The mission is characterized by the following: (1) the unique GRACE ability to observe coupled processes within the Earth's land, ocean, atmosphere, and cryosphere subsystems; (2) the consequent multidisciplinary viewpoint of the users of GRACE data products; and (3) a cost-effective mission implementation achieved through cooperation between NASA and DLR.

Examples of new measurements uniquely determined or enabled by GRACE include the following:

- Mass change in the polar ice sheets, continental glaciers, and the permafrost;
- Mass contribution to sea-level rise, the separation of ocean thermal expansion (heat-content) from mass changes, and the estimation of deep (> 2000 m) ocean heat content;
- Global measurements of the hydrological cycle including seasonal and interannual river basin water storage changes, human influences on regional water storage changes, large-scale evapotranspiration, land-ocean mass exchange, and regional aquifer changes;
- Changes in the deep ocean currents and mass and energy transport, inter-ocean-basin mass variations, and regional oceanic processes;
- Large-scale post-glacial rebound; and
- Episodic mass displacements and mantle flow associated with large earthquakes.

The twin GRACE satellites have collected science data continuously since commissioning in April 2002. Currently, the satellites are in near-circular, polar orbits at ≈337 km altitude and maintain along-track separation of ≈220 ± 50 km. After 15 years in orbit, the science instrumentation has reduced performance. The declining capability of the power system has forced changes in the science operations since 2011. Near the epochs of sun passage through the orbit plane every 161 days, both the accelerometer and the K-Band ranging instruments are turned off, leading to delivery of 8 to 10 monthly gravity field products during recent calendar years.

Scientific Productivity

There have been over 2000 publications based on the GRACE data during its 15 years on orbit, with an average of 200 publications during the past 6 years. Figure B.3 shows the number of publications per year since the launch of the mission.

Permission Pending

FIGURE B.3 GRACE peer-reviewed articles from 2002 to 2016. SOURCE: Byron Tapley.

Impact on the Current and Future Health of the Relevant Scientific Community

Since launch in 2002, the GRACE mission has provided unprecedented knowledge about the interactions of the Earth system. Using global measurements of gravity as a sensor of mass change, GRACE has detected and quantified changes in all major components of the water cycle. In particular, the mission provides fundamental insights into polar ice sheet melt and its contribution to sea level change, ocean mass changes as they relate to ocean circulation, sea level variations and ocean heat content, and detailed views of the world’s surface and underground water resources. Based on the significant advances in both the measurement capability and the interpretative framework during the mission’s 15-year life span, GRACE data is now an essential asset for a number of hazard assessment efforts. With the development of the capability to reduce the product latency, it is now an essential input to operational drought forecasting within the framework of the U.S. National Drought Monitor. In 2016 several international efforts were founded on the GRACE gravity data for disaster prevention and forecasting (the multination European Gravity Service for Improved Emergency Management). In addition to drought and water resource assessment, GRACE also provides crucial information for flood prediction, as shown in recent FY2016 publications. Overall, global measurements of regional water storage are capabilities that are uniquely provided by GRACE, and these measurements will be a unique resource for future water management. In a significant accomplishment GRACE data has been ingested by a Land Data Assimilation Model to demonstrate significant improvements in the spatial and temporal resolution of the Total Water Storage Products and to provide a separation of the columnar total water storage into the surface, soil, and ground water components. The near-real-time provision of these products can support forecast and planning activities related to societal water use for agricultural and consumption purposes. This broad range of applications clearly illustrates the multidisciplinary nature of the GRACE mission and its ability to aggregate scientists from different disciplines in Earth sciences.

The current number of annual users, who extract data from the GRACE data system, exceeds 4500. Figure B.4 shows the evolution of the number of users of GRACE data/products since the beginning of the mission.

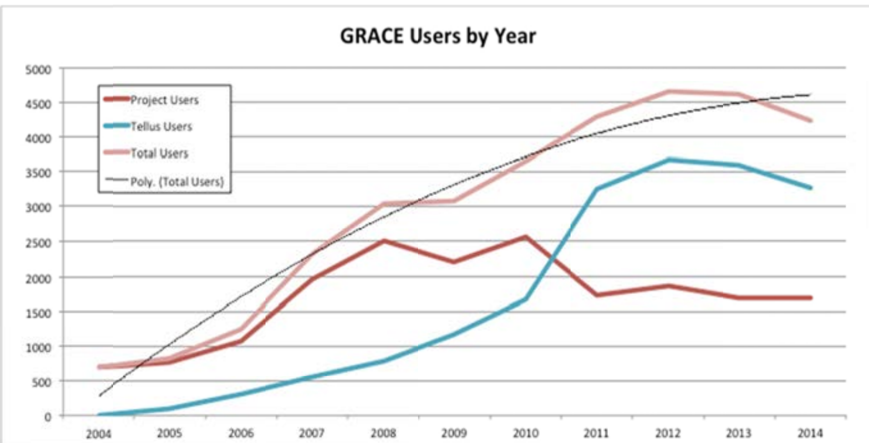

FIGURE B.4 GRACE users by year from 2004 to 2014. SOURCE: NASA data.

A GRACE Follow-on (GRACE-FO) mission is scheduled for launch in 2018. The two GRACE-FO satellites will use the same kind of microwave ranging system as GRACE and so can expect to achieve a similar level of precision. But they will also test an experimental instrument using lasers instead of microwaves, which promises to make the measurement of their separation distance at least 20 times more precise. GRACE-FO is a partnership between NASA and the German Research Centre for Geosciences (GFZ).

Conclusions

Precision gravity measurements by GRACE have enabled global perspectives on large land and ice shifts that would not otherwise have been possible.

Such measurements have provided quantitative data on the loss of mass in the Greenland ice sheet from 2002 to 2016, which has, in turn produced a global rise in sea level at a rate of 0.8 mm per year. In general, GRACE has revealed new details on the ebb and flow of water basin content, for example, in the Amazon, and how the Earth's net water cycle impacts sea level height on a global scale. GRACE also reveals changes in the solid Earth, notably in the mantle and lithosphere during earthquakes and in the isostatic adjustments as land masses rebound following the melting, and subsequent removal via runoff, of ice sheets and glaciers.[3] These measurements will be extended to even higher precision using new technology to be implemented on the GRACE-FO mission.

[3] https://grace.jpl.nasa.gov/applications/overview/#solid-earth and https://grace.jpl.nasa.gov.

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Heliophysics Science Division Missions

The committee requested data on the following heliophysics missions: Aeronomy of Ice in the Mesosphere (AIM), Interstellar Boundary Explorer (IBEX), Interface Region Imaging Spectrograph (IRIS), Van Allen Probes, Solar Terrestrial Relations Observatory (STEREO), Magnetospheric MultiScale (MMS), and the Voyager Interstellar Mission. No data was provided on Voyager.

AERONOMY OF ICE IN THE MESOSPHERE

The Aeronomy of Ice in the Mesosphere (AIM) mission is an Explorer-class spacecraft launched into a polar orbit by a PegasusXL rocket in 2007. The objective of the mission was to monitor noctilucent ice clouds over the Earth's poles. The mission cost $37.6 million in 2006.

Scientific Productivity

There are 88 news articles and press releases as well as 8 special sessions at the American Geophysical Union that featured AIM science.

AIM sponsored more than 15 education and public outreach events, and more than 9 NASA Heliophysics Guest Investigator proposals used AIM data. Five AIM papers were in the top 25 most cited papers in the *Journal of Atmospheric and Solar-Terrestrial Physics* during 2014. Over the course of the mission, many news organizations have published articles on AIM (e.g., CBSnews.com, the *New York Times*, *USA Today*, Discovery Channel TV in Canada, *SpaceNews*, BBC World News, *Cosmos* magazine in Australia, *Forbes*, MSNBC, *Washington Post*, KAALTV [ABC affiliate Rochester Mason City-Austin, Iowa-Minn.], and KSL-TV [NBC affiliate Salt Lake City, Utah]). AIM science continues to be featured in the media and in NASA news releases and announcements. Since the mission was launched in 2007, there have been 8 AIM Science@NASA web articles with accompanying videos as well as several Spaceweather.com articles. Indicative of the growing scientific and public interest in noctilucent clouds, AIM observations of long-term change in the mesopause region were described in the March 18, 2016, NASA Science Mission Directorate weekly highlights; in the April 2016 NASA Advisory Committee minutes; in a July 1, 2016, Spaceweather.com article; and in an August 16, 2016, Science@NASA nowcast. In addition, the AIM team announcement of an early start to the 2016 Southern Hemisphere Polar Mesospheric Cloud (PMC) season received worldwide media attention, appearing on 25 science websites including the Christian Science Monitor, NatureWorldNews, Science Magazine online, NPR, and Rava Tech Insider (Pakistan's premier video curation website), for example. Indicative of the utility of the data, Spaceweather.com publishes daily AIM/Cloud Imaging and Particle Size (CIPS) images during the PMC seasons. In 2014, the *Journal of Atmospheric and Solar-Terrestrial Physics* reported that 5 of its top 25 cited papers of the previous 5 years were based on AIM observations.

