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NASA — National Aeronautics and Space Administration

SCIENCE PLAN 2014

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CHAPTER 1 Our Journey of Discovery

CHAPTER 1

Our Journey of Discovery

NASA leads the nation on a great journey of discovery, seeking new knowledge and understanding of our Sun, Earth, solar system, and the universe out to its farthest reaches and back to its earliest moments of existence. The NASA Science Mission Directorate

(SMD) and the nation's science community use space observatories to conduct scientific studies of the Earth and Sun from space, to visit and return data and samples from other bodies in the solar system, and to peer out into the vast reaches of the universe and beyond.

CHAPTER 1 Our Journey of Discovery

The knowledge gained by researchers supporting NASA's Earth and space science program helps to unravel mysteries that intrigue us all.

- What drives variations in the Sun, and how do these changes impact the solar system and drive space weather?
- How and why are Earth's climate and environment changing?
- How did our solar system originate and change over time?
- How did the universe begin and evolve, and what will be its destiny?
- How did life originate, and are we alone?

NASA SMD has developed science objectives and programs to answer these questions in the context of our national science agenda. Each of SMD's four science divisions—Heliophysics, Earth Science, Planetary Science, and Astrophysics—makes important contributions to address national and Agency goals.

Heliophysics is the study of the physical domain dominated by the Sun and its extension into space—the heliosphere. This physical domain includes our Sun and the space environments of Earth and other planets, and stretches out to the region of interstellar space. Heliophysics is the oldest science discipline studied from space and even pre-dates NASA. In 1958, the first U.S. space satellite, Explorer 1, discovered the Van Allen radiation belts, a fundamental feature of planetary magnetospheres and a critical heliophysics phenomenon. The Sun's variability and extended atmosphere drive some of the greatest changes in our local magnetic environment, affecting our own atmosphere, ionosphere, and our climate. Heliophysics is also the underlying science of space weather. Space weather directly affects the safety of humans in space and on Earth by influencing the operation of electrical power grids, communications and navigation systems, gas and oil pipelines, and spacecraft electronics and orbital dynamics. At the dawn of the Space Age, heliophysicists were focused on these near-Earth assets. Now we view heliophysics as a much broader discipline. NASA has sent probes throughout the solar system and beyond into interstellar space. To protect these robotic assets and the humans who will inevitably follow them, we must learn to predict space weather reliably anywhere, any time, throughout the solar system. From space, researchers view Earth as a planet and study it as a complex, interacting dynamic system with diverse components: the oceans, atmosphere, continents, ice sheets, and life itself. We observe and track changes on a global scale, connecting causes to effects, and we study regional changes in their global context. We observe the role that human civilization increasingly plays as a force of change. Through our partnerships with other agencies that maintain forecast and decision support systems, such as the National Oceanic and Atmospheric Administration (NOAA), United States Geological Survey (USGS), and Environmental Protection Agency (EPA), NASA improves national capabilities to predict climate, weather, and natural hazards; to manage resources; and to develop environmental policy. NASA's Earth science activities are an essential part of national and international efforts to understand global change and use Earth observations and scientific understanding in service to society. NASA's planetary science program extends humankind's virtual presence throughout the solar system via robotic space probes to Earth's Moon, to other planets and their moons, to asteroids and comets, and to icy bodies of the outer solar system. We are continuing humankind's reconnaissance of the solar system by sending missions to fly by Pluto, and to bring back a sample from a near-Earth asteroid. We are also in the midst of a systematic investigation of Mars, launching a series of progressively more capable orbiters, landers, and rovers, with the long-term goal of supporting future sample return and human exploration. Mars is rich with historical evidence of liquid water, helping us answer questions about habitability on alien worlds and the evolution of life in our solar system. We are also focusing research on the moons of Jupiter and Saturn, where we see intriguing signs of surface activity and of liquid water within, knowing that on Earth, where there is water and an energy source, there is also life.

NASA's astrophysics research enables us to learn wondrous things about our physical universe—the Big Bang and black holes, dark matter and dark energy, and the interrelated nature of space and time. Theories explaining these phenomena challenge NASA scientists to develop new methods of observations that can test these theories and our understanding of fundamental physics. We have measured the age of the universe, and now seek to explore its ultimate extremes—its birth, the edges of space and time near black holes, and the mysterious dark energy filling the entire universe. Our space missions are using nearly the full electromagnetic spectrum to observe the cosmos to understand the diversity of planets and planetary systems in our galaxy. In 2014, we will be approaching confirmation of the existence of almost 2000 planets that orbit stars other than our Sun, and will have discovered thousands of candidate planets around other stars. Some of these extrasolar planets are small, rocky bodies where liquid water could exist, and the next step is to confirm their habitability and eventually look for the signs of life. NASA's journey of scientific discovery also helps motivate, support, and prepare for human expansion into the solar system. Science missions characterize the radiation environment of deep space, the pressure and composition of diverse planetary atmospheres, the terrain and geology of planetary surfaces, and the nature and origin of small bodies. They identify the hazards and resources present as humans explore space, and the science questions and regions of interest that warrant detailed examination by human explorers.

NASA's science vision is to use the vantage point of space to achieve with the science community and our partners a deep scientific understanding of the Sun and its effects on the solar system, our home planet, other planets and solar system bodies, the interplanetary environment, and the universe beyond. In so doing, we lay the intellectual foundation for the robotic and human expeditions of the future, while meeting today's needs for scientific information to address national concerns such as climate change and space weather. At every step, we share the journey of scientific exploration with the public, and partner with others to substantially improve science, technology, engineering, and mathematics (STEM) education nationwide. Scientific priorities for future NASA science missions are guided by decadal surveys produced by the National Research Council (NRC) of the National Academy of Sciences. The first Earth science decadal survey was published in early 2007. New decadal surveys in astrophysics, planetary science, and heliophysics were released in 2010–2012, as was the midterm assessment of the Earth science decadal survey. NASA uses these surveys as the principal source of science community input into its science planning processes.

NASA issues a strategic plan every four years. To complement the NASA strategic plan, NASA SMD produces a science plan at the same cadence. This 2014 edition of the science plan focuses on changes to the program planned for 2014–2018. The next edition of the science plan is scheduled for early 2018, and will be informed by a new Earth science decadal survey and potentially the midterm assessments of the astrophysics, planetary science, and heliophysics decadal surveys.

This NASA 2014 Science Plan reflects the direction NASA has received from our government's executive branch and Congress, advice received from the nation's scientific community, the principles and strategies guiding the conduct of our activities, and the challenges SMD faces. The science plan that results enables NASA, as stated by NASA Administrator Charles Bolden, to "do the best science, not just more science."

CHAPTER 2 The National Agenda for Science at NASA

CHAPTER 2

The National Agenda for Science at NASA

NASA science contributes directly and substantially to current national priorities by:
Leading Fundamental Research: NASA is a leading scientific research organization working in and across the fields of heliophysics, Earth science, planetary science, and astrophysics. As of 2014, NASA's science program has close to 125 spacecraft in operation, formulation, or development, generating science data accessible to researchers everywhere. More than 10,000 U.S. scientists in academia, industry, and government laboratories funded by approximately 3,000 competitively selected NASA research awards are working to answer fundamental science questions of societal importance. NASA is unique among government agencies because it supports this broad and inclusive extramural research program with major research and development efforts at its ten centers to create the observational capability, new approaches, and research utilization capabilities that enable the scientific community to continue to make discoveries.

Enhancing Environmental Stewardship: Understanding the causes and consequences of climate change is one of the greatest challenges of the 21st century. NASA's advanced space missions within its Earth science research, applications, and technology program make essential contributions to national and international scientific assessments of climate change that governments, businesses, and citizens all over the world rely on in making many of their most significant investments and decisions. Through the U.S. Global Change Research Program (USGCRP), NASA works in partnership with thirteen other federal agencies to determine the relative impact of human-induced and naturally occurring climate change, addressing an important scientific challenge and providing significant societal benefit.

Inspiring the Next Generation and Creating a World-class Workforce of Scientists and Engineers: Stunning imagery and data visualizations from the Hubble Space Telescope (HST), the Solar Dynamics Observatory (SDO), and the Saturn orbiter Cassini; the exploits of the Mars rovers; and the amazing discoveries of other space and Earth science missions spark imagination, inspire students to pursue STEM education and career fields, and encourage people to become scientifically knowledgeable citizens who will be better able

to participate in science-related activities. The thousands of scientists funded by NASA are, in turn, training graduate students and postdoctoral fellows, teaching undergraduates, and providing research results for use in teacher-tested education tools. Engineers and scientists at NASA and its industrial and university partners are training their junior peers, teaching in formal and informal educational settings, and inventing new design tools for the workforce of the future. Our premier scientific laboratories, mission teams, and NASA-funded academic groups feed the broader U.S. technical workforce with employees that embody the values of excellence, innovation, and service.

Driving Technological Innovation: NASA science missions are engines of innovation, leveraging technologies to solve scientific problems. These technologies enable the advanced space missions of the future, and yield applications in the broader economy in various fields such as health care that rely on imaging, data mining, and visualization technologies. For example, technologies and techniques developed to accurately measure the shape of the mirrors for the James Webb Space Telescope (JWST) have enabled improvements in wavefront sensing technology that are now used by ophthalmologists to collect detailed information about aberrations in the shape of the human eye in seconds, rather than hours. These improvements in measurement technology can improve the diagnosis of ocular diseases and potentially improve the precision of the measurements needed during surgeries.

Extending Partnerships Domestically and Internationally: Science is a broad national and international enterprise. SMD partners with over a dozen U.S. federal agencies and more than 60 different nations and international research organizations to leverage ideas, capabilities, and resources. NASA and the National Science Foundation (NSF) collaborate to advance our understanding of the universe, with NASA providing the space-based observatories, and NSF the ground-based observatories. NASA and the Department of Energy (DOE) partner on selected space missions to study the fundamental physical laws of the universe, and to develop nuclear power sources for robotic space missions. NASA partners with established and emerging spacefaring nations to send spacecraft to asteroids, comets, and other planets. Using spacecraft observations, NASA develops models of space weather and collaborates through the National Space Weather Program with agencies such as NOAA and the Department of Defense (DOD), who use the models in operational forecasting systems.

SMD's Joint Agency Satellite Division (JASD) manages the development and launch of weather satellites for NOAA on a reimbursable basis and works with NOAA as it adopts data and measurement technologies for operational observing systems. The United States Department of Agriculture (USDA), Federal Aviation Administration (FAA), EPA, USGS, and many other agencies are users of NASA's Earth science data. SMD collaborates with the NSF on research about Antarctica that spans all four SMD science disciplines. Like the International Space Station (ISS), NASA's Sun, Earth, solar system, and distant universe observatories are models of international and interagency cooperation and serve to further common scientific interests. As a federal agency, NASA implements policy direction from the government's executive and legislative branches. As a science organization, NASA seeks advice from the broad national science community to identify the most important scientific questions and to define and prioritize the scientific research programs that most effectively address those questions. Based on this direction and advice, NASA defines its science plan.

National Policy Direction on Earth and Space Science

- The National Aeronautics and Space Act of 1958 (P.L. 85-568, July 29, 1958) established NASA's mandate to conduct activities in space to accomplish national objectives, including "the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space" and "the development and operation of vehicles capable of carrying instruments, equipment, supplies, and living organisms through space." The act specifies functions to be performed by NASA including the following:

- Arrange for participation by the scientific community in planning scientific measurements and observations to be made through use of aeronautical and space vehicles, and conduct or arrange for the conduct of such measurements and observations.

- Provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof. In the NASA Authorization Act of 2008 (P.L. 110-422, Oct. 15, 2008), Congress states several findings regarding the science programs at NASA:

- NASA is and should remain a multi-mission agency with a balanced and robust set of core missions in science, aeronautics, and human space flight and exploration.

- NASA should assume a leadership role in a cooperative international Earth observations and research effort to address key research issues associated with climate change and its impacts on the Earth system.

- Human and robotic exploration of the solar system will be a significant long-term undertaking of humanity in the 21st century and beyond, and it is in the national interest that the United States should assume a leadership role in a cooperative international exploration initiative. In the NASA Authorization Act of 2008 Congress also mandates some specific programmatic activities for NASA:

- Monitoring and assessing the health of Earth's stratosphere
- Participating in an interagency program to provide land remote sensing data
- Tracking and characterizing near-Earth objects greater than 140 meters in diameter. The NASA Authorization Act of 2010 (P.L. 111-267, Oct. 11, 2010) states that NASA should remain a multi-mission agency with a balanced and robust set of core

missions. The act also lists several Congressional findings including the following:

- It is critical to identify an appropriate combination of NASA and related United States Government programs, while providing a framework that allows partnering, leveraging and stimulation of the existing and emerging commercial and international efforts in both near Earth space and the regions beyond.

- It is essential to the economic well-being of the United States that the aerospace industrial capacity, highly skilled workforce, and embedded expertise remain engaged in demanding, challenging, and exciting efforts that ensure United States leadership in space exploration and related activities.

- The President issued the National Space Policy of the United States of America on June 28, 2010. The policy includes among NASA's responsibilities the following that pertain to SMD:

- Maintain a sustained robotic presence in the solar system to: conduct scientific investigations of other planetary bodies; demonstrate new technologies; and scout locations for future human missions.

- Continue a strong program of space science for observations, research, and analysis of our Sun, solar system, and universe to enhance knowledge of the cosmos, further our understanding of fundamental natural and physical sciences, understand the conditions that may support the development of life, and search for planetary bodies and Earth-like planets in orbit around other stars.

- Pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalog, and characterize near-Earth objects to reduce the risk of harm to humans from an unexpected impact on our planet and to identify potentially resource-rich planetary objects.

- Conduct a program to enhance U.S. global climate change research and sustained monitoring capabilities, advance research into and scientific knowledge of the Earth by accelerating the development of new Earth observing satellites, and develop and test capabilities for use by other civil departments and agencies for operational purposes.

- Work with NOAA to support operational requirements for environmental Earth observations and weather, including transitioning of mature research and development satellites to long-term operations. NOAA will primarily utilize NASA as the acquisition agent for operational environmental satellites for these activities and programs.

- Work together with the USGS in maintaining a program for operational land remote sensing observations.

- Earth's changing environment impacts every aspect of life on our planet and climate change has profound implications on society. Understanding the causes and consequences of climate change is one of the greatest challenges of the 21st century. In response to the challenge, the government's executive branch increased its emphasis on climate research and monitoring. In 2010, NASA enhanced the Earth science program defined by the 2007 National Research Council decadal survey with the addition of climate-focused measurements, as described in the Agency's climate-centric architecture plan. Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space (NASA, 2010). Efforts towards implementing this architecture within SMD are detailed in chapter 4.2.

Recommendations from the U.S. Scientific Community

As NASA aligns its science programs with national policy, it also works towards implementing the priorities defined in the decadal surveys produced by the National Research Council (NRC) of the National Academies. The decadal surveys are the result of a science and mission prioritization process executed by expert panels using broad community input gathered by representative committees. The NRC analyzes the input with the goal of articulating community priorities within the scientific scope of each survey. As such, decadal surveys represent the broad consensus of the nation's scientific communities and are the starting point for NASA's strategic planning process in the arenas of Earth and space sciences.

The NRC produces decadal surveys for each of NASA's four major science disciplines:

- Solar and Space Physics: A Science for a Technological Society (NRC, 2013)

- Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (NRC, 2007)

- Vision and Voyages for Planetary Science in the Decade 2013–2022 (NRC, 2011)

- New Worlds, New Horizons in Astronomy and Astrophysics (NRC, 2010)

Progress in implementing the science mission concepts recommended in current decadal surveys is described in Appendix A. In some areas, other reports by the NRC provide additional recommendations on matters arising since the publication of the last decadal survey. For example, NRC reports such as Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce (NRC, 2010), Controlling Cost Growth of NASA Earth and Space Science Missions (NRC, 2010), and Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions (NRC, 2011) offer NASA additional insight and advice on how to effectively implement NASA's science program. As intervening accomplishments and new scientific challenges are presented, new NRC studies will provide additional recommendations that NASA will take into consideration.

NASA receives ongoing programmatic advice from the science community through the NASA Advisory Council (NAC) and its Science Committee and subcommittees. The NAC has suggested development of community-based roadmaps that define approaches to

implementing the decadal survey science priorities, and factoring in technology readiness and synergies among science objectives and measurement types. Information on the science subcommittees, including their reports and findings, can be accessed at: <http://science1.nasa.gov/science-committee>. In addition, NASA receives advice from the Astronomy and Astrophysics Advisory Committee (AAAC) and Applied Sciences Advisory Group (ASAG), which were both chartered by Congress. AAAC conveys community input on collaborative program opportunities for NSF, NASA, and DOE, and ASAG provides community strategic and programmatic guidance for Earth science Applied Science Program activities.

