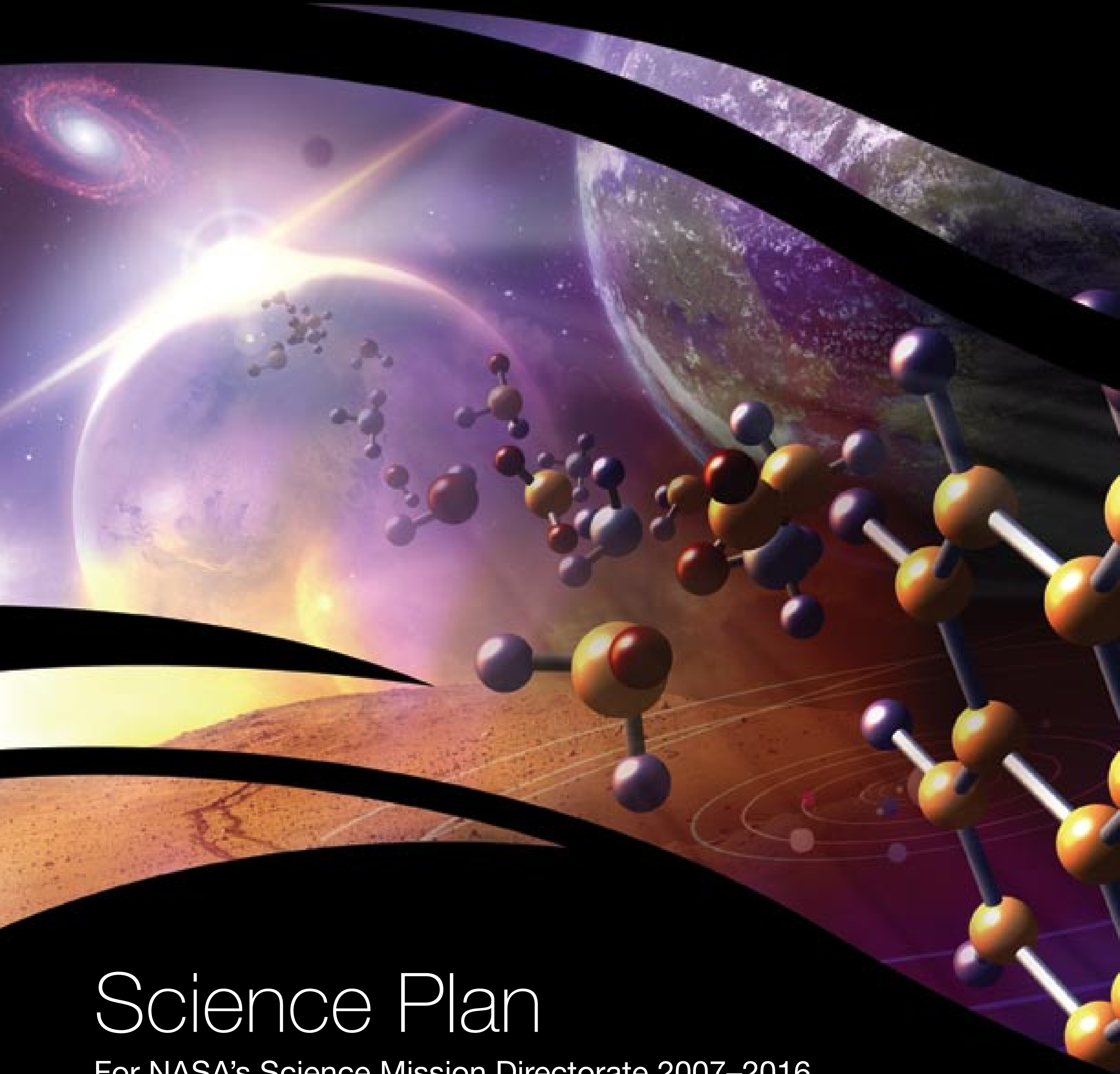
National Aeronautics and Space Administration