Impact on the Current and Future Health of the Relevant Scientific Community

AIM supports the Laboratory for Atmospheric Space Physics Mission Operation Center infrastructure, including voice and data lines, Command and Control software, Planning and Scheduling software (including Tracking and Data Relay Satellite System [TDRSS] scheduling software), data processing software, and so on. The AIM team has developed numerous scientific software applications that are freely available on the Internet. These include models of optics and radiative transfer, an equilibrium PMC model, and a variety of routines to access and analyze satellite data. The team was able to share the cost of maintaining SORCE ground spacecraft simulator (flatsat).

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Technology developed to mitigate AIM on-board S-band receiver failure early in the mission, including the development of autonomous operations and use of Morse Code to command the spacecraft through the TDRSS, has the potential for salvaging future missions with similar problems. AIM has successfully proven the use of autonomous state vector generation and autonomous instrument operations. AIM/TDRSS scheduling technology will be used for the Imaging X-ray Polarimetry Explorer mission. The Solar Occultation for Ice Experiment (SOFIE) instrument used commercial off-the-shelf silicon carbide detectors on orbit for the first time and demonstrated that it has excellent reliability and high performance for future missions. Finally, the Mars Atmosphere and Volatile Evolution (MAVEN)/Imaging Ultraviolet Spectrograph instrument drew heritage from AIM's CIPS instrument.

The AIM spacecraft bus is the same as Solar Radiation and Climate Experiment (SORCE), built on heritage from the SAMPEX, SWAS, TRMM, and other satellites. The spacecraft bus allowed use of the SORCE ground spacecraft simulator (flatsat) and leverage of operational experience (database and procedures). The SORCE battery experience was useful in resolving potential issue on AIM. The AIM/SOFIE instrument was built on heritage from the NASA Upper Atmosphere Research Satellite (UARS)/Halogen Occultation Experiment (HALOE) instrument.

Conclusions

One of the smallest missions conducted by NASA's Heliophysics Science Division, AIM continues to provide new insights into the properties and origins of polar mesospheric clouds and their possible connection to climate change. Initial observations revealed that the clouds appear every day and are highly variable of a variety of times scales and spatial scales. They contain small ice particles responsible for strong radar echoes of the summertime mesosphere, and mesopsheric ice occurs in a single continuous layer from a main peak at ~83 km altitude to over 90 km, while the cloud structures exhibit complex features not unlike those in tropospheric clouds. With the most recent mission extension now having enabled a decade of observations of these clouds, AIM has now shown that the clouds have been continuously increasing, rather than waxing and waning with the solar cycle, a trend that could be related to increasing concentrations of greenhouse gases in the atmosphere. AIM has confirmed that the seed particles of the ice crystals that form the clouds are meteoritic smoke particles, produced by the incineration of meteors in the Earth's atmosphere. AIM has revealed that heat movement in the atmosphere is more likely linked to mesospheric circulation than directly to solar radiation and has provided new insights into the dynamics of planetary waves in the atmosphere, which can influence weather on a global scale.

INTERSTELLAR BOUNDARY EXPLORER

The Interstellar Boundary Explorer (IBEX) mission is an Explorer-class spacecraft launched in 2005. IBEX's mission is to map the boundary between the solar system and interstellar space. The mission cost $110.1 million between 2006 and 2008. The mission featured some international cooperation. The University of Bern performed design, fabrication, testing documentation, and delivery of IBEX Hi and Lo Pre-collimators and Lo ESA.

Impact on the Current and Future Health of the Relevant Scientific Community

IBEX has made many contributions to the scientific community with the discovery of the IBEX Ribbon and many other fundamental discoveries about the heliosphere—our home in the galaxy.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

The Energetic Neutral Atom imaging capability from IBEX basically enables these observations on the Interstellar Mapping Probe mission, which is the next major heliophysics mission. The team's innovative launch capability can fly a small (~100 kg) payload out of Earth's gravitational well to pretty much anywhere in the solar system, given enough time, using a NASA-supplied Pegasus XL rocket.

There were no flight spares, but IBEX was built on general technology from prior missions with a lot of innovation from IBEX's small principal investigator (PI)-led team.

Conclusions

From its vantage point near Earth, IBEX has opened an entirely new perspective on the distant interaction between the heliosphere and Very Local Interstellar Medium (VLISM). By providing energetic neutral atom (ENA) imaging spectroscopy of this far region, IBEX's imaging of the ENA "Ribbon" has provided new constraints on the orientation of the local interstellar magnetic field and, by comparing energy spectra with those of the ionized energetic particles in situ observed by the Voyagers, new constraints on the properties of the interaction region itself. As a new tool now through multiple extended missions, IBEX is also providing information on potential temporal variations in these far regions, and the success of this new technique has motivated the selection of IMAP in the most recent Heliophysics Decadal Survey as the next strategic mission to implement.

INTERFACE REGION IMAGING SPECTROGRAPH

The Interface Region Imaging Spectrograph (IRIS) is a small Explorer-class spacecraft launched in 2013 into a polar orbit. The mission's objective is to study the chromosphere of the Sun.

Technology developed for IRIS feeds forward in many different ways to reduce risk and cost for future missions, including the following:

- Low-cost satellite bus with very stable 3-axis solar pointing;
- Advanced Camera for Surveys (ACS) control software;
- Solc filter for broadband UV imaging;
- Novel primary mirror heat dump, avoiding thermal problems of traditional solar telescopes;
- Combined image-stabilizing and scanning system with no additional mirrors; and
- Spacecraft including X-Band transmitter and precision magnetometer.

Scientific Productivity

This mission was scientifically productive, enabling the construction of a powerful observatory at the cost of a small explorer (SMEX):

- The Guide telescope and ACS solar pointing design came from the Transition Region and Coronal Explorer and Solar Dynamics Observatory (SDO) missions.
- Flight spare camera electronics came from SDO.
- Mechanisms (front door, filter wheels, shutters, wedge motors) rely on design, qualification, and life tests from Hinode, SDO, and the Solar Ultraviolet Imager.
- SDO flight spare instrument computer.
- SDO electrical, electronic, and electromechanical parts and the majority of instrument control electronics and thermal control designs came from Hinode and SDO.
- Data compression firmware and flight software reused from SDO, optics mounts from the Near Infrared Camera, primary and secondary mirror mounts from the Atmospheric Imaging Array (AIA).
- Gravity Recovery and Interior Laboratory (GRAIL) flight spare battery, GRAIL designed reaction wheels, BroadReach avionics, and S-Band transponder from LADEE were used.

Impact on the Current and Future Health of the Relevant Scientific Community

At Lockheed Martin Solar and Astrophysics Laboratory, it was very important to maintain critical scientific and engineering capabilities. Critical capabilities were created and maintained at Goddard Space Flight Center (GSFC) in the areas of microcalorimeter fabrication and applications, low temperature systems technology, high spectral resolution X-ray calibration technology, and atomic physics as applied to X-ray astronomy.

IRIS results have also been the subject of extensive media coverage, with press releases or social media coverage in just the last 19 months alone for the first detection of resonant absorption (August 2015), the Mercury transit (May 2016), solar flare models (June 2016), coronal rain observations (August 2016), collaboration with Atacama Large Millimeter/Submillimeter Array (ALMA) (September 2016), tracking solar waves in sunspots (October 2016), estimating heating from shock waves in the chromosphere (November 2016), and solar new coronal heating insights (December 2016). These stories received widespread, international coverage by a variety of news sources, magazines, television (e.g., BBC Click), and websites. This is illustrated by a Google news search for “IRIS AND solar AND interface,” which reveals 4660+ hits. In addition, IRIS is active in social media, with the IRIS Facebook page receiving semiweekly updates of movies and science nuggets, and 10,400 “likes.”