CHAPTER 3

A Plan for Science at the Frontiers

NASA's 2014 strategic plan outlines the following science goals for the Agency:

- Expand the frontiers of knowledge, capability, and opportunity in space
- Advance our understanding of our home planet and improve the quality of life.

The Agency, through SMD, implements its science goals through four broad strategic objectives, each corresponding to a specific science discipline:

- Understand the Sun and its interactions with Earth and the solar system, including space weather (Heliophysics)
- Advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet (Earth Science)
- Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere (Planetary Science)
- Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars (Astrophysics)

NASA SMD science divisions accomplish the Agency's science objectives. Building on the NRC decadal surveys and interaction with the NAC and its Science Committee and subcommittees, each SMD science division has defined a set of science questions and goals upon which to base its research and mission programs (see chapter 4). Appendix B lists these SMD-generated science goals and correlates them with the Agency's overall goals and science strategic objectives, the decadal survey priorities, and the SMD missions. The principles, strategies, and challenges described in this chapter shape SMD's plans for progress in all of its science disciplines. The principles are enduring over long periods and guide SMD activities. The strategies are also long-range in nature but adapt to changing national goals, new scientific understanding and technologies, and evolving Agency policies. The challenges span all time frames and SMD must continuously look for every opportunity to overcome them.

Principles

SMD's strategic decisions for future missions and scientific pursuits are driven by priorities recommended in the NRC decadal surveys, adjusted to address national needs, and guided by a commitment to preserve a balanced program across the four major science disciplines. The fundamental success criteria for SMD are (1) progress in answering the SMD science questions, (2) implementation of the decadal survey priorities, and (3) responding to direction from the executive branch and Congress. SMD engages the Science Committee of the NAC and its subcommittees annually to rate scientific progress. In addition, Congress directed in the NASA Authorization Act of 2005 (P.L. 109-155, Dec. 30, 2005) that the performance of each division in the NASA Science Mission Directorate shall be reviewed and assessed by the National Academy of Sciences at 5-year intervals. In compliance with this directive, the midterm assessment for Earth science was completed in 2012 with a favorable assessment, and the midterm assessments for astrophysics, planetary science and heliophysics will be released in 2015–2017. The NRC anticipates a new decadal survey for Earth science will also be released in 2017–2018. In addition to the decadal surveys, programs in the Earth Science Division (ESD) are also responsive to national priorities. In 2010, NASA responded to the challenge of climate change by issuing an Agency plan for a climate-centric architecture that would guide missions and scientific pursuits of SMD's Earth Science Division for FY11 and beyond.

Investment choices are based on scientific merit via peer review and open competition. SMD uses open competition and scientific peer review as the primary means for establishing merit for selection of research and flight projects. SMD solicits individual scientist-led research investigations primarily via the annual Research Opportunities in

Space and Earth Sciences (ROSES) omnibus NASA Research Announcement (NRA). Amendments to ROSES are issued, as needed, for new opportunities unanticipated at the time of the ROSES NRA release. For completed space missions, NASA solicits complete scientific investigations involving new space missions via Announcements of Opportunity (AO). For strategic missions, NASA solicits scientific instruments via AOs. Strategic missions are defined based on NRC decadal surveys and national policy direction. NASA also occasionally issues Cooperative Agreement Notices for the establishment of virtual research institutes or for other purposes. Active virtual research institutes include the NASA Astrobiology Institute (NAI), and the NASA Solar System Exploration Research Virtual Institute (SSERVI).

Active participation by the research community beyond NASA is critical to success. SMD engages the external science community in the establishment of science priorities, preparation and review of plans to implement these priorities, analysis of requirements and trade studies, conduct of research, and evaluation of program performance. Strategic-level science advice on priorities is sought from the community primarily through NRC boards, committees, and studies. Tactical-level advice on implementing priorities is sought primarily from the scientific community via the Science Committee of the NAC and its subcommittees. SMD often engages the community through analysis groups that perform technical studies, such as mission architecture analyses, prior to conceptual design. Informal interaction with the science community occurs through meetings of the community's professional societies, such as the American Astronomical Society, the American Meteorological Society, and the American Geophysical Union.

Effective international and inter/intra-agency partnerships leverage NASA resources and extend the reach of our science results. International and interagency partnerships have long been a means to leverage SMD resources to accomplish shared science objectives. Over half of SMD's space missions involve co-investigating partners. These partnerships range from provision of science instruments, spacecraft buses, and launch vehicles, to data sharing arrangements. NASA holds regular bilateral meetings with major partners to discuss the full range of current and potential partnerships. For example, NASA and the European Space Agency (ESA) are actively engaged in dialogue about cooperation on future space missions, operations and data management, planetary protection, and calibration/ validation activities in support of current and future satellite missions. NASA partners with other federal agencies, as well as with state and regional organizations, to enable satellite observations and research to improve the tools used by these organizations to advance scientific understanding and deliver essential services to the nation. These services include weather forecasting, wildfire management, coastal zone management, agricultural crop yield forecasting, air quality assessment, near-Earth object (NEO) tracking, and space weather monitoring. Additionally, SMD partners within NASA to collectively meet complementary goals across mission directorates. For example, SMD partnered with the Human Exploration and Operations Mission Directorate (HEOMD) to measure the radiation environment from inside the spacecraft of the Mars Science Laboratory mission during its cruise to Mars—data that is mutually beneficial to both NASA directorates as they plan for future human and robotic deep space exploration. SMD has also partnered with the Space Technology Mission Directorate on coronagraph technology for future space telescopes. Additional major partnerships are identified in the science division-specific sections of chapter 4. A balanced portfolio of space missions and mission-enabling programs sustains progress toward NASA's science goals. Sustained progress requires particular attention to a balanced science portfolio including basic research, modeling programs, technology development, missions, mission data analysis, and data and information systems. An NRC report, *An Enabling Foundation for NASA's Earth and Space Science Missions* (NRC, 2010), highlighted the importance of mission-enabling programs in meeting NASA's science goals. At NASA, space missions represent the largest area of investment. In accordance with NASA Procedural Requirement 7120.5e: NASA Space Flight Program and Project Management Requirements (NASA OCE, 2012), missions are grouped into distinct categories based on cost, the inclusion of radioactive material for human or robotic spaceflight, the importance of the mission to NASA, the extent of international participation, the uncertainty of new or untested technologies, and mission risk classification. Category 1 missions have a life cycle cost (LCC) that exceeds \$1 billion; offer high-value, broad, and long-range science return; and use the scientific, engineering, and project management expertise resident at NASA Centers and academic and industrial partners. They also provide substantial opportunities for international partnerships. Category 2 missions have an LCC of \$250 million to \$1 billion, and Category 3 missions have an LCC of less than \$250 million. Both Category 2 and 3 missions provide opportunities to broaden our research portfolio, to engage universities and other research institutions in mission development, and to ensure scientific vitality and competition. Appendix C identifies the categories for each SMD program/strategic mission line. Suborbital programs, comprising sounding rockets, balloons, and aircraft, provide complementary observations, opportunities for innovative instrument demonstration, and a means for workforce development, as highlighted by the NRC in its report *Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce* (NRC, 2010). Each SMD science division balances its portfolio based on myriad factors, including, for instance, that division's requirements in the President's budget request and priorities outlined in the decadal surveys. The goals and mission sets of the science divisions are unique and inevitably lead to distinct approaches toward achieving programmatic balance among missions, technology development, and research and analysis. Balance is discussed further in the science division-specific sections of chapter 4. Appendix D depicts the decision process NASA uses throughout the mission lifecycle to maintain a balanced and effective mission portfolio.

The pace of scientific progress is enhanced by rapid, open access to data from science missions. NASA requires that science data from its missions be made available as soon as practical after scientific validation. SMD invests substantially in active archive systems to

enable public access to science data via the Internet and to preserve data that enables long-term records to be established and improved in climate change, comparative planetology, and other key areas.

The NASA mandate includes broad public communication. As a federal agency, NASA has a responsibility to communicate information about its programs and scientific discoveries to the public, and this responsibility is highlighted in NASA's founding legislation. As a research and development agency, NASA seeks to share its scientific discoveries with as broad an audience as possible. In accordance with the guidance and direction established by the National Science and Technology Council (NSTC) Committee on Science Technology, Engineering and Math Education (CoSTEM), and outlined in the Federal Science, Technology, Engineering, And Mathematics (STEM) Education 5-Year Strategic Plan (NSTC CoSTEM, 2013), NASA implements targeted efforts to reach students in order to promote STEM education, improve science literacy, and inspire and train our future workforce.

Accountability, transparent processes, accessible results, and capture of lessons learned are essential features of this federal science enterprise. The nation makes a substantial investment in NASA's science program. Thus, it is incumbent upon SMD to provide a commensurate return on investment, to be accessible to its stakeholders, and to continue to improve based on lessons learned from both successes and failures. NASA reports on its progress through various means, including annual performance reports to Congress, regular meetings of its advisory committees, press releases, town hall meetings, publications in peer-reviewed journals, and frequent posting of developments on its website. SMD's website and the Service and Advice for Research and Analysis (SARA) website (an additional resource for proposal writing) provide portals into SMD's key business processes.

Strategies

Pursue answers to big science questions to which the view from space makes a defining contribution. NASA runs one of the nation's largest science programs, and accordingly, it seeks answers to some of the most profound questions in all of science, as described in chapter 1. A detailed set of science goals designed to answer those questions is given in Appendix B. Answering these questions requires observations and measurements made in and from space, including direct measurements made from the surface of planets and objects in our solar system, and ultimately the analysis of returned samples in Earth-based laboratories. SMD's investments in research and analysis and in technology are focused on: laying the foundation for these space-based missions, inventing and using new space-based observing and sampling capabilities, creating the context and capabilities needed to interpret the resulting data, and maximizing the return on investment in the acquisition of those data. SMD's suborbital and ground-based programs are conducted to enable or complement space-based observations and train future mission scientists and engineers. Sustained Earth observations using mature space-based assets are implemented in partnership with the agencies requiring those observations.

Design and successfully implement programs that accomplish breakthrough science and applications. In NASA, programs comprise a set of projects that together advance science in that program area. Significant tangible societal benefits flow from NASA research in heliophysics, Earth science, and other disciplines. Accomplishing breakthrough science with innovative space missions requires effective management of a program portfolio, and includes:

- Measuring mission success by accomplishment of top-level science requirements
- Establishing a budget for each new mission that matches a probable life-cycle cost defined by engineering studies and independent cost estimates
- Providing budget projections and mission concept cost ranges as basic input to NRC committees formulating decadal surveys
- Obtaining tactical-level community advice on portfolio adjustments via the NAC Science Committee and its subcommittees
- Implementing effective partnerships—international, inter-agency, academic and others—to help leverage NASA resources and extend scientific results, where applicable
- Using special peer review panels of senior scientists to determine the scientific value of continued operation of existing missions beyond their prime mission lifetimes

Partner with other nations' space agencies to pursue common goals. Both longstanding and newly spacefaring nations have scientific interests similar to ours, which can be collaboratively pursued through basic research, suborbital campaigns, and competed or strategic missions. As missions become more ambitious and complex—progressing from fly-bys, to orbiters, to landers and rovers, to future sample return missions exploring other bodies in our solar system (e.g., the Moon, asteroids, and comets)—the cost of implementing them stresses the resources of any one nation. NASA has partnered with ESA and with the Japan Aerospace Exploration Agency (JAXA) successfully on numerous Earth and space science missions, and NASA continues to form additional partnerships with other countries. For strategic missions, international collaboration between agencies is based on an alignment of NASA's and its partners' science priorities, capabilities, and resources. For competed missions, international collaboration is based on scientist-to-scientist collaboration in formulating proposed investigations.

Commit to implementing missions only after focused development has matured required technologies. Technology development programs are essential for expanding the reach of future scientific missions. In fact, progress in scientific understanding typically requires advancement in measurement or platform capabilities. A balanced science program will proactively identify potential technologies, conduct trade studies and assess development risks, and invest in new technologies well in advance of mission implementation. Investments in science-driven technologies then become available to proposers of new instruments and mission concepts throughout the science program.

Share the story, the science, and the adventure of NASA missions and research to engage the public in scientific exploration and contribute to improving science, technology, engineering, and mathematics (STEM) education nationwide. NASA's science is unique among federal agencies. It inspires and engages students and people of all ages to learn about new science discoveries and to acquire new skills in science, technology, engineering, and mathematics. SMD is building strategic educational and public outreach partnerships to enhance the nation's STEM education, as described in the Federal STEM Education 5-Year Strategic Plan.

Challenges

This section discusses the challenges that SMD faces in carrying out its science plan according to the principles and strategies outlined earlier. First the challenges that the Agency outlined in its 2010 Science Plan for NASA's Science Mission Directorate (NASA, 2010) are updated to reflect progress the SMD has made in addressing these challenges: access to space, mission cost estimation and management, technology development and demonstration, and impediments to international collaboration on space missions. Following these challenges are new issues for 2014–2018: protecting the planet while advancing science, national science and technology workforce development, long-term program planning, and unrealized expectations.

SMD relies on commercial expendable launch vehicles (ELVs) acquired for SMD by the Human Exploration and Operations Mission Directorate to launch its science missions into space. In the past few years, access to space has been hindered by the failure, discontinuation, or cost of launch vehicles. For SMD small payload class missions, the small-class launch vehicles on contract to NASA are the Orbital Sciences Corporation (OSC) Pegasus XL and Taurus XL, and the Lockheed Martin Space Systems Company (LMSSC) Athena Ic. The Pegasus XL has had a successful launch history. The Taurus XL has higher lift performance capability than the Pegasus XL, but experienced two successive launch failures for SMD Earth science missions—the first in 2009 for the Orbiting Carbon Observatory (OCO) mission, and the second in 2011 for the Glory mission. The Athena Ic has not yet flown and remains ineligible to compete for the launch of an individual NASA payload. For decades, the predominant medium class launch vehicle utilized by SMD has been the Delta II launch vehicle. As of 2014, one Delta II launch vehicle remains available for acquisition by NASA. Currently the medium-class launch vehicles on contract to NASA are the OSC Antares 120/130 series, the Space Exploration Technologies (SpaceX) Falcon 9, and the LMSSC Athena IIc. Certification activities for the Falcon 9 version 1.1 are underway to support the Jason 3 mission, which is scheduled for launch in March 2015. The Antares 120 successfully completed its first flight in January 2014, and is now eligible to compete for the launch of an individual NASA payload. Neither the Antares 130 nor Athena IIc has yet flown, and both remain ineligible to compete for the launch of a NASA payload. For SMD large payload class missions, the Atlas V has had a successful launch history, albeit at a premium cost, principally due to the fact that it was the only certified launch vehicle on contract for large payload class missions. In addition, the Atlas V manifest is congested, due to competition for launch slots among the civil and military communities. In addition to medium class missions, the Falcon 9 version

is also capable of providing "Atlas V-like" performance for payloads going to low Earth orbit and is expected to be comparable to the smallest Atlas V in performance for some planetary missions and geosynchronous transfer orbit missions. Once the Falcon 9 version 1.1 is certified, it is envisioned that competition between the intermediate-class launch vehicles should assist in lowering costs and may help reduce manifest congestion in the Atlas V fleet. As an alternative to contracting for launch vehicles, NASA is exploring opportunities to fly instruments as hosted payloads on commercial satellites to reduce launch costs. This paradigm is similar to ridesharing or co-manifesting, but instead of sharing a launch vehicle, the instruments share a satellite bus.

SMD continues to develop and implement the cutting-edge technologies necessary to advance exciting scientific discoveries. However, more precise mirrors, advanced power systems, probes and satellites that can withstand hostile environments, and observatories that can be sustained for decades are inherently complex, so cost and schedule risks are inevitable. In an increasingly constrained fiscal environment, it is becoming even more important to execute SMD's missions on time and within budget. In the 2010 Science Plan for NASA's Science Mission Directorate, SMD outlined the Agency's efforts to revise and implement new policies to constrain mission costs and meet schedule goals. These steps include:

- Establishing mission life-cycle budgets at the 70% confidence level
- Obtaining multiple, independently generated internal and external cost estimates
- Reviewing projects at multiple, formal Key Decision Points that function as gates to the next stage of development

As required by the NASA Authorization Act of 2005, preparing a report to Congress on any project expected to exceed 15 percent cost growth or delay its launch date milestone by more than six months from its baseline, identifying corrective actions, their costs, and any alternatives.