Science Plan

For NASA's Science Mission Directorate 2007–2016

Contents

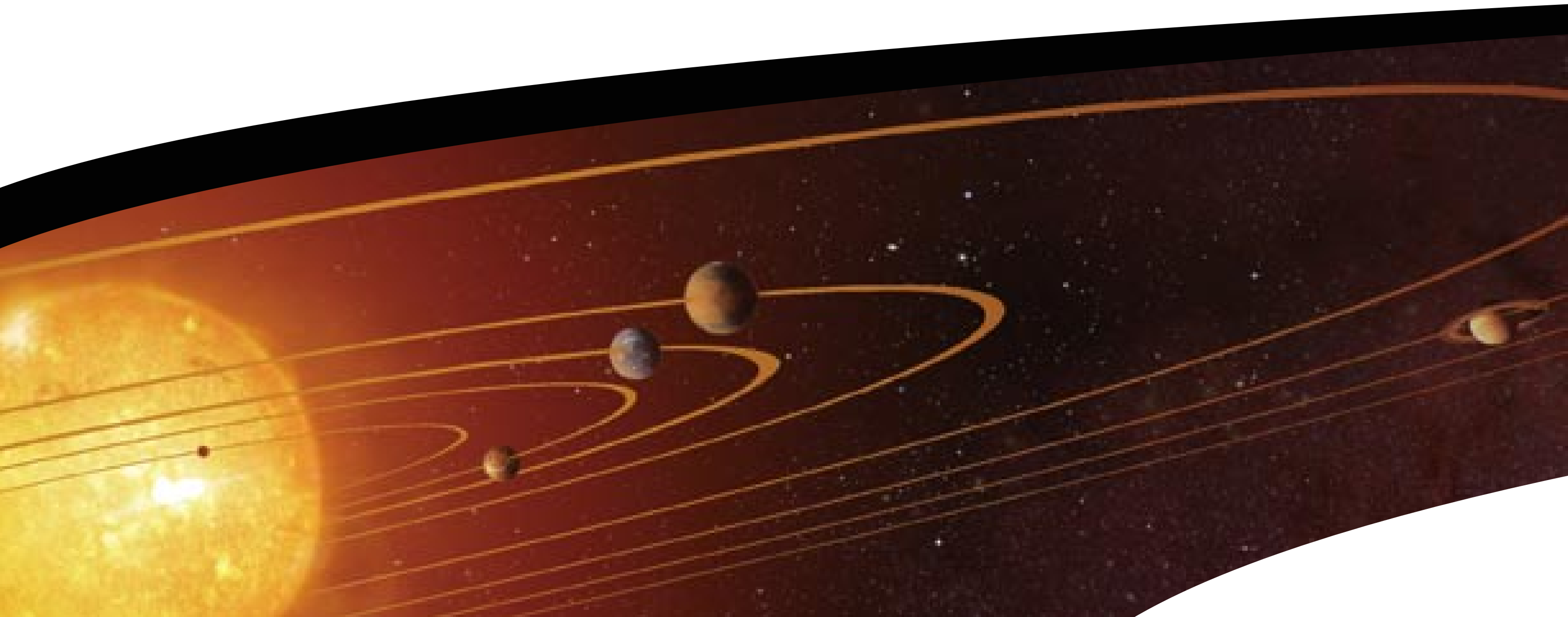
Preamble:

NASA's Vision for Science

NASA's Science Mission Directorate conducts scientific exploration that is enabled by access to space. We project humankind's vantage point into space with observatories in Earth orbit and deep space, spacecraft visiting the Moon and other planetary bodies, and robotic landers, rovers, and sample return missions. From space, in space, and about space, NASA's science vision encompasses questions as practical as hurricane formation, as enticing as the prospect of lunar resources, and as profound as the origin of the Universe.

From space we can view the Earth as a planet, seeing the interconnectedness of the oceans, atmosphere, continents, ice sheets, and life itself. At NASA we study planet Earth as a dynamic system of diverse components interacting in complex ways—a challenge on a par with any in science. We observe and track global-scale changes, and we study regional changes in their global context. We observe the role that human civilization increasingly plays as a force of change. We trace effect to cause, connect variability and forcing with response, and vastly improve national capabilities to predict climate, weather, and natural hazards. NASA research is an essential part of national and international efforts to employ Earth observations and scientific understanding in service to society.

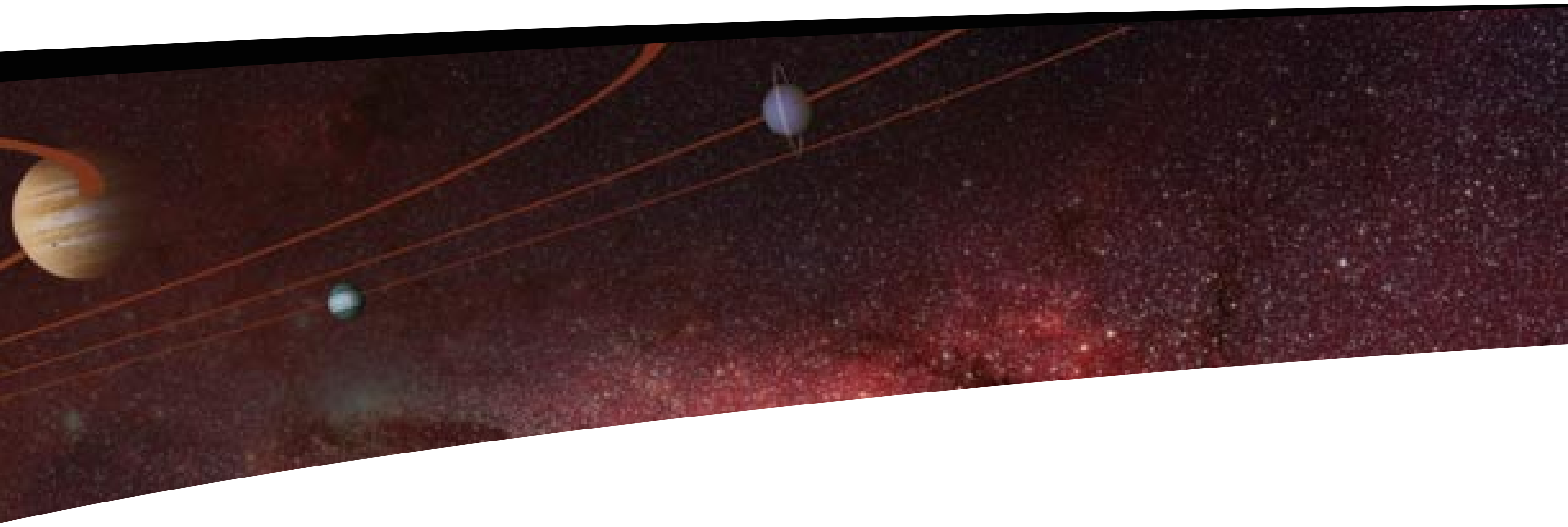
We extend humankind's virtual presence throughout the solar system via robotic visitors to other planets and their moons, to asteroids and comets, and to icy bodies in the outer reaches known as the Kuiper Belt. We are completing our first survey of the solar system with one mission that will fly by Pluto and another that will visit two protoplanets, Ceres and Vesta. We are in the midst of a large-scale investigation of Mars, with one or more robotic missions launching every 26 months when the positions of Mars and Earth are optimal. We are directing our attention to certain moons of the giant planets where we see intriguing signs of surface dynamism and of water within, knowing that on Earth, where there is water and energy there is also life. We are progressing from observers to rovers to sample return missions, each step bringing us closer to our principal goals: to understand our origins, to learn whether life does or did exist elsewhere in the solar system, and to prepare for human expeditions to the Moon, Mars and beyond.