Conclusions

The Interface Region Imaging Spectrograph (IRIS) is a SMEX mission designed to probe the flow of energy from the solar photosphere into the corona remotely from Earth. IRIS probes the condition in and flow of energy through the dynamic chromosphere and transition region of the Sun by obtaining high-resolution UV spectra and images in that region, which are sensitive to nonthermal energy flow, at high time resolution.

Observations have revealed a new layer of complexity of the interplay of fibril structures characterized by large contracts in density and temperature in the transition region. The region has been shown to be extremely active driven by nonthermal processes associated with rapidly evolving twisted magnetic fields and magnetic loops.

VAN ALLEN PROBES

The Van Allen Probes are two spacecraft launched into Earth orbit in 2012. Their mission is to study the radiation belts that surround the Earth.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Van Allen Probes advanced our ability to design for high radiation environments, in terms of analysis and modeling, materials testing, and circuit design.

Van Allen Probes did not use any existing flight spares. In general, Van Allen Probes used the existing base of spacecraft engineering design and body of knowledge and built on it. There was not a specific precursor technology that emerged that enabled the Van Allen Probes mission to kick-off. Energetic Particle, Composition, and Thermal Plasma Suite (ECT) instruments drew heritage both in terms of design and concept from earlier flight instruments, though not to the extent of build-to-print or use of flight spares. Rather, detection techniques, detector types, and advanced electronics developed through other NASA and non-NASA flight programs were used to guide and/or implement the ECT instrumentation. The Electric and Magnetic Field Instrument Suite and Integrated Science sensors—that is, the search coil and the magnetometer that are out on the ends of the booms—have heritage from several prior missions but had some redesign to accommodate the high radiation environment of the Van Allen Probes. Some of the mechanical materials were somewhat different, and the details of the Magnetic Search Coil preamps were designed using high radiation tolerance parts. Electric Field and Waves Suite instruments drew their heritage from THEMIS, Polar, and Cluster.

The "hockey puck" Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE) instrument inherits a long-existing knowledge base of measuring low energy space plasma particles. Early versions were flown on Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) (EPD) and New Horizons (PEPSSI). This particular "hockey puck" design has been flown three times, on Van Allen Probes (RBSPICE), Juno (JEDI), and MMS (EIS), with minor variations specific to those implementations.

Examples of international collaboration or contribution include the following:

- Korea Astronomy and Space Science Institute (KASI)—NASA provides the expertise required for the initial setup of the data system to store, use, and disseminate the science quality SDO data, which will be provided to KASI for the duration of the mission.
- Brazilian Space Agency—Collects space weather data when Radiation Belt Storm Probe (RBSP) spacecraft pass over Brazil antenna site.
- Czech Republic—Receives RBSP space weather beacon data and transmits to the RBSP Mission Operations Center via the Internet. NASA transmitted RBSP space weather beacon data and provided beacon-mode data from RBSP.
- Argentina's National Committee of Space Activities (CONAE)—Collects RBSP space weather data when spacecraft is over Argentina (Brazil AER/CONAE/Czech Rep/KASI—mainly space weather stations).

This mission maintains both scientific and engineering capabilities such as the handling of data, the generation of higher level science products and distribution products for immediate practical use, and the enhancement of capabilities and methodologies to design for and analyze hostile environments.

As of February 2017, the Van Allen Probes bibliography contains over 350 publications,[1] including several articles in high-profile journals that have received substantial press interest, such as *Nature* (6 articles), *Nature Physics* (2 articles), *Nature Communications* (3 articles), *Science* (2 articles), and

[1] http://rbspgway.jhuapl.edu/biblio.

Physical Review Letters (2 articles). The publications also include one special issue of *Space Science Reviews* (18 articles), one special issue of *Geophysical Research Letters* (26 articles), and two special issues of the *Journal of Geophysical Research* (42 and 21 articles). The Van Allen Probes yearly publication rate has been growing every year since the mission launch. This remarkable growth in productivity is attributed largely to the accessibility of the Van Allen Probes data to the international scientific community enabled by the Science Gateway;[2] over 50 percent of Van Allen Probes publications were led by first authors not directly affiliated with the instrument teams.

Conclusions

The twin Van Allen Probes spacecraft were launched into Earth orbits on 30 August 2012 to provide understanding of how populations of relativistic and penetrating ions in space form and change in response to variable inputs of energy. The probes confirmed the existence of a third radiation belt as a predictable consequence of the protection from losses that the plasmasphere provides to a part of the outer radiation belt because the wave environments are so different inside. The probes showed that particle energization is due to a source of nonadiabatic energization within the interior of the radiation belts, as opposed to adiabatic energization from transport-induced compression, and that global acceleration of particles by drift resonance with ultra-low frequency (ULF) is ubiquitous. The probes continue to provide new data on the energization and dynamics of the Earth's radiation belts.

SOLAR TERRESTRIAL RELATIONS OBSERVATORY

The Solar Terrestrial Relations Observatory (STEREO) mission consists of two spacecraft launched into orbit around the Sun in 2006. The goal of the mission was to conduct stereoscopic observations of the Sun. One spacecraft remains in operation. STEREO cost $64.5 million in 2006.

Scientific Productivity

There are regular media releases related to STEREO. On the NASA STEREO portal site, there were six science story-type releases from 2015 to 2017. The mission also had web releases and media interviews related to the STEREO 10th anniversary in October 2016 and to recovery efforts for STEREO-B, also in Fall 2016. STEREO images are available through NASA web sites (in public friendly formats) and through services like Helioviewer.[3] Sometime this interest is off topic ("UFO" spotters and such), but there are clearly members of the public who download the data. There are also apps incorporating STEREO data of the far side of the Sun.[4]

Contributions to Development and Demonstration of Technology Applicable to Future Missions

STEREO is a pathfinder for future missions to the Sun-Earth Lagrange points (L5 and L4). STEREO demonstrated how to operate twin satellites. The Heliospheric Imagers helped reduce risk (and raised the technology readiness levels) for the Solar Orbiter Heliospheric Imager (SoloHI) and particularly for the Wide-field Imager for Parker Solar Probe (WISPR) on the Parker Solar Probe mission (which has two telescopes like the Heliospheric Imagers). The design work and tests for COR2 led directly to the compact coronagraph (CCOR) development. COR2 is, in essence, the blueprint for operational

[2] http://rbspgway.jhuapl.edu.
[3] https://www.helioviewer.org/.
[4] See, for example, http://www.educationalappstore.com/app/3d-sun-1.

coronagraphs of the future (e.g., fields of view, spatial resolution, and cadence). The Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) charge-coupled devices (CCDs) were the basis for the AIA CCDs (just a larger form factor).

The same design (build to print) from the STEREO Solar Wind Electron Analyzer (SWEA) instrument was used on the MAVEN program. Generally, instruments evolve from one project to the next due to a combination of different requirements, improved technology, and new ideas. SWEA used the design as is, which was a cost and schedule savings for MAVEN. The technology and infrastructure developed at the University of New Hampshire (UNH) for Plasma and Supra-Thermal Ion Composition (PLASTIC) has been used in the ion optics of the SoloHIs (expected launch in 2018) and was also used for the IBEX-Lo instrument on IBEX (2008), thus reducing instrument development costs on those missions, at least for the UNH portions.

The Stereo Waves Experiment (SWAVES) instrument was/is a forerunner of, for example, the Parker Solar Probe WAVES instrument (even many of the same team members). In addition, many spare pieces of previous instruments (parts of flight spares, parts of engineering units), much flight software, and a great deal of ground support equipment were used to construct and improve STEREO instruments.

STEREO instruments also inherited their designs from previous missions, improved upon them, and then passed those ideas and lessons learned onto the next projects. The thermal isolators developed for STEREO (originally from an MPE heritage on CLUSTER, but further developed by UNH for STEREO and now available through UNH), have also been used in these other missions. COR2 is a direct derivative of LASCO/C3, and the coronagraph test facility at the U.S. Naval Research Laboratory was maintained thanks to SECCHI and then used for SoloHI and WISPR. The STEREO team used some concepts from Ulysses' Solar Wind Ion Composition Spectrometer, CLUSTER's Composition and Distribution Function (CODIF) analyzer, and FAST Teams' instruments for use in PLASTIC. These experiences then further trained people who played major roles in RBSP and MAVEN project support. The SWAVES instrument built upon Wind Experiment (WIND)/Waves Experiment (WAVES), Ulysses/Unified Radio and Plasma Wave Experiment, and (especially) Cassini/ Radio and Plasma Wave Science.