Additionally, NASA requires that cost estimates of mission concepts submitted by NASA centers to NRC decadal survey committees be reviewed by an independent team of cost/schedule estimators and approved by the SMD Science Division Director. By following these steps over the last three years, NASA has launched several missions either under or within their cost and schedule baselines, demonstrating progress in improving the Agency's mission cost estimation and management tools (see Figure 3.1). This record of cost and schedule performance for SMD is historically unprecedented. The Van Allen Probes (formerly known as the Radiation Belt Storm Probes [RBSP]), Juno, Gravity Recovery and Interior Laboratory (GRAIL), Mars Atmosphere and Volatile Evolution

(MAVEN) mission, and Landsat Continuity Data Continuity (LDCM)/Landsat 8 did not require a re-baseline at any point during implementation.

Recent Cost Performance

Action, and were below the budget level originally promised. For some of the missions that exceeded original forecasts (e.g., Interface Region Imaging Spectrograph (IRIS)) cost overruns were small—within 5% deviation, with minimal to no slip in the launch readiness date. However, as the U.S. Government Accountability Office (GAO) 2013 High-Risk Series update report (GAO, 2013) notes, “it may take several years to assess the effectiveness of NASA’s enhanced cost estimating practices,” and therefore, SMD will continue to rigorously maintain these practices and take additional steps to improve schedule and cost performance, particularly for large strategic missions like the Mars 2020 Rover and the Solar Probe Plus mission. These additional steps include ensuring that cost and schedule performance for all missions, regardless of mission size and scope, remain consistent with baseline commitments in order to maintain the overall balance of SMD’s portfolio.

Recent Schedule Performance

Although SMD has rigorously monitored its cost and schedule estimates over the last several years, the innovative nature of most space research missions and rising expendable launch vehicle (ELV) prices continue to cause the directorate to experience overruns. For example, an astrophysics project, the Gravity and Extreme Magnetism Small Explorer (GEMS), was not confirmed to proceed to the implementation phase. The decision not to proceed was made after an independent cost assessment found that there was a 50% chance the project would overrun by 20–30%. The James Webb Space Telescope (JWST) and the Mars Science Laboratory (MSL) are two other examples of missions that significantly overran projected cost and schedule estimates. An Agency priority, JWST was re-baselined in 2011 utilizing the new cost and schedule policies mentioned above, and continues to meet its cost and schedule commitments for a launch in 2018. MSL launched in November 2011, with the Curiosity rover successfully landing on Mars in August 2012. Since implementation of these efforts to control cost and schedule estimates, NASA has experienced significantly fewer cost and schedule overruns overall. One impact of the policy of budgeting at the 70% confidence level, however, has been to reduce the number of new mission starts. When missions do overrun, SMD endeavors to confine the impacts to the program in which that mission resides. Where that is not possible, SMD explores options such as reducing scope or cancelling the mission. When considering options for resolution, SMD takes into account cost, risk, and the advice of the scientific community, as obtained through the NAC Science Committee and its subcommittees.

Organizations managing complex, near-term development efforts perennially struggle to sustain investments in future capabilities. SMD has implemented technology programs in its science divisions, but in tight budgetary times, the organization finds it challenging to focus on technology developments needed to enable specific missions. NASA created the Space Technology Mission Directorate (STMD) in 2013 to develop space technologies needed by SMD and HEOMD, and to invest in strategic technologies potentially needed in the future. To continue to advance technology needed for its planned missions, SMD is collaborating and partnering with STMD across the full range of its nine technology programs (see Table 6.1 in chapter 6). Consultation and collaboration with STMD span all phases of technology development, and include activities such as identifying new opportunities, developing specific solicitations, partnering to co-fund technology developments, and reviewing and evaluating ongoing developments with a view toward technology infusion.

In 1999, Congress redefined civilian spacecraft as “defense articles” and transferred all aspects of controlling the export of information regarding their design, manufacture, and operation from the Department of Commerce Export Administration Regulations (EAR) to the State Department’s more restrictive International Traffic in Arms Regulations (ITAR). This change introduced a variety of serious legal and administrative complications into the conduct of international cooperative projects involving scientific spacecraft. By impeding the transfer of information on the design, fabrication, assembly, and operation of NASA spacecraft and instruments to foreign colleagues and foreign students and researchers at U.S. universities, ITAR impacts NASA’s ability to work with foreign space agencies and hampers the universities’ collaborative environment, which depends upon the open exchange of information and ideas among students and faculty. ITAR requires that individual Technical Assistance Agreements (TAAs) be established between the U.S. and each foreign entity working on a NASA program. For example, JWST has 210 individual TAAs in place, each approved by the State Department. The executive and legislative branches worked collaboratively to overturn the 1999 statute with passage of the National Defense Authorization Act for Fiscal Year 2013, a prerequisite to considering any regulatory changes. The executive branch is publishing interim-final state and commerce regulations that resolve some of these concerns, particularly with regard to the scope of controlled ITAR activities. The issue of differentiating between scientific spacecraft and weapons, both of which rely on identical technology, is under further study as part of the interim-final regulations. The executive branch’s goal is to publish revised regulations in 2014 that further address these concerns.

SMD’s scientific research not only advances our understanding of the Earth and space, but the knowledge it generates informs the nation’s decision makers, first responders, and communities by providing observations and predictions on climate and extreme weather, space weather, and potentially hazardous near-Earth objects (NEOs). Many instruments

and spacecraft platforms are beyond their prime design lifetimes, but are providing needed long-term measurements. Many space system assets that were originally designed to address research objectives are now being repurposed to gather measurements for operational use by NASA's interagency and international partners, or to detect NEOs. Taking into consideration these challenges, the following details some of the activities we are engaging in to meet societal needs.

Climate and Sustained Land Imaging: Studying the Earth as a system is essential to understand the causes and consequences of climate change and other global environmental concerns. NASA's Earth science programs evolve from an interdisciplinary view of the Earth, exploring the interaction among the atmosphere, oceans, ice sheets, land surface interior, and life itself. This approach enables scientists to measure the global effects of climate change and to inform decisions by governments, organizations, and people in the U.S. and around the world. The FY14 budget transfers responsibility for the sustained climate measurements of solar radiation, global ozone profiles, and Earth radiation balance from NOAA to NASA's Earth

Science Division, starting in the 2020 time frame. In addition, the FY14 budget initiates a new NASA project for the development of a sustained national system for global land imaging, to be developed in collaboration with USGS. These sustained global Earth observations are needed to monitor and study the Earth's climate system, land use, and land cover change, as well as to monitor the impact of weather and extreme weather events such as heat waves, cold waves, precipitation patterns, floods, droughts, and the intensity and distribution of tropical cyclones and tornadoes. Looking forward, under a likely scenario in which budgets remain relatively flat, maintaining a balance between providing the necessary uninterrupted climate measurements and developing new Earth system science missions at the pace recommended in the decadal survey will be difficult. Furthermore, the need to establish an implementation strategy for the climate measurements and land imaging is critical to preventing a data gap in the long-term data sets for each.

Space Weather: Space weather refers to variable conditions on the Sun, in the solar wind, and in the near-space environment that can create risks for humans in space and cause disruption to electric power distribution and satellite operations, communications, and navigation. Heliophysics research provides a foundation to predict space weather events, mitigate the hazards posed to assets both in space and on the ground, and understand space weather impacts throughout the solar system. To meet national and societal space weather needs, NASA coordinates its space weather activities with several interagency and international partners, including NOAA, which is responsible for delivering operational space weather products and services to the nation. NASA's aging fleet of heliophysics spacecraft provide observations of solar and geophysical events that are incorporated into operational space weather forecasts and satellite anomaly assessments for national use. Specifically, space weather data from heliophysics spacecraft are provided either through direct broadcast from satellite or processed in near real time, and made accessible via the Internet. NASA also provides information for safe and efficient operation of its robotic and human missions, including situational awareness alerts and forecasts for NASA assets throughout the solar system. With the launch of the Deep Space Climate Observatory (DSO) mission in 2015, the risk of losing the capability to conduct space weather measurements will be reduced. Other relevant NASA activities include pioneering new mission and instrument capabilities and improving space weather prediction algorithms and models.

Near-Earth Objects: Planetary science research programs and missions help advance our understanding of the formation of planetary bodies, the chemical and physical history of the solar system, and conditions that are capable of sustaining life. In addition, NASA's investments in planetary science protect Earth by identifying and characterizing celestial bodies and environments that may pose threats to our planet. In the future, NASA will conduct a bold new mission to redirect an asteroid to a stable lunar orbit, where astronauts will explore it to increase our understanding of NEOs and the resources they will provide for future human exploration beyond low Earth orbit (LEO). NASA leads the world in the detection and characterization of NEOs, and provides support for the ground-based observatories that are responsible for the discovery of about 98% of all known NEOs. NASA has also conducted robotic missions to study asteroids and comets. NASA uses radar techniques to better characterize the orbits, shapes, and sizes of observable NEOs, and funds research activities to better understand their composition and nature. NASA also funds the key reporting and dissemination infrastructure that allows for worldwide follow-up observations of NEOs, as well as related research activities, including the dissemination of information about NEOs to the larger scientific and engineering community. Consistent with the President's National Space Policy, NASA continues to collaborate with the Department of Defense and other government agencies on planning and exercises for responding to future hazardous NEOs.

Advances in science and technology are drivers for the nation's economic growth, leadership, and security. Enhancing the nation's research and development portfolio and maintaining its scientific capacity are essential if the U.S. is to maintain its competitiveness in the face of rapidly increasing international competition in high-tech industries. Continuing to support the entire scientific knowledge pipeline—from grade school, to postdoctoral programs, to opportunities for early-career scientists—will lead to a strong scientific workforce. SMD research, technology, and flight projects attract and train future science and technical workers at the undergraduate, graduate, and postdoctoral levels. These projects allow students and researchers to gain invaluable NASA science program work experience. The suborbital and small satellite programs (airplanes, sounding rockets, balloons, CubeSats, and future commercial suborbital platforms) and

Principal Investigator-led missions enable students to participate in the entire lifecycle of a science mission, from design and construction, to flight and data analysis. These hands-on opportunities provide experiences in problem solving and increase understanding of the systems engineering that is the underpinning of success within the broader scientific community. Specific programs such as the NASA Postdoctoral Program, NASA Earth and Space Science Fellowship (NESSF) Program, and other early-career programs (e.g., Early Career Fellowships, New Investigator Program in Earth Science, Roman Technology Fellowship Program, Hands-On Project Experience Program, and Student Airborne Research Program) ensure the continued training and nurturing of a highly qualified workforce. However, inadequate support for technical workforce development programs challenges the nation's ability to maintain the scientific capacity needed to drive innovation and economic growth in the future.

Spacecraft, valuable data will be lost and NASA's ability to maintain a long-term, continuous data record in key science areas will be inhibited. Furthermore, with the current and anticipated constrained budget, tradeoffs may need to be made across the various science research areas, potentially impacting the balance of programs and the opportunity to develop the workforce, especially early career scientists. The budgetary environment has evolved since the release of the decadal surveys, and is very different from that assumed when the NRC formulated the survey recommendations. The overall budget level available to implement decadal survey recommendations—particularly future funding for new missions—is significantly reduced from that assumed in the decadal surveys. At the same time, the cost of doing business continues to rise with inflation, while the budget likely will experience limited growth, widening the gap even further between science community expectations for future missions and available resources. Appendix A identifies the status of the flight programs and missions that are included in the FY 2014 budget approved by Congress for SMD, and that respond to decadal survey recommendations and other national priorities.

CHAPTER 4

Detailed Plans by Science Area

Based on national policy direction and recommendations from the nation's science community via NRC decadal surveys, each of the four SMD divisions has developed plans for future missions and supporting research and technology. Each of the four major sections to follow is devoted to a single science discipline, and identifies the top-level science questions to be pursued, the strategy to do so, and the current and planned future missions and research programs for the corresponding SMD science division. The grouping of SMD research into these four science disciplines is a useful management construct, but the science itself knows no such boundaries. Indeed, important scientific opportunities exist in the regions of overlap among them, and across other NASA directorates and foreign and domestic agencies. Therefore, between each of the science sections in this chapter we highlight examples of such crosscutting efforts.

Heliophysics

Strategy

Heliophysics encompasses science that improves our understanding of fundamental physical processes throughout the solar system, and enables us to understand how the Sun, as the major driver of the energy throughout the solar system, impacts our technological society. The scope of heliophysics is vast, spanning from the Sun's interior to Earth's upper atmosphere, throughout interplanetary space, to the edges of the heliosphere, where the solar wind interacts with the local interstellar medium. Heliophysics incorporates studies of the interconnected elements in a single system that produces dynamic space weather and that evolves in response to solar, planetary, and interstellar conditions. All of NASA's space missions (including the inhabited ISS) and much of our nation's communications and navigation infrastructure (such as the critical Global Positioning System [GPS]) are operating in an environment driven by the highly variable output from the Sun. The Sun periodically sends out powerful coronal mass ejections and

flares that accelerate charged particles to nearly the speed of light. These disturbances drive the aurora and powerful electric currents on Earth, inflate the Van Allen radiation belts, violently churn the ionosphere and uppermost layers of the atmosphere, and can disrupt our technologies in space or be harmful to astronauts. NASA's heliophysics program provides the research and technological development necessary for the scientific understanding of how space weather affects human and robotic space exploration and the habitability of Earth and other worlds. The models and research tools NASA develops to interpret heliophysics data lead to substantial improvements in operational space weather monitoring. Heliophysics uses our local space environment as a natural laboratory that can be directly probed with our satellites. Planets and solar systems are commonplace around other nearby stars and probably throughout the universe. The fundamental physical processes active in our near-space environment are also at work in these distant places humans cannot visit. Increasing understanding of our home in space therefore furthers humanity's knowledge of some

THE HEATING OF THE SOLAR CORONA

NASA's High Resolution Coronal Imager, or Hi-C, telescope captured the highest-resolution images ever taken of the Sun's million-degree atmosphere. These observations provide intriguing hints of a mechanism that likely contributes to the heating of the solar corona. Hi-C's images show the evolution of the magnetic field and the repeated release of energy evident through the brightening of the plasma, indicative of heating to 2 to 4 million degrees Fahrenheit, of the most basic working principles of the universe. As exploration extends further into space, and as society's technological infrastructure is increasingly dependent on assets that are impacted by the space environment, a broader and fundamental understanding of these governing processes becomes ever more important and relevant. The Agency's heliophysics strategic objective is to understand the Sun and its interactions with Earth and the solar system, including space weather. The heliophysics NRC decadal survey, *Solar and Space Physics: A Science for a Technological Society* (NRC, 2013), articulates the scientific challenges for this field of study and recommends a slate of design reference missions to meet them, to culminate in the achievement of a predictive capability to aid human endeavors on Earth and in space. The Heliophysics Division addresses its Agency objectives and the NRC decadal survey recommendations in the context of our national space policy by working to answer these fundamental science questions:

- What causes the Sun to vary?
- How do the geospace, planetary space environments and the heliosphere

respond?

- What are the impacts on humanity?

To answer these questions, NASA's Heliophysics Division is implementing a program to achieve three overarching science goals:

- Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system
- Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system
- Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth

With substantial input from the heliophysics community, the NAC Science Committee Heliophysics Subcommittee has developed a Heliophysics science and technology roadmap (NAC Science Committee Heliophysics Subcommittee, 2014) to examine strategies for implementing the decadal survey recommendations. The Heliophysics science and technology roadmap provides the framework for guiding investment choices both on tactical and strategic scales and in the context of the decadal survey.