Our solar system is governed by the Sun, a main-sequence star midway through its stellar life. The Sun's influence is wielded through gravity, radiation, the solar wind, and magnetic fields as they interact with the masses, fields and atmospheres of planetary bodies. Through the eyes of multiple spacecraft, we see the solar system as a "heliosphere," a single, interconnected system moving through interstellar space. On Earth, this interaction with a star is experienced through space weather's modifications to the ozone layer, through climate change, and through effects on radio and radar transmissions, electrical power grids, and spacecraft electronics. We seek to understand how and why the Sun varies, how planetary systems respond, and how human activities are affected. As we reach beyond the confines of Earth, this science will enable the space weather predictions necessary to safeguard the outward journeys of human and robotic explorers.

The greatest minds of the last century perceived wondrous things about the universe itself—the Big Bang and black holes, dark matter and dark energy, and the nature of space and time. Their theories challenge NASA to use its presence in space to put them to the test. NASA's Great Observatories are taking us to the limits of the theories proposed by Einstein, Hubble, Spitzer and Chandrasekhar. We are now poised to move beyond. Having measured the age of the universe, we now seek to explore its ultimate extremes—its stupendous birth, the edges of space and time near black holes, and the darkest space between galaxies. Having exploited nearly the full spectrum of light, we will explore using gravitational waves in space-time. We seek to understand the relationship between the smallest of subatomic particles and the vast expanse of the cosmos. Having discovered more than a hundred giant planets around other stars, we now seek to find Earth-like planets in other solar systems.

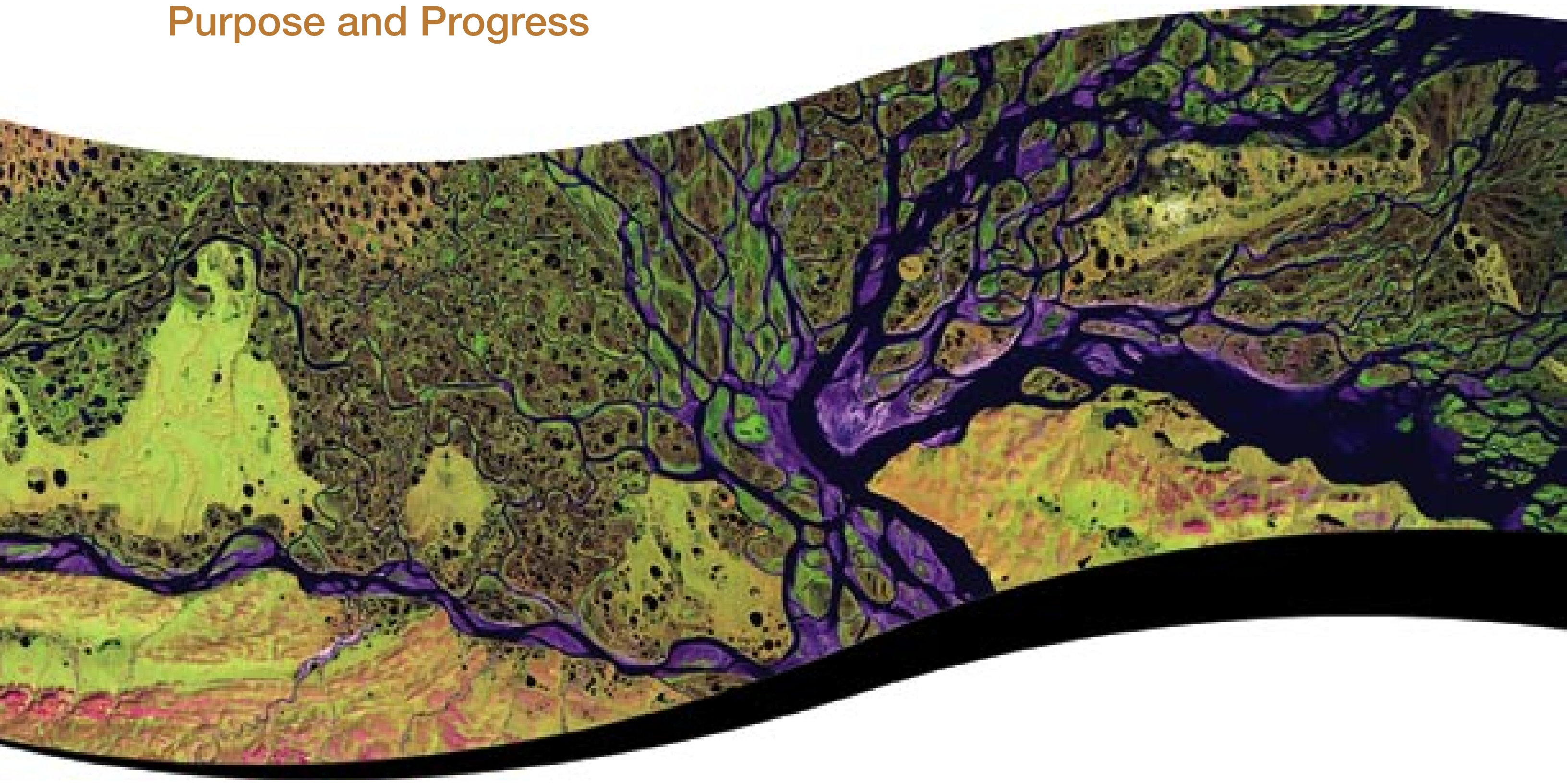
This is NASA's science vision: the scientific exploration of our planet, other planets and planetary bodies, our star system in its entirety, and the universe beyond. In so doing, we lay the intellectual foundation for the robotic and human expeditions of the future. What follows is NASA's plan for turning this vision into scientific discovery.