Conclusions

The twin STEREO spacecraft provided new synoptic views of the Sun and solar phenomena, while allowing for the direct viewing of coronal mass ejections (CMEs) and their propagation to the Earth. By combining CME images with in situ fields and particles measurements at the two platforms simultaneously, the STEREO mission has enabled increased understanding of the three-dimensional structure of CMEs as they propagate through the inner heliosphere from the Sun to the Earth and under what conditions the impact of these plasma and energetic particle environments give rise to varying impacts on the Earth geospace environment, effects collectively now known as "space weather."

MAGNETOSPHERIC MULTISCALE

The Magnetospheric MultiScale (MMS) mission was launched in 2015. The mission consists of four spacecraft flying in formation. The goal of the mission is to gather information about the microphysics of magnetic reconnection, energetic particle acceleration, and turbulence. MMS was a large strategic mission costing $999.2 million between 2006 and 2015.

Scientific Productivity

The MMS mission is still relatively new. Its scientific productivity has not been fully realized.

Impact on the Current and Future Health of the Relevant Scientific Community

MMS is the most ambitious space plasma physics mission ever, and employed a large fraction of the heliophysics research and engineering communities both within and outside GSFC.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

There is substantially reduced risk for future formation flying missions owing to the experience gained with MMS. This experience feeds into future missions being proposed by Goddard and others working with Goddard.

All instruments benefitted greatly from experience with prior versions. The Hot Plasma Composition Analyzer instruments pioneered a new radio frequency filtering technique, and the Fast Plasma Investigation instrument pioneered in the areas of multiplicity of sensors, fast stepping high voltage power supplies, and flexible data compression, among others. The balance of those instruments was based on prior versions and experience.

Conclusions

By providing extremely high cadence measurements on four identically instrumented spacecraft with significant maneuverability and capability for controlled formation flying, MMS has enabled the first in situ microscale plasma physics laboratory within the Earth’s magnetosphere.

Still in its primary mission, MMS has allowed for conclusive fundamental tests of magnetic reconnection, a long-studied but not well understood aspect of collisionless plasma physics in a magnetized plasma. The results are likely to lead to paradigm shifts across space plasma physics from the Earth’s magnetosphere to galactic, astrophysical scales.

The MMS mission may be indicative of future heliophysics missions that will consist of multiple spacecraft flying in formation. It may provide numerous lessons learned for the development of future missions.

D

Planetary Science Division Missions

The committee requested data on several planetary missions including Cassini, Mars Science Laboratory (MSL)/Curiosity, the Mars Exploration Rovers (MER), the Mars Reconnaissance Orbiter (MRO), Juno, and Dawn. The committee sought to evaluate the Cassini and Curiosity large strategic missions compared to the medium-size Juno and MER (which consisted of two rovers), as well as the medium-size Mars Reconnaissance Orbiter and smaller (Discovery class) Dawn. NASA could not produce sufficient data on Cassini for the committee to conduct an assessment. This may be due in part to the fact that Cassini was initiated in the early 1990s and launched in 1997, long before NASA implemented full cost accounting in the early 2000s. NASA did not provide information on Juno. Although NASA did provide information on MER, the committee sought to include representative examples of large, medium-size, and small missions and did not want its examples to be dominated by Mars missions. Therefore, the committee included Curiosity (large), MRO (medium) and Dawn (small).

MARS SCIENCE LABORATORY/CURIOSITY

The Mars Science Laboratory (MSL), also known as Curiosity, is a strategic mission in the Mars Exploration Program designed to answer the question of whether Mars ever had the right environmental conditions to support primitive (e.g., microbial) life. *Curiosity* is a car-size rover equipped with state-of-the-art imaging cameras and laboratory quality instrumentation for characterizing the mineralogy and chemistry of the Martian surface and atmosphere, as well as the local environmental conditions. MSL was slated to launch in 2009, but due to technical challenges associated with spacecraft hardware systems the launch was delayed until 2011, and the spacecraft successfully landed in Gale crater on August 6, 2012. *Curiosity* currently is in its second extended mission, embarking on an ascent of the mound at the center of Gale crater, informally known as Mount Sharp.

Scientific Productivity

Through geological, chemical, and isotopic analyses, the MSL mission has found evidence of a sustained, habitable environment at a location in Gale crater called Yellowknife Bay. Preserved rocks indicative of past water-related environments have been identified and characterized, such as those deposited by or in streams, alluvial fans, deltas, and lakes. Further evidence for the persistence of ground water is the alteration of some of these formations. Organic molecules have been detected in multiple drilled samples, and measurements of methane abundance suggest that this atmospheric component varies seasonally. Measurements of solar radiation have helped to constrain the impacts on the preservation of organic material and the radiation risk to future human explorers.

Impact on the Current and Future Health of the Relevant Scientific Community

The MSL mission has been a key part of the Mars Exploration Program, collecting data sets from the Martian surface with unprecedented accuracy and precision. The diversity of science enabled by the MSL instrument suite, which includes imaging; alpha particle X-ray spectroscopy; X-ray diffraction analysis; laser-induced breakdown spectroscopy; mass spectroscopy; and temperature, wind, and UV measurements has led to the involvement of a large segment of the Mars science community in the analysis of MSL data—the entire science team consists of 485 people at the time of this writing, approximately 40 percent of whom are non-U.S. investigators. Of these, 146 are team members (instrument principal investigators, co-investigators, participating scientists, and the project scientist) and 339 are collaborators (research associates, post-doctoral researchers, students, and technical staff). Personnel rotate on and off the project each year, with an average of about 40 people leaving and 57 people joining. Of the current science team, 62 percent have been on the mission since landing.

A number of team members are supported by nonproject funds. Participating scientists are funded from resources outside the project (including non-U.S. organizations such as foreign space agencies, research institutes, and universities), and many more scientists (including students and post-doctoral researchers) have worked on the project and/or analyzed MSL data through fellowships and the Mars Data Analysis Program. The Radiation Assessment Detector instrument and team (8 scientists) are funded by NASA's Human Exploration Operations Mission Directorate.

Data collected by MSL have been published regularly and integrated by the science community with data collected at Mars by orbiters and prior landers. Since landing, the number of peer-reviewed science papers first-authored by members of the MSL team has increased steadily from 20 in 2013 to 49 in 2014, to 47 in 2015, to 68 in 2016, and to 7 in 2017 (through January 20). (See Figure D.1.) Additional papers using MSL data or results have been published by members of the scientific community who are not MSL team members: 1 in 2013, 19 in 2014, 58 in 2015, 49 in 2016, and 3 in 2017 (through January 20).

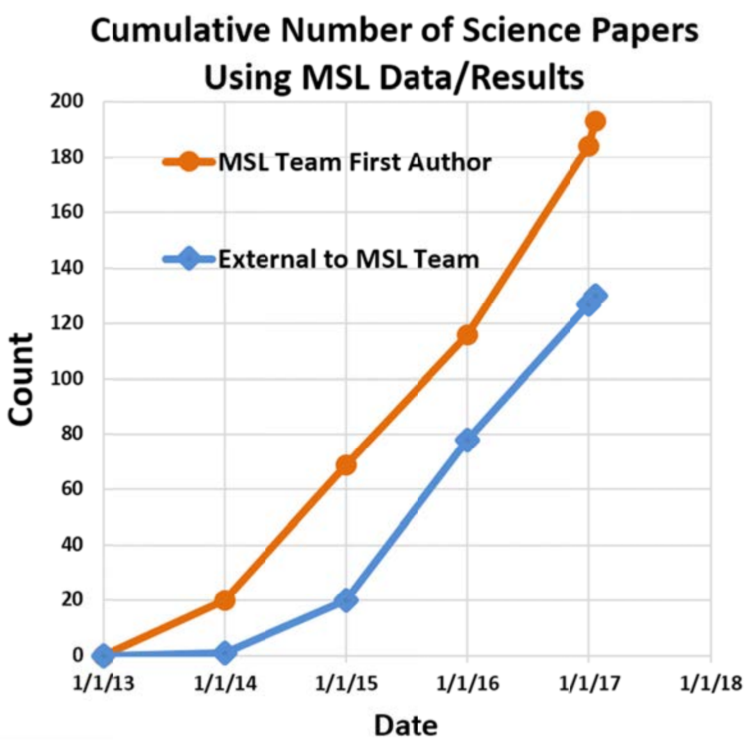

FIGURE D.1 Peer-reviewed scientific publications using MSL data or results.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

One of the most significant and high-profile developments associated with the MSL mission is the Sky Crane technology for safely depositing the rover onto the Martian surface. Airbag technology used for the Mars Pathfinder and Mars Exploration Rovers missions was not scalable to a rover of the size of MSL. The Sky Crane system was specifically designed to allow MSL to land on Mars directly on its wheels. The Sky Crane was recommended for reuse with future landers in the planetary science community's decadal survey, and NASA has adopted this system for the Mars 2020 rover currently in development.