The Heliophysics Division faces all the challenges articulated in chapter 3.3 (e.g., access to space, mission cost estimation and management, technology development and demonstration, impediments to international collaboration, long-term program planning). In particular, a constrained budget, combined with increasing costs associated with access to space, makes it impossible to implement all the decadal survey recommendations within the decade. In this environment, however, SMD's Heliophysics Division remains committed to implementing a balanced mission portfolio that provides the vitality needed to accomplish the breadth of the recent decadal survey's science goals within the limitations of its available resources. In addition, the Heliophysics Division addresses system science that depends on coordinated observations made possible by the constellation of spacecraft that is made up of various scientific research missions, many of which are operating well beyond their design lifetimes. This constellation is known as the Heliophysics System Observatory (HSO). Maintaining and expanding the HSO requires continuing financial support, creating a natural conflict between continuing existing missions and other areas of the budget. In the coming years, as existing missions cease to operate, Heliophysics will be even more challenged by demands to provide the long-term and continuous observations necessary to understand the systemic nature of heliophysics science. If existing missions cease and are not replaced by missions providing similar measurements, potential synergies and opportunities enabled by the overlap of existing HSO measurements and measurements provided by new missions will not be realized. Consistent with the decadal survey recommendations, NASA is working with other agencies through the National Space Weather Program to plan for continuing some solar and solar wind observations beyond the lifetime of current HSO assets.

The need for the connected measurements underscores the criticality of maintaining an

adequate mission cadence and balance. Heliophysics will pursue multiple approaches to optimize the cadence by (1) applying state-of-the-art technologies to meet science goals at reduced expense, (2) optimizing the cost effectiveness of missions by fostering innovative mission designs, (3) leveraging domestic and international partnerships for missions and launch vehicles, and (4) adjusting the scope of the planned missions. The continuity of science measurements is key; without continuity, the opportunities provided by the simultaneous operation of the HSO elements and the new missions discussed here will be lost.

The heliophysics science program consists of three flight programs including the Solar Terrestrial Probes (STP), Living With a Star (LWS), and Explorer Programs. In addition, the Heliophysics Research Program provides the theoretical and analytical foundation and tools that ensure new observations lead to scientific advancement. All of these elements contribute to the development of scientific understanding of the heliophysics system. Partnerships with other national and international agencies and within NASA provide additional opportunities to meet shared science goals. The teamwork between the U.S. and other space agencies augments the capabilities of many heliophysics science missions and permits investigations that could not be achieved separately. Additionally, given the constrained resource environment, the Heliophysics Division will continue to utilize the improved program/project mission cost estimation and management processes articulated in chapter 3.3, as well as integrate new mission management strategies recommended in the decadal survey, to contain cost and ensure successful and efficient implementation and operation of heliophysics programs. The Heliophysics Division is working to rebalance its portfolio, where currently two-thirds of the budget is allocated to the LWS and STP flight programs and one-third is allocated to the Heliophysics Research and Heliophysics Explorer Programs, to a more equitable split as recommended by the decadal survey. This rebalancing recognizes the combined contributions of the Heliophysics Research Program and the Principal Investigator (PI)-led Explorer Program to scientific advancement and discovery, and gives these programs higher priority.

Solar-Terrestrial Probes Program

Missions within this program improve our understanding of fundamental physical processes that exist throughout the universe. Our stellar atmosphere contains rapidly flowing plasma—the solar wind—that creates a cavity in the galaxy called the heliosphere, which extends hundreds of times further than the distance between the Sun and the Earth. Because the Sun's output is highly variable in location, intensity, and time, the near-space environment of the Earth and other planets is profoundly dynamic, and hosts numerous phenomena that can be examined in detail by instruments on spacecraft. We have in essence a laboratory in our own backyard for examining fundamental processes seen at other planets and in other stellar settings. STP missions address unsolved scientific questions about critical physics that determines the mass, momentum, and energy flow within the interconnected Sun-heliosphere-Earth system. The knowledge gained from the focused science approach of the STP missions is critical to and enables the predictive capability addressed by the Living with a Star Program.

Living With a Star Program

This program emphasizes the science necessary to understand those aspects of the Sun and space environment that most directly affect life and society, and develops missions that help us better understand the coupled Sun-Earth system. The LWS missions adopt a systems approach toward understanding how major components of the connected Sun-heliosphere-Earth-planetary environment interact, with the ultimate goal of enabling a predictive capability. LWS missions are coupled with a targeted research program to answer the specific questions needed to understand the linkages among the interconnected systems that impact us. LWS science utilizes and augments the basic physics insights gained from the STP and Heliophysics Research Programs, applying them specifically to the science of space weather. The LWS science component supports targeted research and technology investigations that address unresolved questions crossing the usual boundaries between scientific disciplines and research techniques. These investigations—particularly those that have an applied aspect, such as the science of space weather—develop specific, comprehensive models focused to understand heliophysics as a system. LWS also supports the comprehensive models required for development of a forecast capability for space weather. These strategic capability models are made available for use by the scientific community and for evaluation for potential transition to operational use at the Community Coordinated Modeling Center (CCMC) at NASA's Goddard Space Flight Center.

Heliophysics Explorer Program

The Explorer Program has a well-known history of providing high science return for a relatively small investment and is the highest priority for new missions within the decadal survey. The program complements the two strategic programs described above by providing a mix of small, medium, and large competitively selected PI-led missions required for a robust scientific flight program. Explorer missions have proven historically to be highly successful and cost-effective, providing insights into both the remotest parts of the universe and the detailed dynamics of Earth's local space environment. In combination with other HSO missions, the Explorer missions offer the opportunity to fill critical science gaps in the prescribed program and resolve many open science questions. By responding rapidly to new concepts and developments in science and forging synergistic relationships with larger-class strategic missions, Explorer missions play a major role in the ability of the Heliophysics Division to fulfill its NASA strategic objective. Priorities are based on an

open competition of concepts solicited from the scientific community. The decadal survey emphasizes the importance of frequent flight opportunities for the Explorer missions, as well as the continued high scientific return of Missions of Opportunity (MoOs). The MoOs are characterized by being part of a host space mission other than a strategic mission, and offer an extremely cost-effective platform for achieving science. A robust Explorer mission line is important to maintain current capabilities and will enable significant advances in our understanding of the field.

Heliophysics Research Program

The Heliophysics Research Program directly supports the generation of new knowledge, scientific and technological development, and scientific progress in different ways. Theory and numerical simulations, data analysis techniques, data modeling, and instrument development are fundamental areas of support. Laboratory work is needed to constrain and quantify basic physical processes, radiative transfer and magnetic reconnection being two examples. Low cost access to space is needed to develop the next generation of space hardware. The Heliophysics Division is committed to creating a robust research program by implementing growth as recommended by the decadal survey. This growth will be achieved through the Diversify, Realize, Integrate, Venture, Educate (DRIVE) initiative. DRIVE is designed to more fully develop and effectively implement the entire Heliophysics Division portfolio of missions, experiments, simulations, and theoretical models. The DRIVE initiative can enhance the scientific return from our missions, develop new tools (both hardware and models), and reorganize our research program to better position itself for new scientific breakthroughs. To implement DRIVE, the division will need to focus resources on the most important and highest quality research and be more flexible in utilizing the full range of flight opportunities—sounding rockets, balloons, CubeSats, hosted payloads, etc.—to achieve the highest-priority science. Competed research and analysis (RA) is an important element of the Heliophysics Research Program as it enables utilization of the observational data brought in by HSO missions through open scientific competition. Groundbreaking science results lay the foundation for the formulation of a next generation of unanswered, more specific questions to be addressed by future missions. The RA element uniquely fosters the system science of the HSO, enabling research that crosses mission boundaries. Competed RA supports instrument development and low-cost access to space that allow for a cost-effective, diversified way to develop the next generation of space hardware, train scientists and engineers, and make breakthrough science observations. Another element of the Heliophysics Research Program encompasses development of advanced theories, models, and simulations and their verification through observations and data analysis. The CCMC, part of the Research Program, is the repository for these models and facilitates their validation. Additional elements of the Heliophysics Research Program include ensuring the archiving and accessibility of all heliophysics observational data through support of archive facilities and openly competed innovative data distribution and display concepts. Other project lines within Heliophysics Research consist of the Sounding Rocket Program Office and the Wallops Research Range. Heliophysics manages these shared assets for the benefit of all SMD science divisions. Heliophysics responded to the latest decadal survey by restructuring the Heliophysics Research Program to use resources more effectively and to tackle cross-disciplinary research problems. The Heliophysics-Grand Challenges Research (H-GCR) element supports larger PI-proposed team efforts that require a critical mass of expertise and utilize recent advances in computational power to make significant progress in understanding complex physical processes with broad importance. Previous discipline-specific opportunities were integrated into Heliophysics-wide opportunities, including the Heliophysics-Supporting Research (H-SR) element and the Heliophysics-Guest Investigator (H-GI) element. Results of H-SR investigations guide the direction and content of future science missions. H-GI is focused on maximizing the scientific return of missions in the HSO. The Heliophysics-Technology and Instrument Development for Science (H-TIDeS) element of the Research Program supports Low-Cost Access to Space (LCAS), which includes balloon, CubeSat, ISS, commercial reusable suborbital launch vehicles, and sounding rocket investigations. H-TIDeS also drives the development of instrument concepts that show promise for use on future heliophysics missions. The technological advances feed into future missions and expand their effectiveness beyond current capabilities. The Laboratory Nuclear, Atomic and Plasma Physics sub-element supports advances in relevant laboratory measurements needed for the interpretation of current and future mission data. More information about H-TIDeS can be found in the Technology Development section below.

Using the entire fleet of solar, heliospheric, magnetospheric, ionospheric, and upper atmospheric missions, and data from planetary spacecraft, NASA operates the HSO as a distributed observatory to discover the larger scale and/or coupled processes at work throughout the complex system that makes up our space environment. This distributed observatory has flexibility and capabilities that evolve with each new mission launched. In addition to supplying valued science data, many operating HSO missions provide key observations used to predict space weather. Table 4.1 lists the missions in the currently operating HSO. The HSO is a continuously evolving fleet, with each mission providing key inputs from unique vantage points. Examples include IRIS, the Van Allen Probes, STEREO, TIMED, and Voyager. IRIS observes how solar gases move, gather energy, and heat up through the interface region—information that is key to understanding what heats the Sun's corona. IRIS improves our understanding of the interface region where most of the Sun's ultraviolet emission (which impacts the near-Earth space environment and Earth's climate) is generated. The twin Van Allen Probe spacecraft determine how charged particles in space near the Earth are stored and accelerated to hazardous energies that affect satellites, astronaut safety, and high-latitude aircraft. The first science result of the Van Allen Probes was the discovery of a long-lived relativistic electron storage ring embedded in Earth's outer Van Allen belt. STEREO provided the first view of the whole Sun and three-dimensional views of coronal mass ejections, a major driver of space weather phenomena. TIMED provides a comprehensive overview of the variability of the mesosphere-lower

thermosphere-ionosphere region of Earth's atmosphere. Voyager 1 and 2 are at the edge of the heliosphere, exploring the interaction of the heliosphere with the local interstellar medium. Voyager 1 is now exploring interstellar space.

2014 SCIENCE PLAN

To obtain the greatest science benefits possible within the division's resources, the Heliophysics Division collaborates with other national or international agencies' missions whenever possible. The division routinely partners with other agencies to fulfill space weather research needs and provides input for the operational objectives of the nation. Examples include the real-time space weather data supplied by the ACE, STEREO, SOHO, Van Allen Probes, and SDO missions. The division also utilizes the considerable synergies between heliophysics and other science disciplines. For example, the SDO was a high priority in the 2002 astrophysics decadal survey, as the Sun is an archetype for all similar stars, and the Planetary Science Division's Juno mission fulfills the third-priority mid-scale mission recommendation in the 2003 heliophysics decadal survey. The two ARTEMIS (Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun) probes were re-purposed from the THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission to orbit the Moon's surface and provide new information about the lunar internal structure, plasma, and radiation environment.

The heliophysics missions now in formulation or development for launch over the next decade address some of the priorities in both the 2003 and 2012 Heliophysics decadal surveys. These missions include the Magnetospheric Multiscale (MMS), Solar Orbiter Collaboration (SOC), and Solar Probe Plus (SPP). The newly selected Explorer mission, Ionospheric Connection (ICON), together with the newly selected MoO, Global-scale Observations of the Limb and Disk (GOLD), will focus on the dynamics of the ionosphere. Table 4.2 identifies the missions that are in formulation or development, with launches planned over the 2014–2020 timeframe. The expected launch years are subject to change, but provide the relative timeframes for development. Another upcoming mission in the STP Program is the MMS mission, a four-spacecraft constellation designed to use Earth's magnetosphere as a laboratory to study the micro-physics of magnetic reconnection, a fundamental process that converts magnetic energy into heat and acceleration of charged particles. Magnetic reconnection occurs in all astrophysical plasma systems, but can be studied in detail in our solar system and most efficiently in Earth's magnetosphere.

SOC is a collaborative mission with ESA that will provide close-up views of the Sun's polar regions, which are poorly observed from Earth. SPP will be the first mission to visit a star. The mission will study the streams of charged particles the Sun hurls into space from an unprecedented vantage point: inside the Sun's corona—its outer atmosphere—where the processes that heat the corona and produce solar wind occur. At its closest approach, SPP will zip past the Sun at 125 miles per second, protected by a carbon-composite heat shield that must withstand up to 2,500 degrees Fahrenheit and survive blasts of radiation and energized dust at levels not experienced by any previous spacecraft. By directly probing the solar corona, this mission will revolutionize our knowledge and understanding of coronal heating and of the origin and acceleration of the solar wind, critical questions in heliophysics that have been ranked as top priorities for decades. By making the first direct, in situ measurements of the region where some of the most hazardous solar particles are energized, SPP will make a fundamental contribution to our ability to characterize and forecast the radiation environment in which future space explorers will work and live.

The Heliophysics NRC decadal survey was completed in 2012 and formed the basis for the 2014 Heliophysics science and technology roadmap. To achieve the science goals of the Heliophysics Division, the roadmap recommends a strategy that leverages all program elements of the Heliophysics Division. The recommendations include new missions to be deployed by the Explorer, STP, and LWS mission lines, establishing a queue of science targets as shown in Table 4.3. These targets address the most compelling science questions in heliophysics and provide several new opportunities for discovery. The division's research strategy is based upon prioritized, yet flexible, science goals.

Significant progress toward meeting the scientific and technical challenges for heliophysics over the coming decades hinges on improving observational capabilities and innovative instrumentation. The Heliophysics Division supports development of technologies for its flight missions via mission-specific elements through the flight programs and the newly initiated Heliophysics Technology and Instrument Development for Science (H-TiDeS) element of the Heliophysics Research Program. Heliophysics flight program lines develop medium technology readiness level (TRL) technologies, bringing specific technologies into maturation as required by the mission. For example, technologies developed to enable the SPP mission to fly 20 times closer to the Sun than the Earth and to receive 500 times the solar input are representative of this concept. Key technologies developed for this challenging mission include instruments and a revolutionary carbon-carbon composite heat shield to withstand temperatures over 2500 degrees Fahrenheit. H-TiDeS unifies our development of low- to medium-TRL technologies, as well as instrument feasibility studies and proof of concept efforts. This element of our research program consists of competitive PI-led efforts, awarded via a peer review process based on the science and technical merits of the submitted proposals, and according to the science priorities of the Heliophysics Division as set by the decadal survey. Examples of areas funded through H-TiDeS include X-ray and Gamma-ray detectors, extreme ultraviolet mirror coatings, X-ray optics, high-energy particle detectors, energetic neutral atom detectors, and new nano-dust analyzers. Small satellites, including CubeSats, have tremendous promise in addressing

many heliophysics science objectives. Although small satellite technologies have advanced rapidly over the last few years, significant technological hurdles still remain. H-TiDeS is supporting the development of a number of instrument technologies (e.g., low mass particle spectrometers, and compact interferometers) and working across the Agency to develop the underlying infrastructure. Examples of Agency-wide partnerships for small satellites include investments made by STMD and HEOMD in developing launch systems such as the CubeSat Launch Initiative (CSLI) and deep space operations such as the first test flight, Exploration Mission (EM)-1, of the Space Launch System (SLS). The Heliophysics Division is well poised to take advantage of this new technology.

Crosscutting Applications of Heliophysics Science

Earth Science

Strategy

Our planet is changing on all spatial and temporal scales and studying the Earth as a complex system is essential to understanding the causes and consequences of climate change and other global environmental concerns. The purpose of NASA's Earth science program is to advance our scientific understanding of Earth as a system and its response to natural and human-induced changes and to improve our ability to predict climate, weather, and natural hazards. NASA's ability to observe global change on regional scales and conduct research on the causes and consequences of change position it to address the Agency strategic objective for Earth science, which is to advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet. NASA addresses the issues and opportunities of climate change and environmental sensitivity by answering the following key science questions through our Earth science program:

- How is the global Earth system changing?
- What causes these changes in the Earth system?
- How will the Earth system change in the future?
- How can Earth system science provide societal benefit?