1 Purpose and Progress

Chapter 1

Purpose and Progress



Science in the NASA Strategic Plan

The 2006 NASA Strategic Plan articulates succinctly the three-part Mission of the Agency:

To pioneer the future in space exploration, scientific discovery, and aeronautics research.

NASA has pursued these three areas throughout its history. Fresh impetus is provided by the President's Vision for Space Exploration announced in January 2004, which includes robotic exploration of planetary bodies in the solar system, advanced telescope searches for Earth-like planets around other stars, and studying the origin, structure, evolution, and destiny of the universe, in addition to extending human presence to the Moon, Mars, and beyond. Other Presidential initiatives guide NASA's study of Earth from space and build on NASA's rich heritage of aeronautics and space science research.

Goal 3 in the 2006 NASA Strategic Plan is to "*develop a balanced overall program of science, exploration, and aeronautics consistent with the redirection of the human spaceflight program to focus on exploration.*" In the arena of science, NASA's focus is in disciplines where access to space enables new scientific endeavors or enhances existing ones. Responsibility for defining, planning and overseeing NASA's space and Earth science programs is assigned by the NASA Administrator to the Science Mission Directorate (SMD). The SMD organizes its work into four broad scientific pursuits, each managed by a Division within the Directorate, implementing the four science subgoals in the NASA Strategic Plan:

- **Earth Science:** Study planet Earth from space to advance scientific understanding and meet societal needs
- **Planetary Science:** Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space
- **Heliophysics:** Understand the Sun and its effects on Earth and the solar system
- **Astrophysics:** Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets.

Appendix 1 lists the long-term outcomes associated with each of these areas. Collectively these goal and outcome statements comprise an overview of the science portfolio managed by SMD. Research on bioastronautics and other microgravity sciences is managed by the Exploration Systems Mission Directorate and is not addressed in this Plan.

Fundamental research on profound science questions using space-based observatories and related assets is the hallmark of all four areas of NASA's SMD. Astrophysics pursues answers to questions about the universe that are as old as humanity. Heliophysics and Planetary Science both include elements important to the success of NASA's human exploration endeavors, and the former has practical utility on Earth. Earth Science is inherently beneficial to society in practical ways and requires that means be created to transfer its results for use in decision support and policy making. Research in all four science areas is essential to the fulfillment of national priorities embodied in Presidential initiatives and Congressional legislation, and scientific priorities identified by the Nation's scientific communities.

The scientific scope of NASA's space and Earth science program is unchanged since the publication of the 2003 NASA Strategic Plan, but much has changed in the intervening years. The external environment has changed in three significant ways. First, NASA has received new direction and advice. These are summarized in the balance of this chapter. Second, projected resource levels have changed, as described in Chapter 2. These have been exacerbated by internal challenges in managing the costs of key projects. Third, a fundamental tenet of strategy in Earth Science—the migration of mature measurements to operational systems—requires reassessment due to changes in the baseline for the National Polar-orbiting Operational Environmental Satellite System (NPOESS). But the scientific challenges before us are largely the same, providing a stable framework for planning.

NASA Science in the Vision for Space Exploration

Announced by the President in 2004 and authorized by the Congress in 2005, the fundamental goal of the Vision for Space Exploration is "to advance U.S. scientific, security, and economic interests through a robust space exploration program." For the past three decades, space exploration beyond low Earth orbit has been conducted exclusively by scientific robotic missions. Now NASA is preparing for human expeditions to the Moon, Mars, and beyond, leading to a new era of joint human and robotic exploration.