Many of the Mars 2020 rover instruments and technologies are directly derived or can point to heritage from MSL, including test beds, spare parts, hardware designs, and personnel (engineering, management, and science). Lessons learned have carried forward into new designs, such as a redesign of the rover wheels that will make the Mars 2020 rover wheels more resistant to punctures/damage. Operational lessons learned feed forward into advances in operational efficiency in terms of operations tools, spacecraft system and performance modeling, and tactical planning procedures.

Conclusions

As part of a balanced program of large-, medium-, and small-class Mars missions, MSL has demonstrated the power that large strategic missions have in terms of their ability to make many diverse but complementary scientific measurements that can address scientific questions that are broad in scope and have far-reaching implications for our understanding of Mars and its geologic and climatological history—and by extension the search for life in our solar system. Making such measurements requires ambitious technological approaches to scientific instrumentation as well as spacecraft hardware and operations. Many of these investments are paying off beyond the MSL mission proper as the technologies are carried forward into the next generation of flight hardware and processes.

MARS RECONNAISSANCE ORBITER

The Mars Reconnaissance Orbiter (MRO), a medium-class mission in the Mars Exploration Program, was designed to map the Martian landscape at high resolution for both scientific and programmatic applications. The orbiter carries a suite of moderate- and high-spatial resolution cameras and a visible to near-infrared spectrometer for characterizing the geology and mineralogy of the Martian surface, a radar instrument for characterizing subsurface structure (with emphasis on the polar ice caps), and an atmospheric sounder for measuring Mars's weather. Imaging data from MRO have aided and continue to aid in the selection of landing sites. MRO also functions as a high data volume telecommunications relay, having monitored the entry, descent, and landing events of several missions, and is the primary data relay for the Mars Science Laboratory rover. MRO was launched in 2005 and entered Mars's orbit in 2006. After completing its 2-year primary science phase, MRO entered an extended science phase (through 2010), has subsequently been extended four times, and continues to operate as of this writing.

Scientific Productivity

The very high spatial resolution of several MRO instruments has augmented the scientific community's understanding of the geology and mineralogy of Mars. Key results include the following: (1) the discovery and monitoring of seasonally appearing features known as recurring slope lineae that are associated with hydrated salts and suggest some role for water in their activity; (2) details of localized deposits of water-bearing clay minerals; (3) evidence that the north polar cap is geologically young (<~5

My) and contains layered dust and ice indicative of obliquity-driven climate change; (4) observations of dynamic processes such as sand dune movement; and (5) the identification of a three-event pattern of dust storms initiating in the southern spring and summer.

Impact on the Current and Future Health of the Relevant Scientific Community

The MRO mission continues to play a significant role in the Mars Exploration Program, both scientifically and programmatically. As with many planetary missions, MRO engages a large segment of the Mars science community, primarily through the analysis of MRO instrument data sets. The MRO science team proper (not including post-doctoral researchers and students) consists of 88 people, 15 of whom are foreign nationals. In addition, co-investigators on the Italian-supplied Shallow Radar instrument are appointed by the Italian Space Agency. Over the lifecycle of the mission, approximately a dozen people have left the team or are inactive, and 28 new co-investigators have been added (9 of whom were originally appointed as Participating Scientists).

Scientific results from the MSL mission have been published regularly by the mission team and the broader science community. (See Figure D.2.) From 2007 to 2016, the MRO team published 335 papers, and non-team members published another 681 (note that team publications were funded by the MRO project and other sources such as the Mars Data Analysis Program).

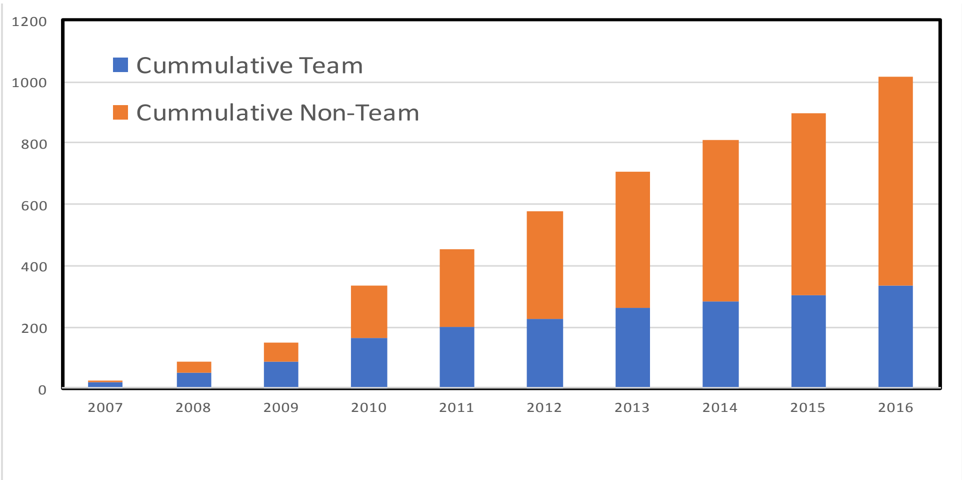

FIGURE D.2 Peer-reviewed scientific publications using MRO data or results.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Vertical profiling of the atmosphere has helped to improve databases for engineering models that are used to design and implement entry, descent, and landing activities for other missions. The MRO spacecraft was a new design that became the basis for subsequent missions (OSIRIS-REx and MAVEN) and Discovery-class proposals.

Conclusions

The MRO science team is one of many successful examples of how NASA works to integrate U.S. and foreign scientists, as well as engage the broader scientific community. Orbiters like MRO can provide a synoptic view of a planetary body, as well as acquire targeted data at very high spatial resolutions (e.g., tens of centimeters to tens of meters) that support science analyses and programmatic needs. Whereas landed spacecraft can explore a small area of Mars in great detail, medium-size orbiters contribute to the broader context.

DAWN

Dawn is the ninth mission in the Discovery Program of relatively small, principal investigator (PI)-led missions. Indeed, of the planetary missions for which this committee received data from NASA, Dawn had the lowest development cost. The total life cycle cost is slightly greater than that of Gravity Recovery and Interior Laboratory (GRAIL) because of Dawn's unusually long prime mission duration of nearly 9 years. (Only the larger Cassini and New Horizons had longer prime mission phases.) Dawn was designed to conduct detailed investigations of Vesta and Ceres, the two largest bodies in the main asteroid belt between Mars and Jupiter. Dawn was developed before NASA instituted key decision point date tracking. The project completed its preliminary design review in September 2003 but was canceled the following December. It was restarted in February 2004 and completed its critical design review in June 2004. Development work was put on hold in October 2005, and Dawn was cancelled for a second time in March 2006. Later that month, NASA restarted the project, and launch took place in September 2007. Dawn's capability to accommodate significant schedule changes was a direct result of its use of solar electric propulsion, which can provide planetary launch periods of years instead of weeks. The project completed its prime mission in June 2016, having met or exceeded all its original requirements, and at the time of this writing is conducting an extended mission at Ceres.

Scientific Productivity

Dawn's first target was Vesta, which the spacecraft orbited from July 2011 to September 2012. Vesta was the first object in the main asteroid belt to be studied from orbit, allowing a detailed investigation. Dawn thoroughly mapped Vesta in visible and near-infrared wavelengths; acquired extensive stereo images for topographical mapping; collected a rich set of gamma-ray, visible, infrared, and neutron spectra; and measured the gravity field (allowing the interior structure to be inferred). Dawn's data showed that Vesta, with a mean diameter of 525 kilometers, is more closely related to the terrestrial planets than to typical asteroids. Dawn entered orbit around Ceres in March 2015. Ceres was the first dwarf planet discovered (January 1801) and the first dwarf planet to be explored by a spacecraft. Dawn performed the same measurements as at Vesta. The mission revealed a world of rock, ice, and salt. Ceres may have had a global ocean early in its history, and Dawn provided evidence of geologically recent activity, including a cryovolcano.