These science questions translate into seven overarching science goals to guide the Earth Science Division's selection of investigations and other programmatic decisions:

- Advance the understanding of changes in the Earth's radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition (Atmospheric Composition). Improve the capability to predict weather and extreme weather events (Weather)
 - Detect and predict changes in Earth's ecological and chemical cycles, including land cover, biodiversity, and the global carbon cycle (Carbon Cycle and Ecosystems).
- On the left, brown landscapes and bare mountains show that California is clearly dry in this view from MODIS on NASA's Terra satellite, taken January 18, 2014. The image on the right, taken January 18, 2013, contrasts last year's drought conditions with this year's current extreme conditions.

CALIFORNIA DROUGHT

- Enable better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change (Water and Energy Cycle)
 - Improve the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land and ice in the climate system (Climate Variability and Change)
 - Characterize the dynamics of Earth's surface and interior, improving the capability to assess and respond to natural hazards and extreme events (Earth Surface and Interior)
 - Further the use of Earth system science research to inform decisions and provide benefits to society

Two foundational documents guide the overall approach to the Earth science program: the NRC's 2007 Earth science decadal survey and NASA's 2010 climate-centric architecture plan.

The NRC decadal survey articulates the following vision for Earth science research and applications in support of society:

Understanding the complex, changing planet on which we live, how it supports life and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important challenges for society as it seeks to achieve prosperity, health, and sustainability. The 2007 decadal survey recommended a broad portfolio of missions to support the research that is needed to provide answers to the key science questions and accomplish the related science goals. Recognizing the pressing challenge of climate change, NASA addressed the need to ensure the continuity of key climate monitoring measurements in its 2010 climate-centric architecture plan. The plan reflects the need to collect additional key climate monitoring measurements, which are critical to informing policy and action, and which other agencies and international partners had not planned to continue. The plan also accelerated key decadal survey recommendations to address the nation's climate priorities. NASA's ability to view the Earth from a global perspective enables it to provide a broad, integrated set of uniformly high-quality data covering all parts of the planet. NASA shares this unique knowledge with the global community, including members of the science, government, industry, education, and policy-maker communities. For example, NASA plays a leadership role in a range of federal interagency activities, such as the USGCRP, by providing global observations, research results, and modeling capabilities. It also maintains an expansive network of partnerships with foreign space agencies and international research organizations to conduct activities ranging from data sharing agreements to joint development of satellite missions. These interagency activities and international partnerships substantially leverage NASA's investments and provide knowledge essential for understanding the causes and consequences of climate change and other global environmental concerns.

NASA is facing the growing challenge of continuing to advance Earth systems science (including research endeavors, observational capabilities, and data systems) while simultaneously addressing increasing demands to provide sustained climate observations.

Data-related issues are another growing challenge. As explained in the Agency's 2010 climate-centric architecture plan, "many existing system components and functions need to be updated and improved, driven by challenging new requirements. Data rates and data volumes will increase dramatically." Further, the decadal survey notes that the "high availability of data will require significant enhancements to existing science data system processing and distribution infrastructure." The Earth Science Division's programs and programmatic elements are responding to data challenges by implementing innovative cloud storage agreements, investing in data and information systems, and developing supercomputing capabilities.

NASA's Earth Science Division is organized around four programmatic areas: flight, research, applied sciences, and technology. Together these areas include programs and projects that are responsible for: conducting and sponsoring research to advance scientific understanding of Earth as a system, collecting and disseminating new observations, developing new technologies and computational models, and building the capacity to develop innovative applications of Earth science observations and research results. Flight mission development—from advanced concept studies, to flight hardware development, to on-orbit operation—is managed within the Earth Systematic Missions (ESM) and Earth System Science Pathfinder (ESSP) Programs. ESD conducts research, applied science, and technology efforts through its respective Earth Science Research, Applied Sciences, and Earth Science Technology Programs.

Earth Systematic Missions Program

The ESM Program includes a broad range of multi-disciplinary science investigations aimed at developing a scientific understanding of the Earth system and its response to natural and human-induced forces. The ESM Program implements the Earth Science Division's strategic missions, including the foundational missions. The program also includes the systematic missions recommended by the decadal survey and most of the missions providing additional sustained measurements, including land imaging and climate continuity missions.

Earth System Science Pathfinder Program

ESSP implements low- to moderate-cost research and applications missions that foster revolutionary science and train future leaders in space-based Earth science and applications fields. This program includes the new Earth Venture missions recommended in the Earth science decadal survey, which consist of low-cost, PI-led, competed suborbital and orbital missions, as well as instruments for MoOs. The ESSP program also includes operating missions that were competitively selected and Orbiting Carbon Observatory (OCO)-2, which is a follow-on mission to OCO, an ESSP mission that was lost as the result of a launch vehicle failure.

Earth Science Research Program

The Earth Science Research Program aims to advance understanding of the components of the Earth system, their interactions, and the consequences of changes in the Earth system for life. These interactions occur on a continuum of spatial and temporal scales; Earth scientists investigate phenomena that range from short-term weather, to long-term climate and motions of the solid Earth and that have local, regional, and global effects. These Earth system components involve multiple, complex, and coupled processes that

affect climate, air quality, water resources, biodiversity, and other features that allow our Earth to sustain life and society. A major challenge is to predict changes that will occur on time scales from the next decade to century, both naturally and in response to human activities. To do so requires a comprehensive scientific understanding of the entire Earth system—how its component parts and their interactions have evolved, how they function, and how they may be expected to further evolve on all time scales. The Earth Science Research Program sponsors research to advance the overarching ESD goals pertaining to Atmospheric Composition, Weather, Carbon Cycle and Ecosystems, Water and Energy Cycle, Climate Variability and Change, and the Earth Surface and Interior. The research program is also designed to leverage NASA's unique space observation capabilities in relation to research carried out by, and in collaboration with, other federal agencies. For example, NASA participates in many of the interagency subcommittees of the NSTC Committee on Environment, Natural Resources, and Sustainability (CENRS). Similarly, using the observations from ESD flight programs, the research program both advances the interdisciplinary field of Earth system science and provides much of the scientific basis for major periodic assessments of climate change such as the World Meteorological Organization's and United Nations (UN) Environment Programme's quadrennial ozone assessment, the Assessment Reports of the Intergovernmental Panel on Climate Change, and the National Climate Assessment. The following programmatic elements contribute to a broad range of activities within the Earth Science Research Program. They involve the development of capabilities whose sustained availability is important for the Earth Science Division's future.

Modeling: The Earth Science Research Program approaches modeling from a global Earth system context, with a goal of understanding the Earth as a complete, dynamic system. Model predictions are compared with observations as a means of determining the extent to which we understand the physical processes driving the Earth system. Model predictions are integrated with observations to provide a best estimate of the current state of many Earth system components, using a method known as data assimilation. In addition, models are used to provide short-term forecasts that support field missions, and longer-term forecasts to assess potential responses of the Earth system to various drivers of change. Two large-scale modeling efforts include the Goddard Institute for Space Studies Model E, a global Earth system model designed to address decadal- to centennial-scale problems, and the Goddard Earth Observing System Version 5 (GEOS 5) Earth system model and data assimilation system, which is utilized for shorter time scale problems such as weather forecasting and data assimilation, and short term climate forecasting.

Airborne Science: The airborne science element of the Earth Science Research Program provides access to platforms that can be used for in situ observation and remote sensing of the Earth's atmosphere and surface. NASA maintains a diverse fleet of aircraft, ranging from small propeller planes to unmanned aircraft systems that can remain in the air for more than 24 consecutive hours. These resources are made available to the research community for missions ranging from short, low-altitude flights from the aircraft's home base, to large, multi-aircraft campaigns deployed around the world that can cover long distances for many hours. Airborne platforms may be used to test new measurement approaches, collect detailed in situ and remote-sensing observations to better document and test models of Earth system processes, and provide calibration/ validation information for satellites.

Aircraft have proven to be of particular value in Earth system science research for investigation of specific processes.

They provide the capability to obtain high-resolution temporal and spatial measurements of complex local processes, which can be coupled to global satellite observations for a better understanding of the Earth system. A full listing of aircraft and program details can be found at <https://airbornescience.nasa.gov>.

Surface-Based Measurements: NASA maintains and contributes to a variety of surface-based measurements that provide unique observational capability not otherwise available, as well as calibration/validation/algorithm testing capability for current and future satellite measurements. These networks involve partnerships with agencies, institutions, and scientists all around the world. They address parameters as varied as the concentration of radiatively and chemically active trace gases regulated under the Montreal Protocol on Substances that Deplete the Ozone Layer (UN, 2007); the distribution and properties of atmospheric aerosols that can impact clouds, radiative forcing and human health; and the terrestrial reference frame that is so critical in providing the rigorous information that underlies gravimetric and altimetric measurements that are applied to a broad range of terrestrial and oceanic studies.

Data and Information Systems: NASA's principal Earth science information system is the Earth Observing System

Data and Information System (EOSDIS), which has been operational since August 1994. EOSDIS acquires, processes, archives, and distributes Earth science data and information products created from satellite data, which arrive at the rate of more than five trillion bytes (five terabytes) per day. EOSDIS provides services and tools needed to enable use of NASA's Earth science data in new models, research results, and decision support system benchmarking. EOSDIS also supports the executive branch's Big Earth Data Initiative focusing on interoperability between environmental data systems at NASA, NOAA, and USGS, and has helped pave the way for the USGCRP's Global Change Information System (GCIS). NASA Earth science information is archived at 12 Distributed Active Archive Centers (DAACs) located across the United States. The DAACs ensure that the data is easily accessible to researchers around the world. Although they specialize by topic area, DAACs also provide services to users whose needs may cross the traditional science discipline boundaries. The NASA Earth Exchange (NEX) is a new research and

collaboration platform for the Earth science community that provides a mechanism for scientific collaboration and knowledge sharing. NEX combines state-of-the-art supercomputing, Earth system modeling, workflow management, NASA remote sensing data, and a knowledge sharing platform to deliver a complete work environment in which users can explore and analyze large datasets, run modeling codes, collaborate on new or existing projects, and quickly share results with Earth science communities. High-End and Scientific Computing: ESD is responsible for providing high-end computing, networking, and storage capabilities that are critical enablers for Earth system and space sciences. Satellite observations must be converted into scientific data products through retrieval and/or data assimilation processes. Long-term data sets must be synthesized together and become a physically consistent climate-research quality data set through reanalysis. These data products, in turn, provide initial and boundary conditions, validation and verification references, and internal and external constraints to the models that describe the behavior of the Earth system. Two supercomputer systems, with more than 200,000 computer processor cores, serve the unique needs of all NASA mission directorates including the HEOMD, Aeronautics Research, SMD, and STMD, and NASA-supported PIs at universities. More than 20 petabytes of online disk system and 150 petabytes of tape archive are available for data storage. There is also a small grants program to build the next-generation computational modeling infrastructure, including new computing architecture, data processing and management systems for model-data inter-comparison, and refactoring of computational models.

Applied Sciences Program

As we pursue the answers to fundamental science questions about the Earth system, we realize many important results that can be of near-term use and benefit to society. The overarching purpose of the Applied Sciences Program is to leverage NASA Earth science satellite measurements and new scientific knowledge to provide innovative and practical uses for public and private sector organizations. The program enables near-term uses of Earth science knowledge, discovers and demonstrates new applications, and facilitates adoption of applications by non-NASA stakeholder organizations that have connections to users and decision makers. Specifically, the Applied Sciences Program has three primary goals: enhancing applications research, increasing collaborations, and accelerating applications. The Applied Sciences Program consists of four application areas (Disasters, Ecological Forecasting, Health and Air Quality, and Water Resources) and the Capacity Building Program (CBP). CBP spans nine societal benefit areas, comprised of the program's four application areas, plus Agriculture, Climate, Energy, Oceans, and Weather. CBP oversees several capacity building efforts including the Applied Remote Sensing Training (ARSET) program, which provides training to access and utilize Earth observing tools and services; DEVELOP, which focuses on workforce development through 10-week applied research project opportunities; the Gulf of Mexico Initiative (GOMI), which focuses on region-specific coastal challenges through partnerships with state and local agencies; and the Regional Visualization and Monitoring System (SERVIR), which is a collaboration with the U.S. Agency for International Development (USAID) and builds capacity to use geospatial information in national decision processes through partnerships with developing countries. SERVIR has hubs—active partnerships with regional institutions—in East Africa and the Hindu-Kush Himalayas, with a new hub in South East Asia planned for 2014 and more expansion under consideration. A hub in Central America that operated from 2004–2011 under the auspices of SERVIR now continues to operate independently, still drawing on SERVIR-provided data and tools and garnering support from other international donor agencies. Through SERVIR, the hubs develop national environmental information systems, promote and co-develop cutting-edge applications of satellite data and models with NASA to address environmental challenges, and take advantage of the view from space to assist in the response to dozens of natural disasters. Together with the Earth Science Research Program, the Applied Sciences Program supports efforts across NASA to use the Agency's expertise in climate observations and models to enhance understanding of climate impacts and inform the nation's ability to anticipate and adapt to a changing climate. One example is the Climate Adaptation Science Investigators (CASI) work group, which investigates climate risks at NASA centers. Additionally, ESD supports researchers at NASA centers and in the broader science community to conduct science that informs USGCRP National Climate Assessments and grows the capacity of the science community to contribute and participate in assessment activities. The Applied Sciences Program also encourages potential users to envision and anticipate possible applications from upcoming satellite missions and to provide input to mission development teams. For example, the Soil Moisture Active/Passive (SMAP) mission team has created an "early adopters effort" to assist groups who would like to apply their own resources to demonstrate the utility of SMAP data for their particular system or model so that they will be prepared to use the data as soon as possible after the spacecraft is on orbit. Through these types of efforts, the Applied Sciences Program serves as a bridge between the data and knowledge generated by NASA Earth science initiatives and the information and decision-making needs of public and private organizations.

Earth Science Technology Program

The Earth Science Technology Program, operated through the Earth Science Technology Office (ESTO), demonstrates and provides technology research and development projects that advance Earth observing instrumentation, mission components, and information systems to make future missions feasible and affordable. This program is based on a science-driven strategy that employs open peer-reviewed solicitations to produce the best appropriate technologies. ESTO holds a broad portfolio of more than 700 past and active investments at over 100 institutions nationwide. More information about ESTO's program implementation can be found in the Technology Development section below.

To address the challenges involved in recording simultaneous observations of all Earth components and interactions to generate new knowledge about the global integrated Earth system, NASA and its partners developed and launched Earth observing missions and ancillary satellites. As shown in Table 4.4, 17 satellites comprise today's fleet of NASA Earth observing missions. The scientific benefit of simultaneous Earth observation—the Earth System Science construct—is substantial. NASA's A-Train constellation of satellites is the first Earth science space “super-observatory.” The A-Train consists of five satellites in orbits that cover the same region within 15 minutes, recording near-simultaneous observations of a wide variety of parameters, such as comprehensive measurements of atmospheric chemistry and composition, including clouds and aerosols, using powerful imaging capabilities. NASA's Aqua, Aura, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and CloudSat satellites, and Japan's Global Change Observation Mission—Water (GCOM-W1, also known as the SHIZUKU) satellite comprise this powerful international constellation. OCO-2 is on the launch manifest to join the configuration in 2014. The Earth science decadal survey identified five foundational missions to bridge the gap between the aging Earth Observing System and the recommended decadal survey missions to follow. These foundational missions include Glory, Aquarius, Suomi NPP, Landsat Data Continuity Mission (LDCM)/Landsat 8, and Global Precipitation Measurement (GPM). Although Glory was unfortunately lost due to launch vehicle failure, Aquarius, Suomi NPP, and LDCM/Landsat-8 are making critical Earth observation measurements and the recently launched GPM will contribute measurements after it completes on-orbit checkout.

In May 2012, the NRC published the midterm report, Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey (NRC, 2012). NASA's progress towards achievement of the NRC's overall recommendations for Earth observations, missions, technology investments, and priorities for Earth system science received a favorable assessment in this report. The report endorsed the refinements to the NASA Earth science portfolio of planned missions, which include missions and instruments to meet the nation's needs for sustained climate measurements, although it cautioned that the inclusion of initiatives described in NASA's 2010 climate-centric architecture plan could result in an impact on the pace at which the program will be able to conduct the recommended research.