Science both enables and is enabled by human exploration. For this reason the President's Commission on Implementation of U.S. Space Exploration sketched out a broad scientific program of research to advance understanding of the origin, evolution, and fate of the Earth, the solar system, and the universe beyond. While organized along spatial rather than temporal lines, the scope of the SMD program mirrors that outlined by the President's Commission.

NASA has assigned responsibilities and authorities to its Mission Directorates for achieving these objectives. For some, such as robotic exploration of Mars and advanced telescope searches for Earth-like planets, SMD has sole responsibility. For the Moon, which is the next target for human exploration of space, SMD plays a program scientist role, providing scientific expertise needed to enable successful human exploration and exploiting the opportunities afforded by human explorers and exploration systems to conduct research. A detailed description of SMD's role in fulfilling the return to the Moon portion of the Vision for Space Exploration and the key activities of the next few years in this area are given in Chapter 8.

NASA Science in National Strategies for Planet Earth

In June 2001, the President announced the Climate Change Research Initiative to augment the long-standing U.S. Global Change Research Program and form the U.S. Climate Change Science Program. NASA is a leader in this interagency effort, along with the National Oceanic and Atmospheric Administration (NOAA) and others, and provides global environmental observations and scientific research, modeling, assessment, and applications research. NASA also provides input on monitoring for the companion Climate Change Technology Program led by the Department of Energy (DOE). NASA, NOAA, the U.S. Geological Survey (USGS), the National Science Foundation (NSF), and the Office of Science and Technology Policy (OSTP) provide leadership for the interagency effort to develop the U.S. Integrated Earth Observation System, America's contribution to the Global Earth Observation System of Systems. Finally, NASA has a key role in the U.S. Oceans Action Plan (the President's response to the Congressionally chartered U.S. Oceans Commission Report) and the emerging Ocean Research Priorities Plan in partnership with NOAA, NSF, and the U.S. Navy (USN).

NASA Science in the National Strategy for Physics and Astronomy

In 2004, the President's Science Advisor adopted the National Science and Technology Council's report, *The Physics of the Universe: A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy*. This document, inspired by the NRC's report *Connecting Quarks with the Cosmos*, identifies investments and actions NASA, NSF, and DOE should take to advance scientific knowledge in cosmology, astronomy, and fundamental physics in light of recent discoveries in these fields. These discoveries suggest "the basic properties of the universe as a whole may be intimately related to the science of the very smallest known things." As the Nation's provider of civil space-based observatories, NASA has a prominent role in implementing this plan.

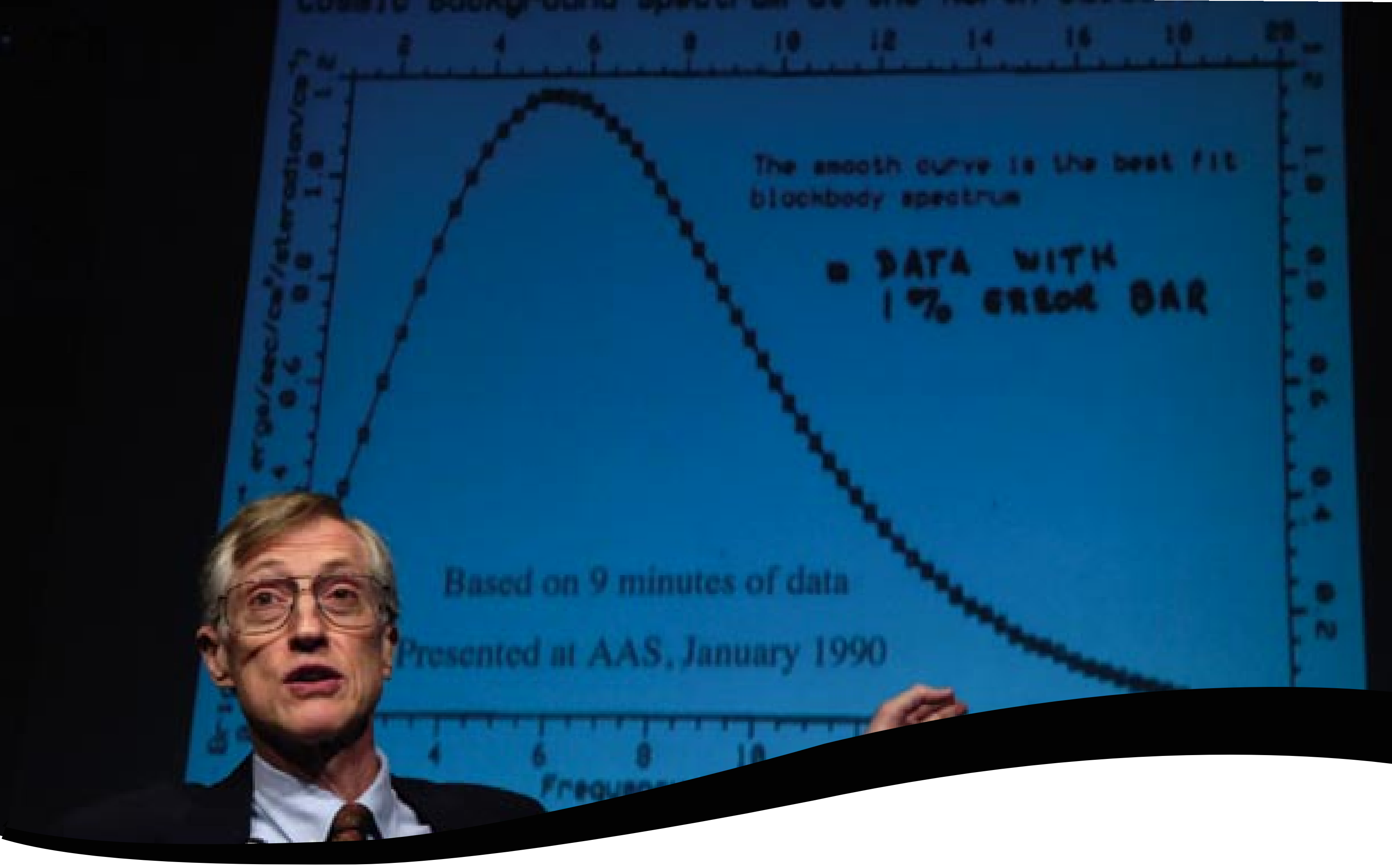
Implementing Science Community Priorities