Impact on the Current and Future Health of the Relevant Scientific Community

Dawn has been vital to the scientific vigor of the small body community, providing the only orbital data on objects in the main asteroid belt and the only data on objects of such large size (sometimes described as protoplanets). Moreover, Dawn is the only spacecraft to reach a main belt object during a period of nearly 15 years and the only spacecraft to reach large ones in a span of 20 years. When Dawn arrived at Vesta, the previous spacecraft to fly by an object in the main asteroid belt was 4 years earlier, when ESA's Rosetta conducted a brief encounter with Lutetia in July 2010. No other missions are scheduled to main belt asteroids until NASA's Lucy mission flies by the 4-km-diameter Donaldjohanson in April 2025. The next mission to a large object in the asteroid belt is currently planned to be NASA's Psyche, which will arrive at the ~ 250-km-diameter asteroid of the same name in August 2030. Therefore, Dawn has been vital in providing data to the extensive community of scientists studying main belt asteroids, especially large ones. In exploring Ceres, Dawn also has provided the most detailed view of a world with a substantial inventory of water ice, displaying some similarities to the moons of Jupiter and Saturn that have been investigated only with flyby missions.

Contributions to Development and Demonstration of Technology Applicable to Future Missions

Dawn has advanced the state of the art in the use of solar electric propulsion (SEP), implemented as an ion propulsion system (IPS). The IPS was inherited from Deep Space 1 (DS1). From a hardware standpoint, compared with DS1, Dawn used three ion engines instead of one, two digital control units instead of one, and two power processing units instead of one. Dawn launched with 425 kg of xenon, compared to 81.5 kg on DS1. Therefore, the Dawn project extended the system design. Dawn used the new system engineering principles developed on DS1 that are now recognized to be essential for any SEP mission The Dawn project also developed methods of operating an SEP spacecraft in orbit around planetary bodies, whereas DS1 remained in orbit around the Sun. The new operational methods Dawn developed will reduce cost and risk on future SEP missions. Dawn maintained NASA’s unique expertise in designing and flying SEP missions, for the subsystem, system, and mission. That expertise was developed and brought to an operational capability on DS1, maintained and enhanced on Dawn, and will be applied on subsequent missions, including Psyche.

Conclusions

Despite being one of the smaller planetary missions, Dawn yielded a wealth of valuable scientific data on two previously unexplored worlds. In orbiting two targets beyond Earth, it also accomplished a mission unique in the history of planetary exploration, even among large strategic missions. Dawn obtained a significant benefit from international collaboration, with foreign partners investing about 12 percent of NASA’s cost. Dawn clearly demonstrates that small missions can achieve impressive results and represent an important element of a balanced program.

E

Statement of Task

This study will examine the role of large, strategic missions within a balanced program across NASA Science Mission Directorate (SMD) space and Earth sciences programs. The study will consider the role and scientific productivity of such missions in advancing science, technology and the long-term health of the field, and provide guidance that NASA can use to help set the priority of larger missions within a properly balanced program containing a range of mission classes.

The National Academies of Sciences, Engineering, and Medicine will appoint an ad-hoc committee that will:

1. Provide recommendations to help guide future prioritization by NASA of large strategic space and Earth science missions within a balanced program containing a range of mission classes. That is, what are general principles that SMD could use (e.g., a figure of merit approach) to trade off within a limited budget between development and operation of large, strategic missions and the cadence and/or cost caps of medium size and small PI-led mission lines?

The committee will not offer prioritized recommendations on any specific current or future missions, which is a function of each science theme's decadal survey process.

2. In this framework, assess the impact of current and recent SMD missions with a range of life cycle costs. A representative subset of missions within each of SMD's four science theme areas may be selected for analysis. The committee's analysis of each representative mission will include a discussion of the relation between mission scientific impact and mission life cycle cost (or cost to date) in order to understand the return on expenditures for various mission classes. In describing the impact of the chosen missions the committee should consider dimensions such as:

- Scientific productivity;
- Impact on the current and future health of the relevant scientific community; and
- Contribution to development and demonstration of technology applicable to future missions.

F

Biographies of Committee Members and Staff

COMMITTEE

RALPH L. McNUTT, JR., *Co-Chair*, is a senior space physicist at the Johns Hopkins University Applied Physics Laboratory. Dr. McNutt is currently the project scientist and a co-investigator on the MESSENGER Discovery mission to Mercury, deputy principal investigator for the Plasma Instrument for Magnetic Sounding (PIMS) instrument on the Europa flyby mission (in development), a co-investigator of the Parker Solar Probe mission (in development), a co-investigator on the New Horizons mission to Pluto, and a co-investigator on the Voyager Plasma Science and Low-Energy Charged Particles experiments. He is also a member of the Ion Neutral Mass Spectrometer Team for the Cassini Orbiter spacecraft. He has worked on the physics of the magnetospheres of the outer planets, the outer heliosphere (including solar wind dynamics and properties of very low frequency radiation), Pluto's atmosphere, pulsars, high-current electron beams, the physics of active experiments in the mesosphere/thermosphere (artificial aurora), and the solar neutrino problem. He received his Ph.D. in physics from Massachusetts Institute of Technology. Dr. McNutt has served as a member of the Academies' Committee for the Review of the Next Decadal Mars Architecture, Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion: A Vision for Beyond 2015, Committee on the Assessment of Solar System Exploration, and Committee on New Opportunities in Solar System Exploration. He was the co-chair of the Committee on Radioisotope Power Supplies and a member of the Steering Committee on Planetary Science Decadal Survey: 2013-2022.

KATHRYN C. THORNTON, *Co-Chair*, is a professor at the University of Virginia in the Department of Mechanical and Aerospace Engineering. Dr. Thornton has extensive human spaceflight experience and served for 12 years as a NASA astronaut, flying on four space shuttle missions and performing extravehicular activities (i.e., spacewalks) on two of them. Dr. Thornton is currently on the board of directors of the Space Foundation and Astronaut Scholarship Foundation. She earned her Ph.D. in physics from the University of Virginia. She served as a member of the Academies' Aeronautics and Space Engineering Board (ASEB), the Committee for Technological Literacy, the Committee on Meeting the Workforce Needs for the National Vision for Space Exploration, the Mitigation Panel for Defending Planet Earth: Near-Earth Objects Surveys and Hazard Mitigation Strategies, and as vice-chair of the Committee on Science Opportunities Enabled by NASA's Constellation System.

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

JOEL N. BREGMAN is the H.D. Curtis Professor of Astronomy at the University of Michigan. Prior to his time at the University of Michigan he was an associate scientist at the National Radio Astronomy Observatory. His research interests include high-energy astrophysics, gaseous components of the universe, intermediate-mass black holes, elliptical galaxies, and globular clusters. He earned his Ph.D. in astronomy and astrophysics from the University of California, Santa Cruz (Lick Observatory). He served on the Academies' Task Group on the Availability and Usefulness of NASA's Space Mission Data.

ANNY CAZENAVE is director of Earth science at the International Space Sciences Institute, Bern and senior scientist at the Laboratoire d'Etudes en Geophysique et Oceanographie Spatiale at Observatoire Midi-Pyrénées in Toulouse. Dr Cazenave has extensive experience in using remote sensing data for a variety of applications in Earth sciences (geodesy, Earth rotation, gravity and internal Earth' structure, sea level rise and climatic causes, land hydrology). She has been involved in satellite altimetry missions for long, in particular the TOPEX/Poseidon and Jason series. Dr. Cazenave was elected to the French Academy of Sciences and the National Academy of Sciences, and she was the recipient of the William Bowie Medal. Dr. Cazenave received her Ph.D. in geophysics from the University of Toulouse. She has served on the Academies' Committee on the Assessment of NASA's Earth Science Programs and Committee on National Requirements for Precision Geodetic Infrastructure.