Many of these upcoming missions intend to demonstrate multiple scientific and societal benefits accruing from the synergies that exist between data and observations collected during similar periods of time. In fact, the timing of some missions, like SMAP, has been accelerated. As a result, the SMAP, GPM, and GRACE Follow-on (GRACE FO) missions, and, possibly the Surface Water and Ocean Tomography (SWOT) mission, have the potential to address global and regional water-balance studies together in a manner that could not be achieved by individual investigations. Table 4.5 identifies Earth science missions that are in formulation or development, with launches planned over the 2014–2020 timeframe. The expected launch years are subject to change, but provide the relative timeframes for development.

Table 4.6 identifies the Earth science missions that are in the pre-formulation phase, with planned launches beginning in 2020. The future missions under study include decadal survey missions, sustained climate and land imaging measurement missions, and Earth Venture missions, instruments, and sub-orbital investigations.

The Earth Science Technology Office (ESTO) is the lead technology office for the Earth Science Technology Program. The primary science requirements for ESTO technologies are derived from the Earth science decadal survey. In general, the second and third tier Earth science decadal survey missions involve inherent technological challenges. A number of the recommended instruments will contain active components such as radars and/or lasers. Other second and third tier missions will require larger collection optics and antennas to meet requirements. Therefore, ESTO is principally focused on advancing technologies needed for the second and third tier missions and measurements. The

Earth Science Technology Program consists of the following four elements.

Advanced Technology Initiatives (ATI): The ATI element conducts technology concept studies that help establish the range of technical capability requirements that the technology program must address, and identify the pros and cons of available technology implementation options. The ATI element also includes the Advanced Component Technology (ACT) sub-element. ACT leads research, development, testing, and demonstration of component- and subsystem-level technologies for use in state-of-the-art Earth science instruments and information systems. ACT is primarily geared toward producing technologies that reduce the risk, cost, size, mass, and development time of future space-borne and airborne missions.

Instrument Incubator Program (IIP): The IIP element provides funding to support new instrument and observation techniques, from concept development through breadboard and flight demonstrations. Instrument technology development of this scale outside a flight project consistently leads to smaller, less resource-intensive flight instruments. Developing and validating these technologies before their use in science missions and campaigns improves their acceptance, enables infusion, and significantly reduces costs and schedule uncertainties.

Advanced Information Systems Technologies (AIST): Advanced information systems play a critical role in the collection, handling, and management of large amounts of Earth science data, in space and on the ground. Advanced computing and transmission concepts that permit the dissemination and management of terabytes of data are essential to NASA's vision of a unified observational network. The AIST element develops and demonstrates information system technologies to facilitate the communication, processing, and management of remotely sensed data, as well as the efficient generation of data products and models. AIST employs an end-to-end approach to evolve these critical technologies from the space segment, where the information pipeline begins, to the end user, where knowledge is advanced.

In-Space Validation of Earth Science Technologies (InVEST): Since 1998, NASA's Earth

Science Division has sought to facilitate space demonstrations of key technology projects through partnerships, such as the NASA CSLI, and follow-on projects, particularly under other NASA programs such as ESSP. In 2012, NASA established InVEST as a nimble, competitive Earth Science Technology Program element to retire risk and space-validate technologies. The first InVEST solicitation, which sought small instruments and instrument subsystems relevant to Earth science measurements, targeted the CubeSat platform. Four (of 24) proposals were selected in April 2013 that included a polarimeter, a radiometer, a photon-counting laser detector, and a carbon nanotube-based bolometer.

Earth and Space Science from the International Space Station

Planetary Science Strategy

Planetary science is a grand human enterprise that seeks to understand the history of our solar system and the distribution of life within it. The scientific foundation for this enterprise is described in the NRC planetary science decadal survey, *Vision and Voyages for Planetary Science in the Decade 2013-2022* (NRC, 2011). Planetary science missions inform us about our neighborhood and our own origin and evolution; they are necessary precursors to the expansion of humanity beyond Earth. Through five decades of planetary exploration, NASA has developed the capacity to explore all of the objects in our solar system. Future missions will bring back samples from some of these destinations, allowing iterative detailed study and analysis back on Earth. In the future, humans will return to the Moon, go to asteroids, Mars, and ultimately other solar system bodies to explore them, but only after they have been explored and understood using robotic missions. NASA's planetary science program pursues a strategy of surveying the planetary bodies of our solar system and targeting repeated visits to those bodies likely to enable greatest progress toward answering fundamental science questions. For selected planetary bodies, science drivers require successive visits that progress from fly-by missions, to orbiters, to landers and entry probes, to rovers, and, ultimately, to sample return missions. With the imminent fly-by of the dwarf planet Pluto by the New Horizons mission in 2015, NASA will have made significant progress towards an initial reconnaissance of all the major bodies in the solar system within 33 Astronomical Units (AU) of the Sun. In addition, with the arrival of the Dawn spacecraft at the dwarf planet Ceres; the completion of the Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) mission at Mercury; and continuing robotic exploration of Mars; NASA has built on previous reconnaissance efforts with more in-depth studies of nearby targets. Missions in development NASA's strategic objective in planetary science is to ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.

Saturn eclipsing the Sun, seen from behind from the Cassini orbiter. The image is a composite assembled from images taken by the Cassini spacecraft on September 15, 2006.

SATURN ECLIPSE

This goal by seeking answers to fundamental science questions that guide NASA's exploration of the solar system:

- How did our solar system form and evolve?
- Is there life beyond Earth?
- What are the hazards to life on Earth?

The Planetary Science Division has translated these important questions into science goals that guide the focus of the division's science and research activities:

- Explore and observe the objects in the solar system to understand how they formed and evolve
- Advance the understanding of how the chemical and physical processes in our solar system operate, interact and evolve
- Explore and find locations where life could have existed or could exist today.
- Improve our understanding of the origin and evolution of life on Earth to guide our search for life elsewhere
- Identify and characterize objects in the solar system that pose threats to Earth, or offer resources for human exploration

In selecting new missions for development, NASA's Planetary Science Division strives for

balance across mission destinations, using different mission types and sizes. Achievement of steady scientific progress requires a steady cadence of missions to multiple locations, coupled with a program that allows for a consistent progression of mission types and capabilities, from small and focused, to large and complex, as our investigations progress. The division also pursues partnerships with international partners to increase mission capabilities and cadence and to accomplish like-minded objectives.

Many of the key challenges the Planetary Science Division faces in carrying out the NASA 2014 Science Plan are common across all of the SMD science divisions, and are well articulated in chapter 3.3 (e.g., access to space, mission cost estimation and management, technology development and demonstration, and impediments to international collaboration). The budget environment assumed by the decadal survey has not been realized, impacting the Planetary Science Division's ability to implement all the decadal survey recommendations within the decade. In a constrained budget environment, NASA may need to make tradeoffs between competed and strategic missions, across planetary destinations, and among research and technology investments—all while supporting the most meritorious science and technology investigations proposed, as well as providing opportunities to develop the workforce, especially early-career scientists. In addition, NASA faces concerns regarding the availability of Plutonium 238 (Pu-238), which fuels the Radioisotope Power Systems (RPS) that provide electrical power for spacecraft and planetary probes where the Sun is too far distant, not consistently observable, or too obscured to rely on solar energy. U.S. production of Pu-238 ceased in the 1980s and the limited, existing supply has continued to age. Because availability of Pu-238 is so important to planetary science, and ultimately to human exploration, the Planetary Science Division was assigned the responsibility for funding the infrastructure required to produce a reliable supply of Pu-238 and RPS. The Planetary Science Division is working with DOE to restart domestic production of Pu-238 under a reimbursable agreement. This effort will ensure an RPS capability is maintained to allow planetary missions throughout the solar system for decades to come. Finally, much of the Planetary Science Division's technology development has come from investments made in implementing the larger strategic missions, such as Cassini, Mars Reconnaissance Orbiter (MRO), and Mars Science Laboratory (MSL). With fewer potential strategic missions planned for the future, investments in technology are also being reduced to support existing commitments to missions in development and those currently operating.

The Planetary Science Division includes programs with three major classes of mission destinations:

- Inner planets: Earth's Moon, Mars and its satellites, Venus, and Mercury
 - Outer planets: Jupiter and its rings and moons, especially Europa; Saturn and its rings and moons, especially Titan and Enceladus; Uranus and its moons; Neptune and its moon Triton; the dwarf planet Pluto and its small moons; and other Kuiper Belt Objects
 - Small bodies: Comets, asteroids, and the dwarf planet Ceres in the asteroid belt
- The division manages missions to these destinations (including any associated research) through three mission development programs, and two research programs.

Discovery Program

This program is designed to develop a series of small, PI-led, innovative planetary missions on a frequent basis, solicited from the community as complete scientific investigations through an open, competitive AO. Since the Discovery Program was created in 1992, 11 missions have been selected, and 10 have completed development and launched.

New Frontiers Program

This program is designed to develop a series of medium, PI-led, cost-capped, competed planetary missions solicited from the community as complete scientific investigations through an open AO. New Frontiers missions differ from Discovery missions due to a larger cost cap size, and the restriction that proposed missions are limited to a list provided in the AO. In the past this mission list has been recommended by the NRC's planetary science decadal survey. New Frontiers has selected three missions, and two have completed development and launched. New Frontiers may also develop instruments for international MoOs.

Mars Exploration Program

The Mars Exploration Program (MEP) is a science-driven, technology-enabled effort to characterize and understand Mars as a system, including its current environment, climate and geological history, and biological potential. In a strategy generally known as "Follow the Water," measurements were carried out using robotic assets at Mars over the past decade. With mounting evidence of a wet and warm past on Mars, the program's focus is shifting to answering the next logical question, "Did life ever arise on Mars?" The successes of recent missions have led NASA to conclude that Mars could have supported microbial life. Therefore, the program is evolving to focus on determining whether Mars was ever habitable and, through a strategy of "Seeking Signs of Life," if evidence of extinct or extant life can be identified. Although constrained budgets do not support a sample return mission in the foreseeable future, the eventual collection and return of samples from Mars remains the highest strategic priority in the decadal survey. MEP is a loosely coupled program, meaning new mission objectives are built on discoveries arising from past and present objectives. MEP also maintains a data relay network of Ultra-High Frequency (UHF) radios on all orbiters that NASA sends to the Red Planet to enable communication with future NASA and international partner landers and rovers. Currently, all rover data is relayed via the two NASA science orbiters at Mars—MRO and Mars Odyssey.

Planetary Science Research and Analysis Program

Completed research and analysis enables utilization of the data returned by planetary science missions. Discoveries and concepts generated by the Planetary Science Research and Analysis (R&A) Program are the genesis of scientific priorities, new mission concepts, and science instruments, and provide the crucial context within which mission data are interpreted. Planetary science is inherently crosscutting, spanning ground-based telescope observations, theoretical work, laboratory studies, fieldwork, and the continuing analysis and modeling of data and returned samples from past missions. New, emergent fields of research sometimes lead to new research program elements such as the interdivisional, exoplanets program coordinated between the Planetary Science and Astrophysics Divisions (highlighted on page 87). The division has recently reorganized its planetary science instrument development into two new projects—MatSSE (Maturation of Instruments for Solar System Exploration) and PICASSO (Planetary Instrument Concepts for the Advancements of Solar System Observations)—which address low-TRL (TRL 1-3) and mid-TRL (TRL 3-6) technologies, and are further discussed in the Technology Development section. The Planetary Science Research and Analysis Program provides unique mission support capabilities to enable and facilitate planetary science research:

- Sample return curation facilities to store, disseminate, and support the analysis of extraterrestrial samples, including those returned from other planetary bodies
- The Planetary Data System (PDS) to archive and disseminate data from planetary science missions
- Virtual institutes such as the NASA Astrobiology Institute (NAI) and the new Solar System Exploration Research Virtual Institute (SSERVI) to enable broad collaboration on key scientific foci

Near-Earth Objects Program

NEOs are comets and asteroids that have been nudged by collisions and the gravitational influence of nearby planets into orbits that allow them to enter the Earth's neighborhood. NASA leads the world in the detection and characterization of NEOs and provides critical funding to support the ground-based observatories that are responsible for the discovery of NEOs. In particular, the NEO Program has catalogued more than 95% of all NEOs over one-kilometer in size and enabled flight missions to study asteroids and comets. The Planetary Science Division funds research activities to better understand the motions, compositions and nature of these objects, including the use of optical and radar techniques to better understand their orbits, shapes, sizes and rotation states. Asteroids are not only important when they cross the Earth's orbit; studying asteroids can provide insights into the origins of the solar system. The NEO Program provides unique mission support capabilities to enable and facilitate this research:

- The Minor Planet Center at the Smithsonian Astrophysical Observatory to catalog all asteroids, comets, Kuiper Belt objects, and other small bodies and all known NEOs in our solar system
- Nationally unique facilities that complement robotic space explorers, including the Infrared Telescope Facility in Hawaii, the Goldstone Solar System Radar, and SMD's partnership with NSF in the operation of the Arecibo planetary radar

The Planetary Science Division currently has ten satellites in orbit, two rovers on Mars, and is participating in five international missions. Table 4.7 highlights the current planetary science missions. Current missions to inner planets include the Discovery missions: Dawn, which has completed its survey of the asteroid Vesta and is on its way to survey the dwarf planet Ceres; and MESSENGER, which is in its final year of surveying Mercury. Two missions are currently orbiting the Moon: Lunar Atmosphere and Dust Environment Explorer (LADEE) was launched in September 2013, for a four-month mission to investigate the tenuous atmosphere of the Moon and the dust lofted into the lunar atmosphere; and Lunar Reconnaissance Orbiter (LRO) is in its 5th year orbiting the Moon, investigating volatiles in the polar regions, the early processes that formed the Moon, the impact history recorded by the Moon, and the Moon's interaction with the solar wind and space environment. Additionally, the Mars Exploration Program has two missions orbiting Mars (Mars Odyssey and MRO) and two rovers on the Martian surface. Opportunity continues to rove and conduct science investigations, and Curiosity continues to make new discoveries with its suite of advanced tools and analytical instruments. MAVEN, which launched in 2013, will explore Mars's upper atmosphere, ionosphere, and interactions with the Sun and solar wind to determine the role that loss of volatile compounds—such as carbon dioxide, nitrogen dioxide, and water—from Mars's atmosphere to space has played through time. This research will provide insight into the history of the planet's atmosphere, climate, liquid water, and habitability. NASA also participates in the payloads and scientific investigations of the current ESA Mars Express orbiter, as well as the ESA Venus Express orbiter, and the JAXA Venus Climate Orbiter. Current missions to outer planets include: Cassini, now in its extended mission in the Saturnian system; New Horizons, now on its way to visit Pluto in 2015; and Juno, which will arrive at Jupiter in 2016. New Horizons and Juno are missions in the New Frontiers Program.

In addition, NASA is participating with ESA in the Rosetta comet rendezvous mission.

The NRC planetary science decadal survey provides science priorities and guidance that the Planetary Science Division uses to develop its portfolio of missions. The survey outlines the need for a balanced suite of Discovery, New Frontiers, and strategic missions to enable a steady stream of new discoveries and capabilities to address challenges such as potential sample return missions and outer planet exploration. In support of these objectives, NASA also collaborates with the planetary exploration programs of other countries to maximize opportunities for science, providing opportunities for NASA-led

science instruments on foreign missions.

The decadal survey identifies priorities for future planetary missions, with emphasis on maintaining a balance of Discovery, New Frontiers, and strategic missions. Work on the highest strategic mission priority has begun with the Mars Rover 2020 mission, which is now in formulation. The decadal survey ranked a mission to Europa as the second priority strategic mission, because Europa's subsurface ocean has the greatest potential to harbor extraterrestrial life. The Planetary Science Division has invested in concept studies looking at preliminary design proposals, necessary instrument technology, spacecraft design, planetary protection sterilization procedures, and instruments and systems that can withstand those procedures. In 2014, NASA will issue a Request For Information to assess options to accomplish the decadal survey scientific objectives at Europa for significantly less cost than currently considered mission concepts. The results of the studies will inform a future potential mission to Europa. Consistent with the decadal survey priorities, and subject to the future availability of funds, the Planetary Science Division expects to implement a set of missions over the decade as outlined in Table 4.9.