In planning its science programs, NASA works to implement the priorities defined by the National Research Council (NRC) in its decadal surveys and other reports. These reports represent the broad consensus of the Nation's scientific communities in their respective areas. NASA also engages the broad science community in development of community roadmaps for each of SMD's four science areas that define pathways for implementing NRC-defined priorities. The most recent roadmaps were published in 2006 (see Appendix 3), and were initiated by science committees and subcommittees of the NASA Advisory Council (NAC) as it existed in 2004. These roadmaps provided the starting points for development of the science chapters of this Plan. In addition, NASA receives science advice from the Astronomy and Astrophysics Advisory Committee chartered by the Congress to convey community input in these areas to NSF, NASA, and DOE.

Implementing a Balanced Science Program

The NASA Authorization Act for 2005 calls for a balanced set of programs to carry out the Nation's space exploration, science, and aeronautics research goals. The Act further calls for NASA to submit a plan to guide the science programs of NASA through 2016. This document is intended to answer that call. It also responds to the NASA Strategic Plan and the science "roadmaps" developed by the science community in each of the four science areas. As evidenced by the NRC's report, *An Assessment of Balance in NASA's Science Program* (NRC, 2006), a proper balance across all the relevant dimensions is difficult to achieve. That is true in part because it is difficult to define. At the Agency level, one defining consideration is consistency "with the redirection of the human spaceflight program to focus on exploration." Over the next several years, the Agency is working in parallel to complete the International Space Station, fly the associated Space Shuttle missions and retire that transportation system, and begin development of the new transportation system needed to implement the Vision for Space Exploration. During this same period, SMD is planning to service the Hubble Space Telescope, develop the James Webb Space Telescope, continue robotic exploration of Mars and beyond, and attempt to implement a new NRC decadal survey for Earth science in the context of a substantial downscaling of the climate monitoring capabilities of the converged civilian/military environmental satellite system. For all these reasons and more, a balanced program in the near term may look different from a balanced program over the longer term. The common thread is fulfillment of national objectives within the available resources.

The next chapter provides a summary of science questions and prioritized missions for all four areas. The commonalities and distinctions of the four areas shape SMD's modes of operation and partnerships. Common elements of strategy are described in Chapter 3. The unique objectives, research, and missions of each of the four science areas follow in Chapters 4 through 7. Each of these chapters has its own character as befits the nature of science in each area and as maintains accord with the science community roadmaps from which they were derived. The practicalities of the interaction of science and exploration are described in Chapter 8. Chapter 9 provides a brief, concluding glimpse of the great expanse of scientific achievement to be made possible by NASA and its partners.



NASA Scientist Wins 2006 Nobel Prize in Physics

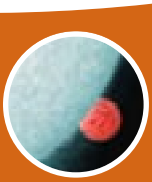
NASA Scientist, Dr. John C. Mather shows some of the earliest data from the NASA Cosmic Background Explorer (COBE) Satellite during a press conference held at NASA Headquarters in Washington, DC. Dr. Mather was a co-recipient of the 2006 Nobel Prize for Physics.
Photo Credit: NASA/Bill Ingalls

“The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2006 jointly to **John C. Mather** NASA Goddard Space Flight Center, Greenbelt, MD, USA, and **George F. Smoot** University of California, Berkeley, CA, USA ‘*for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation*.’”

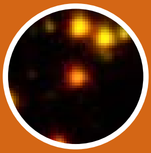
“This year the Physics Prize is awarded for work that looks back into the infancy of the Universe and attempts to gain some understanding of the origin of galaxies and stars. It is based on measurements made with the help of the COBE satellite launched by NASA in 1989...The success of COBE was the outcome of prodigious team work involving more than 1,000 researchers, engineers and other participants. **John Mather** coordinated the entire process and also had primary responsibility for the experiment that revealed the blackbody form of the microwave background radiation measured by COBE. **George Smoot** had main responsibility for measuring the small variations in the temperature of the radiation.”