ANNE R. DOUGLASS is a senior scientist at NASA's Goddard Space Flight Center (GSFC) with the Atmospheric Chemistry and Dynamics Laboratory. Dr. Douglass is the project scientist for Aura, the Earth Observation System (EOS) atmospheric chemistry mission. She was deputy project scientist for Aura and for the Upper Atmosphere Research Satellite. Her research uses atmospheric constituent observations along with models to understand and predict the evolution of stratospheric ozone and other species that are important to ozone and climate. She is co-lead for the Goddard Earth Observing System Chemistry Climate Model, a three-dimensional model that couples a general circulation model with a representation of relevant stratospheric and tropospheric photochemical processes. She is recipient of the Nordberg Award for Earth Sciences, a NASA Exceptional Scientific Achievement Medal, and a NASA Outstanding Leadership Medal and is a fellow of the American Meteorological Society and the American Geophysical Union. She earned her Ph.D. in physics from Iowa State University.

VICTORIA E. HAMILTON is a staff scientist and section manager at Southwest Research Institute (SwRI) in Boulder, Colorado, in the Department of Space Studies. Dr. Hamilton has extensive experience with laboratory spectroscopy and Mars data analysis as an affiliate of the Mars Global Surveyor

Tropospheric Emission Spectrometer (TES) science team, as a participating scientist on the Mars Science Laboratory mission, and as deputy principal investigator for the THEMIS instrument on the 2001 Mars Odyssey mission. She is a science team co-investigator and deputy instrument scientist on the OSIRIS-REx asteroid sample return mission launched in 2016, and a co-investigator and deputy instrument principal investigator on the Lucy Trojan asteroid survey 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 Mars Science Laboratory Science Office Development and Operations Team, 2001 Mars Odyssey Thermal Emission Imaging System Team, and Mars Global Surveyor Thermal Emission Spectrometer Team. She received her Ph.D. in geology from Arizona State University. She was a member of the Academies' Committee on Cost Growth in NASA Earth and Space Science Missions and Committee on NASA Science Mission Extensions.

MARC L. IMHOFF is a visiting research scientist with the University of Maryland's Earth System Science Interdisciplinary Center concentrating on the use of Earth observations, models, and tools for addressing sustainability and the human enterprise. He spent three decades as a principal scientific investigator, science team leader, and project scientist for satellite missions and programs at NASA's Goddard Space Flight Center, where he focused on satellite observations of biogeochemical cycles and human dimensions of global environmental change. Dr. Imhoff led scientific research projects using data from Landsat, the Space Shuttle imaging radar, NASA's Earth Observing System satellites, and the Defense Meteorological Satellite Program (DMSP) addressing a broad range of landcover measurements and quantitative estimates of human impacts. Dr. Imhoff pioneered the development of the DMSP low-light nighttime "city lights" imaging combined with other satellite data to study urbanization, urban heat islands, and impacts on life-critical functions of the biosphere. Dr. Imhoff was Project Scientist for the Earth System Science Pathfinder 3 and for the EOS-AM1 Flagship Earth Science Mission - Terra. After leaving NASA, Dr. Imhoff served as deputy director and interim director of Pacific Northwest National Laboratory's Joint Global Change Research Institute supporting the development of integrated assessment models for climate change and energy policy. Dr. Imhoff was a Sigma Xi Distinguished Lecturer and received both the Robert H. Goddard Exceptional Achievement Award for Science and NASA's Outstanding Leadership Medal. Dr. Imhoff holds a B.S. in geography and an M.S. in agronomy from the Pennsylvania State University and a Ph.D. in biological sciences from Stanford University.

CHARLES D. NORTON is a program manager and principal technologist at the Jet Propulsion Laboratory (JPL) at the California Institute of Technology. He is the engineering and science directorate formulation lead for Small Satellites at JPL. His research interests are small satellites for spaceborne technology validation, high-performance computing for Earth and space science modeling, and advanced information systems technologies. He has managed CubeSat flight projects and co-led a Keck Institute study, "Small Satellites: A Revolution in Space Science." Prior to joining JPL, he was a National Research Council Postdoctoral Fellow. He is a recipient of numerous awards for new technology and innovation, including the JPL Lew Allen Award and the NASA Exceptional Service Medal, and is a member of the Institute of Electrical and Electronics Engineers (senior level), AIAA, and the American Geophysical Union. He holds a B.S.E. from Princeton University and an M.S and a Ph.D. in computer science from Rensselaer Polytechnic Institute.

CAROL S. PATY is associate professor at the Georgia Institute of Technology (GT) in the School of Earth and Atmospheric Sciences. At GT, Dr. Paty established and developed the planetary science program and helped launch the interdisciplinary Center for Space Technology and Research. Dr. Paty's research is focused on understanding planetary magnetospheric dynamics and moon-magnetosphere interactions using a combination of computational simulations and data collected by various space-based instruments. She pioneered the application of multi-fluid plasma dynamic simulations to icy moons and outer planet magnetospheres and the inclusion of plasma-neutral interactions in global simulations. Dr. Paty was a participating scientist on the Cassini mission to Saturn and is currently a co-investigator on the Plasma Environment Package for the European mission to Ganymede (JUICE). She is also a co-investigator on both PIMS and the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) instruments for NASA's mission to Europa. Previously, Dr. Paty worked at SwRI in the Space Sciences and Engineering Division. She earned her Ph.D. in geophysics and space physics from the University of Washington.

MARC D. RAYMAN is a fellow of JPL, the highest technical position, recognized for "extraordinary technical contributions made over an extended period." He is currently the mission director and chief engineer for NASA's Dawn mission, which has orbited and explored Vesta and the dwarf planet Ceres. He held similar positions on Deep Space 1, the first deep-space mission to use solar electric propulsion and NASA's first mission to return close-up images of the nucleus of a comet. His portfolio of work also includes optical interferometry missions for detecting planets around other stars, a Mars sample return mission, a Mars laser altimeter, the Spitzer Space Telescope, and the development of systems to use lasers instead of radios to communicate with interplanetary spacecraft. Dr. Rayman is the recipient of numerous NASA honors, including three Exceptional Achievement Medals and three Outstanding Leadership Medals. He received his Ph.D. in physics from the University of Colorado, Boulder. He previously served on the Academies' Planetary Science Decadal Survey Primitive Bodies Panel.

WILLIAM S. SMITH is vice president of ScienceWorks International. Previously, Dr. Smith served as president of the Association of Universities for Research in Astronomy (AURA). AURA is a consortium of 46 major academic research institutions that promotes the advancement of astronomy and its related sciences. In this capacity Dr. Smith led in the advocacy and construction of major cutting edge astronomical facilities and built strong relationships with a wide variety of public and private universities in the United States and in other countries such as Chile, Australia, Canada, Mexico, Spain, and Japan. He also served for 14 years as a key staff member of the Subcommittee on Space of the Committee on Science for the U.S. House of Representatives. He is a recipient of a NASA Exceptional Service Award. He earned his Ph.D. in chemistry from Texas A and M University. He has not previously served on an Academies committee.

EDWARD L. WRIGHT is professor of physics and astronomy at the University of California, Los Angeles (UCLA). At UCLA, Dr. Wright has been the data team leader on the Cosmic Background Explorer, a co-investigator on the Wilkinson Microwave Anisotropy Probe, an interdisciplinary scientist on the Spitzer Space Telescope, and the principal investigator on the Wide-field Infrared Survey Explorer (WISE). Dr. Wright is well-known for his Cosmology Tutorial website for the informed public and his web-based cosmology calculator for professional astronomers. He earned his Ph.D. in astronomy from Harvard University. He is a member of the National Academy of Sciences, and he has recently served on the Academies' Committee to Study Autonomy Research in Civil Aviation, Committee on an Assessment of the Astrophysics Focused Telescope Assets Mission Concepts, Committee on Achieving Science Goals with CubeSats, and Committee on the Review of Progress Toward the Decadal Survey Vision in New Worlds, New Horizons in Astronomy and Astrophysics.

GARY P. ZANK is director of the Center for Space Physics and Aeronomic Research at the University of Alabama, Huntsville. He is also an eminent scholar and a distinguished professor in the Department of Space Science and chair of the Department of Space Science. Previously, Dr. Zank was Chancellor's Professor of Physics and Astronomy at the University of California, Riverside. His research interests cover space physics, astrophysics, and plasma physics. He earned a Ph.D. in applied mathematics from the University of Natal (Durban), South Africa. He is a member of the National Academy of Sciences, and he has previously served on the Academies' Committee on Heliophysics Performance Assessment and the Space Studies Board (SSB).

STAFF

DWAYNE A. DAY, *Study Director,* a senior program officer for the ASEB, has a Ph.D. in political science from the George Washington University. Dr. Day joined the Academies as a program officer for 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 Analyses and for 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*, *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).