Technology Development

Future planetary science missions will require maintenance of existing capabilities and development of new technologies in power generation, propulsion, navigation, aerocapture, instrumentation, miniaturization, radiation hardening, planetary protection implementation, and sample acquisition, handling, return, analysis and containment. The Planetary Science Division is developing plans to guide technology investments over the next decade to ensure past investments are adequately sustained and to identify the highest priority investments in new capabilities. The division works with STMD to guide Agency investments, and to identify opportunities to demonstrate new technologies on planetary missions. The division makes investments in future radioisotope power systems capabilities, working through the RPS Program Office at NASA's Glenn Research Center and with DOE to build current and future systems.

The Planetary Science Division manages its instrumentation technology development through two projects in the Planetary Science Research and Analysis Program: MatISSE (Maturation of Instruments for Solar System Exploration) and PICASSO (Planetary Instrument Concepts for the Advancements of Solar System Observations). MatISSE involves mid-TRL technologies and is intended to enable timely and efficient infusion of technology into NASA planetary science missions. PICASSO focuses on low-TRL technologies and funds instrument feasibility studies, concept formation, proof-of-concept instruments, and advanced component technology development to the point where the technologies may be proposed for MatISSE. Organizing all instrument technology development and demonstration projects for planetary science into these two programs has enabled better management of technology activities, and the possibility for larger awards and subsequently faster maturation timescales, specifically through MatISSE.

CHAPTER 4 Detailed Plans by Science Area

The Science That Enables Exploration

Astrophysics

Strategy

Astrophysics is the study of phenomena occurring in the universe and of the physical principles that govern them. Astrophysics research encompasses a broad range of topics, from the birth of the universe and its evolution and composition, to the processes leading to the development of planets and stars and galaxies, to the physical conditions of matter in

extreme gravitational fields, and to the search for life on planets orbiting other stars. In seeking to understand these phenomena, astrophysics science embodies some of the most enduring quests of humankind. Through its Astrophysics Division, NASA leads the nation on a continuing journey of transformation. From the development of innovative technologies, which benefit other areas of research (e.g., medical, navigation, homeland security, etc.), to inspiring the public worldwide to pursue STEM careers through its stunning images of the cosmos taken with its Great Observatories, NASA's astrophysics programs are vital to the nation. NASA's strategic objective in astrophysics is to discover how the universe works, explore how it began and evolved, and search for life on planets around other stars. Three broad scientific questions flow from this objective:

- How does the universe work?
- How did we get here?
- Are we alone?

Each of these questions is accompanied by a science goal that shapes the Astrophysics Division's efforts towards fulfilling NASA's strategic objective:

- Probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity
- Explore the origin and evolution of the galaxies, stars and planets that make up our universe
- Discover and study planets around other stars, and explore whether they could harbor life

The scientific priorities for astrophysics are outlined in the NRC decadal survey *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2010). These priorities

THE TARANTULA NEBULA

Several million young stars are vying for attention in this NASA Hubble Space Telescope image of a raucous stellar breeding ground in 30 Doradus, located in the heart of the Tarantula Nebula. 30 Doradus is the brightest star-forming region visible in a neighboring galaxy and home to the most massive stars ever observed. The image comprises one of the largest mosaics ever assembled from Hubble photos include understanding the scientific principles that govern how the universe works; probing cosmic dawn by searching for the first stars, galaxies, and black holes; and seeking and studying nearby habitable planets around other stars. The multidisciplinary nature of astrophysics makes it imperative to strive for a balanced science and technology portfolio, both in terms of science goals addressed and in missions to address these goals. All the facets of astronomy and astrophysics—from cosmology to planets—are intertwined, and progress in one area hinges on progress in others. However, in times of fiscal constraints, priorities for investments must be made to optimize the use of available funding. NASA uses the prioritized recommendations and decision rules of the decadal survey to set the priorities for its investments. NASA's Astrophysics Division has developed several strategies to advance these scientific objectives and respond to the recommendations outlined in the decadal survey on a time horizon of 5-10 years. The successful development of JWST is an Agency priority. Since its re-baseline in 2011, the project has remained on schedule and within budget for an October 2018 launch. JWST and the science it will produce are foundational for many of the astronomical community's goals outlined in the 2010 decadal survey. NASA's highest priority for a new strategic astrophysics mission is the Wide Field Infrared Survey Telescope (WFIRST), the number one priority for large-scale missions of the decadal survey. NASA plans to be prepared to start a new strategic astrophysics mission when funding becomes available. NASA also plans to identify opportunities for international partnerships, to reduce the Agency's cost of the mission concepts identified, and to advance the science objectives of the decadal survey. NASA will also augment the Astrophysics Explorer Program to the extent that the budget allows. Furthermore, NASA will continue to invest in the Astrophysics Research Program to develop the science cases and technologies for new missions and to maximize the scientific return from operating missions. The NASA Astrophysics Division has laid out its strategy for advancing the priorities of the decadal survey in its Astrophysics Implementation Plan (NASA SMD Astrophysics Division, 2012). With substantial input from the astrophysics community, the NASA Advisory Council's Astrophysics Subcommittee has developed an astrophysics visionary roadmap (NAC Science Committee Astrophysics Subcommittee, 2013) to examine possible futures of the discipline in the longer term.

The Astrophysics Division faces many of the same challenges in carrying out the NASA 2014 Science Plan as other SMD divisions; these common challenges are described in chapter 3. Some of these challenges particularly impact the Astrophysics Division's programs. There are also some challenges that are specific to the Astrophysics Division, and many of them arose after the completion of the 2010 decadal survey. The budget environment assumed by the decadal survey has not been realized. In reality, it will be impossible to implement all the decadal survey recommendations within the decade. As described in the Astrophysics Implementation Plan, the Astrophysics Division has initiated studies for several versions of WFIRST. In 2011, but following the decadal survey, NASA established a new launch date and cost commitment for JWST. The executive branch has made the successful completion and launch of JWST an Agency priority. NASA has committed funding with adequate reserves to JWST development to ensure a launch in 2018. Because of budget limitations and the need to focus on JWST, no new strategic astrophysics missions can be started until funds become available near or following the completion and launch of JWST. NASA's international partners are pursuing new astrophysics missions that address areas of science that are recommended in the decadal survey; they provide an opportunity for the U.S. to leverage its spaceflight investments by partnering on some of these missions. The implementation of these missions, however, may represent a challenge. Aligning schedules and priorities with potential partners, as well as the restrictions on partnerships due to export control regulations like ITAR,

contribute to this challenge. With the current and anticipated constrained budget, trade-offs may need to be made across the various astrophysics research areas, potentially impacting the balance of programs. It will also be challenging to continue to support all the highly meritorious science and technology investigations proposed, while still providing opportunities to develop the workforce, especially early-career scientists.

The Astrophysics Division implements its astrophysics science through three focused and two crosscutting programs. The focused programs—Physics of the Cosmos, Cosmic Origins, and Exoplanet Exploration—provide an intellectual framework for advancing science and strategic planning, with each program primarily addressing one of the three broad scientific questions outlined above. Each focused program comprises one or more missions in formulation, development, and/or operation, as well as the strategic research and technology development necessary to realize future strategic missions. Two crosscutting programs complement the focused programs: the Astrophysics Explorers Program, which develops and operates smaller, PI-led missions, and the Astrophysics Research Program, which supports basic and applied research activities, including suborbital flight investigations, as well as the development and maturation of technologies for future strategic and competed missions.

Physics of the Cosmos Program

This program addresses the most extreme physical conditions of the universe and the study of the building blocks of the universe at the most basic level: the space, time, matter, and energy that constitute it. The scope of the Physics of the Cosmos Program includes understanding birth and evolution of the universe (dark energy and cosmic microwave background), the conditions of matter in strong gravitational fields and the hot universe (X-rays and Gamma-rays), and the detection and characterization of gravitational waves from space.

Cosmic Origins Program

This program seeks to understand how the universe has evolved since the Big Bang, and how its constituents were produced—the familiar night sky we see today, the planet we live on, and all the chemical elements that sustain life. To explore these topics, NASA's Cosmic Origins space telescopes explore the origin and evolution of the galaxies, stars, and planets that make up our universe.

Exoplanet Exploration Program

This program seeks to discover and study planets orbiting around other stars. Since the first exoplanet was discovered in 1992, there has been explosive growth in the number of exoplanets identified. The Exoplanet Exploration Program aims at discovering planets around other stars, characterizing their properties, and identifying candidates that could harbor life.

Astrophysics Explorer Program

Smaller, PI-led astrophysics missions and missions of opportunity are competitively selected under the Astrophysics Explorer Program. Astrophysics Explorer missions provide opportunities for innovative science and fill the scientific gaps between the larger missions, while addressing a wide range of science topics. The Astrophysics Explorer Program also provides opportunities for smaller MoOs.

Astrophysics Research Program

Sponsored basic and applied research programs prepare for the next generation of missions through both theoretical research and applied technology investigations. They also exploit data from current missions and use suborbital science investigations to advance NASA's science goals. Suborbital investigations, an integral part of the astrophysics research program, include sounding rocket and balloon campaigns that provide new scientific discoveries, demonstrate measurement technologies, and train future mission PIs, scientists, and engineers. Astrophysics research investigations are competitively solicited through the ROSES NASA Research Announcement. Basic and applied astrophysics research investigations are essential for maximizing scientific return, pioneering new approaches to advancing the science objectives, and developing the workforce required to ensure future competitiveness.

Current astrophysics missions include three Great Observatories originally planned in the 1980s, launched over the past 20 years, and continuing to deliver science results in the extended operation phase. The suite of operating Great Observatories includes the Hubble Space Telescope (HST), the Chandra X-ray Observatory, and the Spitzer Space Telescope. Innovative Astrophysics Explorer missions such as the Swift Gamma-ray Explorer and NuSTAR complement these strategic missions. Many of these missions have achieved their prime science goals, but continue to produce spectacular results in their extended operation phases. Table 4.10 provides a complete list of the currently operating missions in Astrophysics. The Kepler Space Telescope is a medium-size mission launched in March 2009 to determine the frequency of Earth-like planets in orbit around other Sun-like stars. Kepler has revolutionized our knowledge about extrasolar planets in the Milky Way galaxy, including the discovery that most stars have planetary systems and that small, rocky extrasolar planets are common. In May 2013, the Kepler spacecraft lost the second of

four gyroscope-like reaction wheels, which are used to precisely point the spacecraft, ending new data collection for the original mission. In 2014, the Astrophysics Division will review continued operation of all operating missions, including a revised Kepler mission, in a competitive senior review, and decisions will be made regarding the future of Kepler and other operating missions.

JWST, the next astrophysics strategic mission, is under development and on schedule to be launched in 2018. In addition to JWST, NASA is also developing the Astrophysics Explorer missions Transiting Exoplanet Survey Satellite (TESS) and Neutron star Interior Composition Explorer (NICER), partnering with ESA on the Laser Interferometer Space Antenna (LISA) Pathfinder and Euclid missions, and completing the Soft X-ray Spectrometer instrument for JAXA's ASTRO-H mission. NICER is partially funded by STMD to support tools for celestial navigation applications of pulsars. Table 4.11 identifies the missions that are in formulation or development, with launches planned over the 2014–2020 timeframe. The expected launch years are subject to change, but provide the relative timeframes for development.

Table 4.12 identifies the future potential missions for Astrophysics. One important goal of the Astrophysics Division is to begin a strategic mission, subject to the availability of funds, which is responsive to the decadal survey and is launched after JWST. To this end, and as detailed in the Astrophysics Implementation Plan, the division is undertaking a specific series of actions to put in place the planning needed prior to initiating a strategic mission. In 2011–2012, detailed studies of mission concepts for WFIRST, the top priority of the decadal survey in the large mission class, were conducted by the astrophysics community. These efforts produced two reports: one describing a full version of the WFIRST as recommended by the decadal survey (including a 1.3 m telescope), and a second report describing a probe-size version, which is capable of addressing many of the full-size WFIRST mission objectives for reduced cost. After certain 2.4 m telescope assets were made available to NASA, in 2012–2013, the division established a Science Definition Team (SDT) and pre-formulation study to investigate possible use of these assets to address WFIRST science—namely, dark energy, exoplanets, and an infrared (IR) survey of the Milky Way galaxy. The study team is also investigating the potential inclusion of a coronagraph to the mission to address the New Worlds priorities of the decadal survey. In 2013, the Astrophysics Division also started Science and Technology Definition Team studies for several smaller, probe-class mission concepts to respond to the other priorities in the decadal survey. These studies included exoplanet probes and an X-ray probe. Following ESA's selection of "The Hot and Energetic Universe" (to be addressed by an advanced X-ray observatory) as the theme of their next large mission for launch in 2028, and concurrent with NASA's interest in contributing to ESA's advanced X-ray observatory to fulfill the decadal survey recommendations for an International X-ray Observatory (IXO), NASA will no longer pursue the option of a probe-size X-ray mission. ESA has also chosen "The Gravitational Universe" as the theme of its subsequent large mission for launch in 2034; NASA has expressed interest in contributing to ESA's gravitational wave observatory to fulfill decadal survey recommendations for a LISA mission. Another important goal of the Astrophysics Division is to augment the Astrophysics Explorer Program. The decadal survey recommends that four missions and four smaller MoOs be selected over the decade. The division plans two or three AOs during the remainder of the decade, with the intent of selecting one mission and one MoO from each AO. One such AO will be issued in fall 2014 with the goal of down-selecting a mission in 2016. Looking towards the longer term, the astrophysics visionary roadmap provides a compelling 30-year vision for astrophysics at NASA.

Technology Development

The Astrophysics Division supports development of technologies for its future missions primarily through two program elements: the Astrophysics Research and Analysis (APRA) element of the Astrophysics Research Program, and Strategic Astrophysics Technology (SAT) elements in the three focused programs (Cosmic Origins, Exoplanet Exploration, Physics of the Cosmos). The recently initiated SAT elements support research and technology efforts in each program, and aim to bring promising technologies closer to flight readiness. Both APRA and SAT are competitive activities; grants are awarded competitively via a process of peer review based on the science and technical merits of the submitted proposals, and the strategic priorities of the division as set by the decadal survey. The SAT element also includes directed technology development efforts. The APRA element supports development of low- to mid-TRL technologies, as well as instrument feasibility studies, and proof of concept efforts. The APRA element also supports development of instruments for suborbital flight opportunities including scientific balloons and sounding rockets. The SAT element focuses on mid-TRL technologies, and brings these technologies to maturation for infusion into astrophysical missions. Technologies that are supported by the APRA and SAT elements are strongly tied to the broad science questions addressed by the Astrophysics Division's three focused programs. Examples of areas funded by SAT and APRA include IR and X-ray detectors, optical/ultraviolet mirror coatings, X-ray optics, lasers, and micro thrusters for gravitational wave studies. NASA is partnering with ESA to develop and test technologies necessary for a future gravitational wave observatory. ESA's LISA Pathfinder mission is a technology demonstration mission, and NASA is providing colloidal micronewton thrusters and a drag-free dynamic controller to be co-manifested with ESA's LISA Test Package. Development of technology relevant to future astrophysics missions also benefits from investments made by STMD. STMD is contributing to basic and innovative technology relevant to future operating missions, as well as developing technology for two potential missions—the Station Explorer for X-ray Timing and Navigation (SEXTANT) for NICER and a potential coronagraph for WFIRST. SEXTANT will use the pulsar timing information collected by NICER to perform a flight demonstration of pulsar navigation techniques. The WFIRST SDT has concluded that a

WFIRST mission could be enhanced by the addition of a coronagraph for direct imaging of nearby exoplanets. STMD is partnering with the Astrophysics Division to mature the technologies required for two candidate coronagraph architectures for possible infusion into a WFIRST coronagraph.

Studies of Exoplanets Crosscutting Work Between the Astrophysics and Planetary Science Divisions

Exoplanets are currently a topic studied in both SMD's Planetary Science and Astrophysics Divisions at NASA, and are a priority according to the decadal surveys of both disciplines. The Planetary Science Division's Research and Analysis Program and the Astrophysics Division's Exoplanet Exploration Program coordinate their studies of exoplanets to determine the origins of stellar systems that are similar to our own. The specific goals of the Astrophysics Division include searching for planets and planetary systems around stars in our galaxy, determining the percentage of planets that are in or near the habitable zone of a wide variety of stars, and characterizing planets around other stars for their habitability and other physical characteristics. The Planetary Science Division's specific goals include understanding the origin and evolution of the atmospheres of planets and their satellites, understanding the formation and early evolution of planetary systems, and providing the fundamental research and analysis necessary to characterize those planetary systems, including their habitability. While the Astrophysics Division emphasizes observational detection and study of exoplanets, the Planetary Science Division primarily focuses on the knowledge necessary for understanding exoplanets through modeling, data analysis, theoretical studies, and ground-based observations.