From the Nobel Foundation website:
http://nobelprize.org/nobel_prizes/physics/laureates/2006/press.html

Recent SMD Highlights

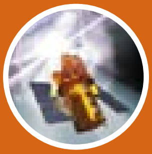


The Spitzer telescope detected first light from an extrasolar world, picking up the infrared glow from two Jupiter-sized planets.



The Spitzer telescope provided the first observational evidence of dark matter, seen in the distribution of mass in the aftermath of the collision of two galaxies.

Using the Hubble Space Telescope, researchers discovered that dark energy was present in the early universe, which appears to agree with Einstein's prediction that a repulsive form of gravity emanates from empty space.



NASA solved a 35-year-old mystery regarding gamma-ray bursts, through coordination of observations from several ground-based telescopes and NASA's Swift and other satellites. The flashes are brighter than a billion suns, yet last only a few milliseconds—too fast for earlier instruments to catch.

oyager 1 reached the edge of the solar system, entering the heliosheath—the vast, turbulent expanse where the Sun's influence ends and the solar wind crashes into the thin gas between stars. It is the human artifact furthest from the Earth.

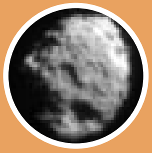
e Imager for Magnetopause-to-Aurora Global Exploration MAGE) and Cluster satellites showed that a sustained bright-glowing spot in the auroral region was a signature of magnetic econnection in the Earth's magnetosphere. The stability of the spot is the first observational evidence that magnetic reconnection could be a steady process.

The Solar and Heliospheric Observatory (SOHO) spacecraft has evealed a process by which the direction of the Sun's magnetic field may reverse every 11 years. The cumulative effect of more than a thousand huge eruptions, called Coronal Mass Ejections, flips the magnetic field of the entire Heliosphere.

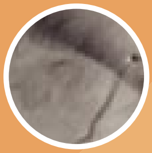
At Saturn, Cassini found geyser-like water vapor spurts on Enceladus and the European Space Agency's (ESA's) Huygens probe found that Titan's surface has been shaped by flowing liquid and blowing winds, much like the Earth's.

The Deep Impact spacecraft rendezvoused with comet Tempel 1, and its impactor collided with the target's nucleus, giving researchers the best-ever data and images of a comet.

The Stardust mission successfully returned to Earth samples from comet Wild 2. The year before, the Genesis mission sampled the solar wind, collecting charged particles implanted in high-purity materials. These represent the first return of samples from space since the Apollo program.



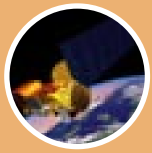
The Mars Exploration Rovers Spirit and Opportunity found evidence that water once flowed across the Martian surface. Both have completed a full Martian year of exploration and discovery. Opportunity has reached Victoria Crater.



ICESat has confirmed accelerated movement of glaciers in the Antarctic Peninsula, following the breakup of the floating ice shelf into which the glaciers flowed. ICESat also confirmed that part of the West Antarctic ice sheet has been increasingly getting thinner.

The twin Gravity Recovery And Climate Experiment (GRACE) satellites demonstrated the ability to measure variability in the water quantity continental underground reservoirs, where most of Earth's liquid fr water is stored.

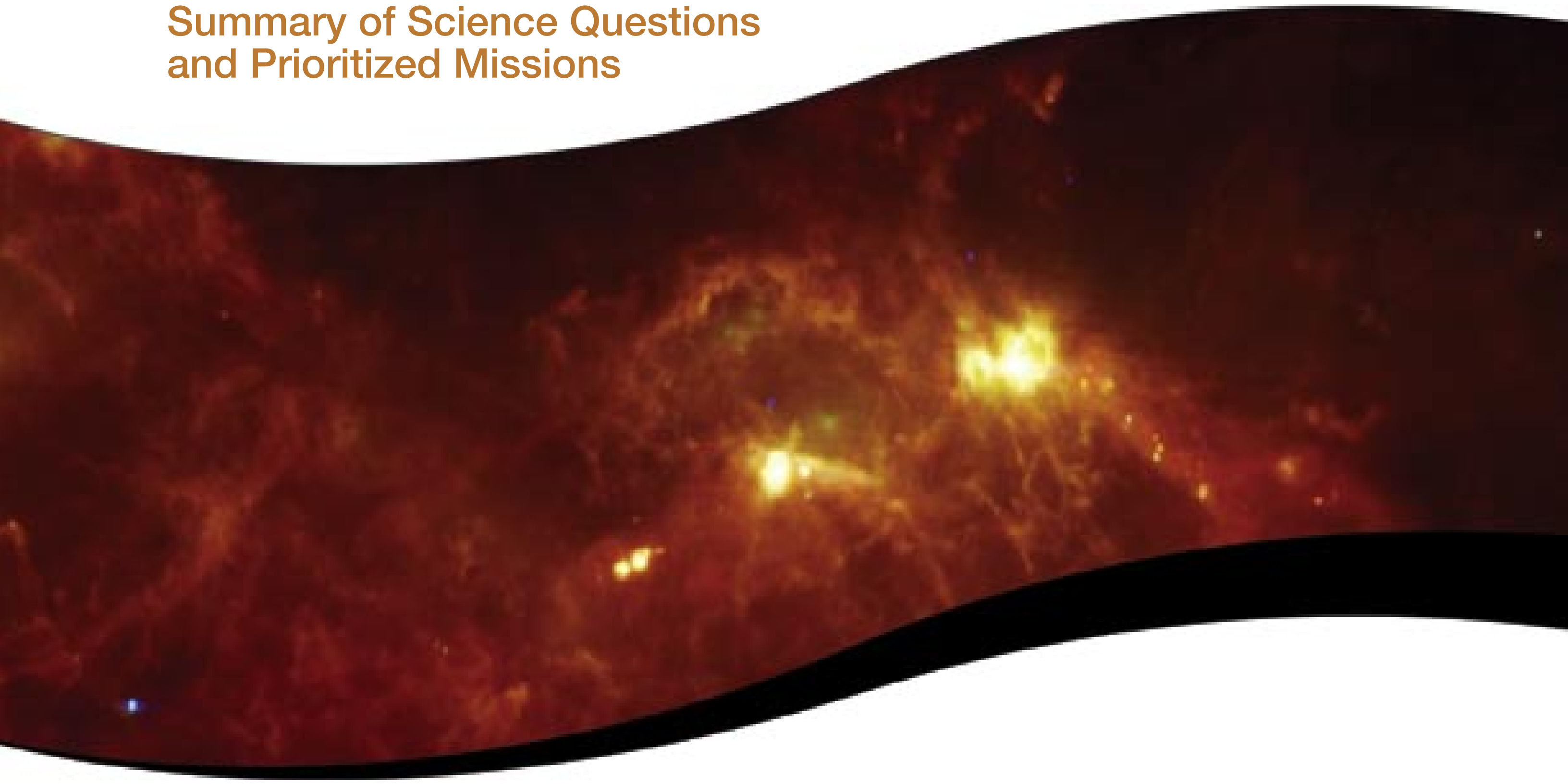
Researchers at NASA and the U.S. Environmental Protection Agency (EPA) developed a data fusion of observations from the Terra and Aqua satellites with the EPA *in situ* monitoring network to improve the air-quality forecasts issued throughout the United States.