MICHAEL MOLONEY is the director for Space and Aeronautics at the SSB and the ASEB of the Academies. Since joining the ASEB/SSB, Dr. Moloney has overseen the production of more than 40 reports, including 4 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 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 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.

G

Acronyms

ABI	Advanced Baseline Imager
ACE	Advanced Composition Explorer
ACMAP	Atmospheric Composition Modeling and Analysis Program
ACS	Advanced Camera for Surveys
ADR	adiabatic demagnetization refrigerator
AGU	American Geophysical Union
AIA	Atmospheric Imaging Array
AIAA	American Institute of Aeronautics and Astronautics
AIM	Aeronomy of Ice in the Mesosphere
AIRS	Atmospheric Infrared Sounder
AIS	All-Sky Imaging Survey
ALMA	Atacama Large Millimeter/Submillimeter Array
AMSR-E	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AO	Announcement of Opportunity
APL	Applied Physics Laboratory
ASEB	Aeronautics and Space Engineering Board
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATHENA	Advanced Telescope for High-Energy Astrophysics
AU	astronomical unit
AURA	Association of Universities for Research in Astronomy
AVHRR	Advanced Very High Resolution Radiometer
CADRe	Cost Analysis Data Requirement
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CATE	cost and technical evaluation
CCD	charged-coupled device
CCOR	compact coronagraph
CERES	Clouds and the Earth’s Radiant Energy System
CGRO	Compton Gamma-Ray Observatory
CIPS	cloud imaging and particle size
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CNES	Le site du Centre national d’études spatiales (French Space Agency)
COBE	Cosmic Background Explorer
CoBRA	complexity-based risk assessment
CODIF	Composition and Distribution Function
CONAE	Comisión Nacional de Actividades Espaciales (Argentina’s National Committee of Space Activities)
COS	Cosmic Origins Spectrograph
COSTAR	Corrective Optics Space Telescope Axial Replacement

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CSA	Canadian Space Agency
CuSP	CubeSat to Study Solar Particles
CYGNSS	Cyclone Global Navigation Satellite System
DIS	Deep Imaging Survey
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Agency)
DMSP	Defense Meteorological Satellite Program
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DS1	Deep Space 1
DSCOVR	Deep Space Climate Observatory
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ECT	Energetic Particle, Composition, and Thermal Plasma Suite
EGRET	Energetic Gamma Ray Experiment Telescope
EM	engineering model
ENSO	El Niño Southern Oscillation
EoC	explanation of change
EOS	Earth Observing System
EOSDIS	Earth Observing System Data Information System
ESA	European Space Agency
ESSP	Earth System Science Pathfinder
ESTO	Earth Science Technology Office
ESTP	Earth Science Technology Program
EV	Earth Venture
FGS	Fine Guidance Sensor
FIELDS	Field Measurement Experiment
FO	follow-on
FOC	Faint Object Camera
FOS	Faint Object Spectrograph
FTE	full-time equivalent
FUV	far ultraviolet
FY	fiscal year
GALEX	Galaxy Evolution Explorer
GAO	U.S. Government Accountability Office
GeV	gigaelectron volts
GFZ	German Research Center for Geosciences
GHRS	Goddard High Resolution Spectrograph
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow-ON
GRAIL	Gravity Recovery and Interior Laboratory
GRB	gamma-ray bursts
GSFC	Goddard Space Flight Center
GSICS	Global Space-based Inter-Calibration System
HALOE	Halogen Occultation Experiment
HIRDLS	High Resolution Dynamics Limb Sounder
HSD	Heliophysics Science Division
HSP	High Speed Photometer

HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
ICESat	Ice, Cloud, and land Elevation Satellite
ICRP	Independent Comprehensive Review Panel
IPS	ion propulsion system
IR	infrared
IRIS	Interface Region Imaging Spectrograph
ISIS	Integrated Science Investigation of the Sun
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
K	Kelvin
KASI	Korea Astronomy and Space Science Institute
KBO	Kuiper Belt object
KDP	key decision point
KeV	kiloelectron volts
km	kilometer
LAT	Large-Area Telescope
LDCM	Landsat Data Continuity Mission
LIGO	Laser Interferometer Gravitational-Wave Observatory
LRO	Lunar Reconnaissance Orbiter
MAVEN	Mars Atmosphere and Volatile Evolution
MAX-C	Mars Astrobiology Explorer-Cacher
MER	Mars Exploration Rover
MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
MeV	megaelectron volts
MIDEX	medium explorer
MinXSS	Miniature X-Ray Solar Spectrometer
MIS	Medium Imaging Survey
MISR	Multi-Angle Imaging Spectroradiometer
MLS	Microwave Limb Sounder
MMS	Magnetospheric MultiScale
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements of Pollution in the Troposphere
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NCAR	National Center for Atmospheric Research
NEOCam	Near-Earth Object Camera
NEOWISE	Near-Earth Object Wide-field Infrared Survey Explorer
NEOWISE-R	Near-Earth Object Wide-field Infrared Survey Explorer-Reactivation
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NOAA	National Oceanic and Atmospheric Administration
NPR	NASA Procedural Requirement
NRO	National Reconnaissance Office
NSF	National Science Foundation

NuSTAR	Nuclear Spectroscopic Telescope Array
NUV	near ultraviolet
OCO	Orbiting Carbon Observatory
OLI	Operational Land Imager
OMB	Office of Management and Budget
OMI	Ozone Measuring Instrument
OSTP	Office of Science and Technology Policy
PACE	Plankton, Aerosol, Cloud, and Ocean Ecosystem
PDR	Preliminary Design Review
PI	principal investigator
PIMS	Plasma Instrument for Magnetic Sounding
PLASTIC	Plasma and Supra-Thermal Ion Composition
PMC	Polar Mesospheric Cloud
ps	parsec
PSDS3	Planetary Science Deep Space SmallSat Studies
QWIP	quantum well infrared photodetector
R&A	research and analysis
RAD	Radiation Assessment Detector
RBI	Radiation Budget Instrument
RBSP	Radiation Belt Storm Probe
RBSPICE	Radiation Belt Storm Probes Ion Composition Experiment
ROSES	Research Opportunities in Space and Earth Sciences
SDO	Solar Dynamics Observatory
SDSM	solar diffuser stability monitor
SECCHI	Sun-Earth Connection Coronal and Heliospheric Investigation
SEP	solar electric propulsion
SES	Space Environment Simulator
SLAC	Stanford Linear Accelerator Center
SM	servicing mission
SMAP	Soil Moisture Active Passive
SMD	Science Mission Directorate
SMEX	small explorer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOFIE	Solar Occultation for Ice Experiment
SoloHI	Solar Orbiter Heliospheric Imager
SORCE	Solar Radiation and Climate Experiment
SR	Senior Review
SRCA	spectroradiometric calibration assembly
SSB	Space Studies Board
STEM	science, technology, engineering, and mathematics
STEREO	Solar Terrestrial Relations Observatory
STIS	Space Telescope Imaging Spectrograph
STScI	Space Telescope Science Institute
SWAVES	Stereo Waves Experiment
SWEA	Solar Wind Electron Analyzer
SWEAP	Solar Wind Electrons Alphas and Protons

SWIR	shortwave infrared
SwRI	Southwest Research Institute
SXS	Soft X-ray Spectrometer
TDRSS	Tracking and Data Relay Satellite System
TES	Tropospheric Emission Spectrometer
TIR	thermal infrared
TIRS	Thermal Infrared Sensor
TQ	transition quarter
TRL	technology readiness level
TROPICS	Time-resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of SmallSats
TWINS	Two Wide-angle Imaging Neutral-atom Spectrometers
UARS	Upper Atmosphere Research Satellite
UCAR	University Corporation for Atmospheric Research
UFE	unallocated future expenses
ULF	ultra-low frequency
UNH	University of New Hampshire
USGS	U.S. Geological Survey
UV	ultraviolet
UVOIR	ultraviolet/optical/infrared
VIIRS	Visible Infrared Imaging Radiometer Suite
VLISM	Very Local Interstellar Medium
VNIR	visible and near infrared
WAVES	Waves Experiment
WFC	Wide-field Camera
WFIRST	Wide-field Infrared Survey Telescope
WFPC	Wide-field Planetary Camera
WIND	Wind Experiment
WIRE	Wide-field Infrared Explorer
WISE	Wide-field Infrared Survey Explorer
WISPR	Wide-field Imager for Parker Solar Probe
WTE	whole-time equivalent