CHAPTER 5

A Plan for Joint Agency Missions

This chapter outlines the Joint Agency Satellite Division (JASD)—an SMD organization with broad crosscutting responsibilities. In partnership with NOAA, JASD manages the development and launch of several operational environmental monitoring satellite programs, projects, and instruments on a reimbursable basis.

Joint Agency Satellite Division

Strategy

JASD implements the nation's space policy for environmental Earth observation and weather (as documented in the President's National Space Policy) by managing in partnership with NOAA the acquisition of several operational L1, geostationary, and polar satellite programs, projects and instruments. JASD helps to achieve the NRC recommendations on Earth science and heliophysics observations. The NRC stated in its 2007 Earth science decadal survey that "sustained measurements of key climate and weather variables are part of the committee's strategy to achieve its vision for an Earth observation and information system in the next decade." In 2012, the NRC stated in its heliophysics decadal survey that it "recommends that NASA, NOAA and the Department of Defense work in partnership to plan for the continuity of solar and solar wind observations beyond the lifetimes of ACE, SOHO, STEREO, and SDO." JASD advances these efforts by working with other agencies to obtain such measurements through the management and oversight of the Joint Polar Satellite System (JPSS) Program, the Geostationary Observational Environmental Satellite (GOES)-R Series Program, the Joint Altimetry Satellite Oceanography Network (Jason) 3 project, and the DSCOVR project, and by providing instruments for the European Organisation for the Exploitation of Meteorological Satellites' (EUMETSAT) Meteorological Operational (MetOp) satellite program via NOAA's international agreements. SMD established JASD in April 2010, following an executive branch decision to replace the National Polar-orbiting Operational Environmental Satellite System (NPOESS) with the NOAA/NASA JPSS and the DOD Defense Weather Satellite System (DWSS). JASD builds on NASA's history of well-managed reimbursable partnerships with NOAA, including GOES and the Polar-orbiting Operational Environmental Satellites (POES). NOAA provides the requirements and budget, and NASA is responsible for development and acquisition of the space systems—and in some cases the ground systems—following NASA's rigorous flight program and project management process. JASD funding is fully reimbursable; the only JASD-related expense NASA incurs is the employment of the NASA Headquarters employees who staff JASD. Since its inception in 2010, JASD has consistently delivered to NASA's partner agencies and the science community. For example, Suomi NPP was the first system completed

FIRST LIGHT

The Visible Infrared Imager Radiometer Suite (VIIRS) on the United States' newest Earth-observing satellite, NPP, acquired its first measurements on November 21, 2011. This image shows a broad swath of eastern North America, from the Great Lakes to Cuba. The image shows the full scene from Hudson Bay to the northern coast of Venezuela, and launched under JASD management. After a successful launch in October 2011 and check-out in March 2012, NASA transferred operational control of Suomi NPP to NOAA. A top priority for JASD is to ensure that Suomi NPP continues to operate optimally and is able to overlap with the planned follow-on polar orbiting weather satellite, JPSS. To that end, NASA and NOAA will continue to collaborate during the mission's five-year prime operations phase to ensure that the agencies' shared objectives are being met. The system's value is already apparent; Suomi NPP data are publicly available and are being used by the National Weather Service for weather forecasting. In September 2012, MetOp B successfully launched carrying several U.S. instruments that were transitioned into JASD via the new partnership with NOAA. The instrument suite included the Advanced Microwave Sounding Unit-A (AMSU-A), the Advanced Very High Resolution Radiometer (AVHRR), and the Space Environment Monitor (SEM). These instruments are providing key measurements to U.S. and international meteorological and space weather communities. The latest JASD success, TCTE, built under a NASA contract for NOAA, was launched aboard a U.S. Air Force Space Test Program Satellite-3 (STPSat-3) on the Operationally Responsive Space-3 (ORS-3) mission in November 2013. TCTE provided a means to transfer the absolute calibration of the Total Solar Irradiance (TSI) measurement, currently provided by the aging SORCE spacecraft, to the follow-on TSI measurement instrument, thus extending the 35-year record of space-based measurements on solar variations that affect Earth's weather and climate.

JPSS Program

The JPSS Program provides continuity of critical observations for accurate weather forecasting, reliable severe storm outlooks, and global measurements of atmospheric and oceanic conditions such as sea surface temperatures, ozone, and more. JPSS also provides operational continuity of satellite-based observations and products for NOAA's POES and the Suomi NPP satellite. The program consists of the currently orbiting Suomi NPP and two planned missions, JPSS-1 and JPSS-2, along with a ground system for satellite command and control and data acquisition, processing, and dissemination.

GOES-R Series Program

The GOES-R Series program consists of a system of environmental satellites in geostationary orbit that provide continuous weather imagery and monitoring of meteorological data for the United States, Latin America, much of Canada, and most of the Atlantic and Pacific ocean basins. The GOES-R Series satellites provide atmospheric, oceanic, climatic, and solar products supporting weather forecasting and warnings, climatologic analysis and prediction, ecosystems management, and safe and efficient public and private transportation. The GOES-R Series satellites also provide a platform for space environmental observations and auxiliary communications services that provide for GOES data rebroadcast, data collection platform relay, low resolution imagery, emergency

weather communications, and satellite-aided search and rescue. The GOES-R Series Program includes spacecraft, instruments, launch services, and all associated ground system elements and operations for four satellites (GOES-R/S/T/U).

Reimbursable Projects Program

The Reimbursable Projects Program (RPP) is an uncoupled portfolio of independent projects with unique mission-specific objectives. Currently the RPP consists of follow-on missions to operational weather and climate instruments and satellites whose purpose is to continuously observe the Sun and the Earth's atmosphere and oceans. The RPP projects include: POES/MetOp, JASON-3, and DSCOVR.

JASD fulfills the standard management and oversight role for NOAA's reimbursable satellite development missions described in Table 5.1.

JASD participates in strategic planning discussions with NOAA regarding future follow-on environmental monitoring operational missions. NOAA has the primary responsibility for future mission planning, requirements development, and budgeting for follow-on operational environmental monitoring missions. JASD provides expertise and advice to NOAA regarding optimum acquisition strategies and implementation concepts.

CHAPTER 6

Advancing Technology for Science

NASA invests in crosscutting, transformational space technologies that have high potential for offsetting mission risk, reducing cost, and advancing capabilities for increasingly complex and challenging missions. Drawing on talent from NASA's workforce, academia, and the broader industrial base, technological advancements enable a new class of science missions, strengthen our nation's leadership in Earth and space science, and foster a technology-based economy. NASA's investment strategy spans the entire technology lifecycle, from conceptual studies to discover new technologies (TRL 1-3), to rapid development and ground-based testing (TRL-3-5), to flight demonstration in a relevant environment (TRL 5-7). NASA implements technology development at all appropriate organizational levels in the Agency. Two organizations are responsible for developing and implementing the Agency's technology strategy—the Office of the Chief Technologist (OCT) and STMD. OCT advises and advocates for NASA on matters concerning Agency-wide science and technology policy and programs. OCT coordinates and tracks technology investments across the Agency; develops and executes innovative technology partnerships with other government agencies, academia, and the commercial aerospace community; and leads the Agency's technology transfer and commercialization efforts. As described in chapter 3, STMD is responsible for developing the crosscutting, pioneering, new technologies and capabilities needed by the Agency to achieve its current and future missions. Table 6.1 lists STMD's nine technology programs, and provides examples that show how each program is relevant to SMD. At the directorate level, the SMD Chief Technologist is the SMD interface to OCT and assists in establishing appropriate Agency-level technology policy, practices, and partnerships. As the lead point-of-contact to STMD, the Chief Technologist serves as an advocate and a resource for alignment of STMD technology development with SMD science objectives. Within the directorate, the SMD Chief Technologist is responsible for coordinating the development and utilization of technology across the four science disciplines. Working closely with the Division Technologist in each science division, the SMD Chief Technologist establishes an understanding of the programmatic requirements for the directorate and actively searches for collaborative opportunities to advance the necessary technology within the divisions to enable future science missions. One of the primary responsibilities of the SMD Chief Technologist is to facilitate opportunities for collaboration with partners external to the directorate who share a common goal with SMD. As part of this effort, the Chief Technologist ensures such stakeholders are informed about SMD's technology requirements and planned investments. Awareness of SMD's technology development priorities could lead other organizations to make investment decisions that are beneficial to SMD, and lead to opportunities for cost sharing and other forms of partnership. At a

minimum, maintaining awareness and sharing information about technology requirements and development efforts will reduce the likelihood that either partner will needlessly invest in technology areas already being explored by the other partner. There are six primary interfaces SMD must maintain to enable collaboration with external partners and ensure advancement of technology needed to conduct Earth and space science research:

- **OCT and STMD:** SMD participation in and awareness of OCT/STMD technology initiatives is necessary to increase the likelihood of successful technology infusion into future science missions.
- **Other NASA mission directorates:** Common goals such as robotic and human exploration of Mars lead to opportunities for technology collaboration on common mission requirements such as entry, descent, and landing.
- **Other U.S. government agencies:** Many government agencies share technology interests with SMD, including the science-based technology overlaps with NOAA, NSF, and USGS; and the remote sensing, data analysis, archiving, and mission operations systems technologies shared with several national security agencies.
- **Industry:** Aerospace corporations often invest significant resources on internal research and development of technologies that have the potential to support future science missions.
- **Academia:** Much of the early work needed to advance technology is conducted at universities with funds they receive to study future mission concepts.
- **Other international space agencies:** The success of many high-profile mission concepts for breakthrough science depends upon collaboration with international partners who might be further along in their technology development for a particular area of science. SMD also undertakes technology development activities in each science division, as described in chapter 4.

Technology development programs are essential for extending the reach of scientific discovery. The comprehensive approach employed by SMD encompasses both near-term and long-term technology development, partnerships with external organizations, and internal technology development, thus enabling the advancement of technologies necessary for future science missions.

CHAPTER 7

Engaging the Next Generation

Strategy

SMD's education and public outreach (E/PO) strategy directly contributes to the executive branch's framework to effectively deliver STEM education to more students and teachers across the nation and supports the Agency's education objective articulated in NASA's 2014 strategic plan: "Advance the Nation's STEM education and workforce pipeline by working collaboratively with other agencies to engage students, teachers, and faculty in NASA's missions and unique assets." SMD remains focused on realizing the unique contribution NASA science makes towards meeting the nation's education needs and on enhancing the public's understanding of science. SMD's vision for E/PO is To share the story, the science, and the adventure of NASA's scientific explorations of our home planet, the solar system, and the universe beyond, through stimulating and informative activities and experiences created by experts, delivered effectively and efficiently to learners of many backgrounds via proven conduits, thus providing a direct return on the public's investment in NASA's scientific research. At the same time, SMD must be responsive to national priorities and directives. In May 2013, the NSTC CoSTEM released the Federal STEM Education 5-Year Strategic Plan, outlining goals in five priority STEM education investment areas. In response to this plan, SMD will continue to support and collaborate with other agencies in the priority areas identified by the plan:

- Improve STEM Instruction
- Increase and Sustain Youth and Public Engagement in STEM
- Enhance STEM Experience of Undergraduate Students
- Better Serve Groups Historically Under-represented in STEM Fields
- Design Graduate Education for Tomorrow's STEM Workforce

Furthermore, the President's FY 2014 budget request proposed a cohesive framework for delivering STEM education to students and teachers effectively. The President's FY 2015 budget request included several changes to the original STEM proposal to ensure a smooth transition to the new framework, incorporating feedback from a wide range of stakeholders on how best to approach STEM education. The FY 2015 budget includes

dedicated funding for SMD, which is evidence of the important role that NASA's science program plays in inspiring students, teachers, and the public about science and in particular, STEM careers. While SMD is still developing policies and processes for implementing a more focused and cohesive portfolio of education programs, the directorate has established several tenets that are consistent with the executive branch's new STEM framework and the NSTC CoSTEM Federal STEM Education 5-Year Strategic Plan :

- SMD will maintain an important role in science education and public engagement for the nation.
- In cooperation with NASA's Office of Education, SMD will ensure alignment with the CoSTEM goal structure.
- Existing E/PO activities will be evaluated for effectiveness to determine if they should continue and future E/PO activities will be competed.

NASA's science program is unique among federal agencies. Through competitive selection and strategic partnerships, SMD's E/PO opportunities inspire students, teachers, and the public at large to seek out new science discoveries and to acquire new skills in science, engineering, technology, and mathematics.

Ever since it formally established E/PO policies in 1995, SMD has strived to increase science literacy rates for the U.S. population. Consistent with that objective, SMD E/PO efforts encompass both science education and workforce development. SMD integrally implements its E/PO efforts primarily through two means. First, it embeds E/PO projects in certain flight programs and missions, which allocate a portion of their mission budgets for E/PO activities. These missions develop E/PO plans during the early phases of the mission lifecycle, and these plans are subjected to thorough review and approval processes similar to those used for mission subsystems. SMD also offers proposal opportunities for E/PO efforts as part of its annual competitive solicitation process. SMD may award solicited or unsolicited E/PO proposals, or fund E/PO efforts as elements of a major research-enabling program (e.g., suborbital science, science instrumentation, data and information systems, etc.). Science mission staff—especially researchers—are particularly encouraged to become active participants in E/PO activities.

Science Education

Currently, science experts share the results of NASA missions and research with audiences through a portfolio of education and outreach projects targeted to students in higher education, elementary, and secondary school and the general public. These E/PO efforts are delivered by both paid and volunteer networks, such as the Solar System Ambassadors and Educators and the Night Sky Network. One aim is to attract and retain students in STEM disciplines by energizing science teaching and learning. In addition, E/PO projects promote inclusiveness and provide opportunities for minorities, students with disabilities, students at minority universities, and other target groups to compete for and participate in science missions, research, and education programs. Collaboration is critical to building and sustaining nationwide programs that contribute to improving teaching and learning at the precollege level and to increasing the scientific literacy of the general public. SMD fosters such collaboration by building on existing programs, institutions, and infrastructure and by coordinating activities and encouraging partnerships with other ongoing education efforts both within and external to NASA. SMD has established informal education alliances with science centers, museums, and planetariums through the NASA Museum Alliance, as well as with public radio and television program producers. SMD also works to enrich the STEM education efforts of community groups such as the Girl Scouts, 4-H Clubs, and the Boys and Girls Clubs of America. The strength of each of these partnerships relies on the combination of the science content knowledge and expertise of SMD and the educational expertise and context of each partner.

Most educational products created under the auspices of SMD are readily available to the public through www.nasawavelength.org. The resources included in the on-line catalog have all passed the SMD Education Product Review, where resources are reviewed for both content accuracy and pedagogy. In addition, this site provides direct links to other relevant NASA sites, as well as other national databases containing educational materials. SMD also utilizes independent education experts to evaluate and provide feedback on the quality and impact of all E/PO projects. In 2009, SMD established Science E/PO Forums (SEPOFs) to facilitate NASA collaboration with external science, education, and outreach communities. In 2014, SMD will assess the effectiveness of the SEPOFs to determine if they will be continued as part of the overall SMD E/PO restructuring.

Workforce Development

To prepare America's future workforce, NASA makes many professional development opportunities available that are firmly rooted in the science and technology of NASA science missions. SMD aids in workforce development by supporting students at the undergraduate, graduate, and postdoctoral levels. Students may be embedded in SMD research, technology, or flight projects, or may participate in other distinct educational opportunities. The university-based research and technology projects sponsored by SMD allow students and postdoctoral researchers to gain invaluable NASA science program work experience as part of their educational and professional training. Suborbital programs (airplanes, unmanned aircraft systems, rockets, and balloons) and PI-led missions enable students to participate in the entire lifecycle of a science mission, from design and construction, to flight and data analysis. These hands-on opportunities provide students with experiences in problem solving and enable increased understanding of the systems engineering concepts that are the underpinning of successful science missions. In addition, the Student Airborne Research Program offers advanced undergraduat

students hands-on research experience in all aspects of a major scientific campaign. Furthermore, the NASA Post-doctoral Program, NASA Earth and Space Science Fellowship Program, and other early-career programs (e.g., Early Career Fellowships, New Investigator Program in Earth Science) ensure the continued training and nurturing of a highly qualified workforce to help NASA continue the scientific exploration of Earth and space. SMD also supports the Presidential Early Career Awards for Scientists and Engineers, led by the Office of Science and Technology Policy.