2 Summary of Science Questions and Prioritized Missions

Chapter 2

Summary of Science Questions and Prioritized Missions



NASA's Science Mission Directorate works continually with the science community to identify the highest science priorities and the best strategies and missions to address those priorities. These priorities are drawn from the decadal surveys and other reports of the NRC. Each of SMD's four science divisions sponsors a triennial strategic roadmapping effort, generally using committees comprised largely of members of the external science community and led by a senior leader in that community, to lay out NRC decadal survey priorities into a decadal (and longer) roadmap of missions and research programs. These committees operate under the auspices of the NASA Advisory Council (NAC) and its subordinate bodies. The products of these efforts are the building blocks of NASA strategy documents, including this Science Plan. The NRC and the NAC then review the strategy documents to assure NASA has adequately reflected community priorities given budgetary, programmatic, and related constraints.

NASA seeks advice from the science community before, during, and after mission development. At the outset, NASA works with NAC and its subordinate bodies on implementing science priorities and plans. Later, NASA relies on peer review involving the broader scientific community to evaluate proposed investigations and mission concepts. Then, during the proposed development phase of major missions, competitively selected mission science teams conduct trade studies, develop algorithms, and analyze science data returned from other missions, all to ensure that the mission will successfully accomplish its primary science objectives. Further, NASA draws on science community expertise when needed to assess potential impacts of major cost, science content, or schedule changes. In addition, to determine the merits of extending the operation of missions that have exceeded their primary mission lifetimes, NASA seeks science community peer review. More generally, NASA engages in dialog with the science community on priorities and plans by participating in meetings of professional societies such as the American Geophysical Union, the American Astronomical Society, and the American Meteorological Society.

2.1 Science Questions

Working with the broader scientific community and in response to national initiatives and NRC decadal surveys, NASA has defined a set of space and Earth science questions that can be best addressed using the Agency's unique capabilities. These are listed in Table 2.1. The science questions in this table originated in the community roadmaps in each science area, which in turn are sourced in NRC decadal surveys. The research objectives in this table are a form of the long-term outcomes set forth in the 2006 NASA Strategic Plan.

Answering these science questions requires comprehensive research programs be conducted by NASA and its many partners. Components of these programs include scientific research and analysis, space missions, suborbital missions, field campaigns, data management, computational modeling, and advanced technology development. Because of their centrality to NASA's role in science and to the request from the Congress for this Science Plan, space missions and mission priorities are addressed in the balance of this chapter.

2.2 Setting Priorities

NASA's approach to setting the balance of investment among science areas is based on the following considerations:

- A commitment is made to **reasonable progress on the long-term outcomes associated with each of the four SMD-assigned science objectives in the NASA Strategic Plan** shown in Appendix 1;

- **Long-term outcomes are science based, not mission based; thus suborbital and research and analysis (R&A) programs are part of the discussion**—it is not simply a matter of weighing a mission in one area against a mission in another;

- Progress is assessed against community roadmaps laid out for each science area;

- The pace of progress can be influenced by ties to other NASA and Federal programs, e.g., human exploration timelines, in the case of the Mars Exploration Program, and the U.S. Climate Change Science Program and NPOESS in the case of Earth science;

- Some science objectives can be accomplished using a mix of small, medium and large missions; others require large missions which are more difficult to initiate.

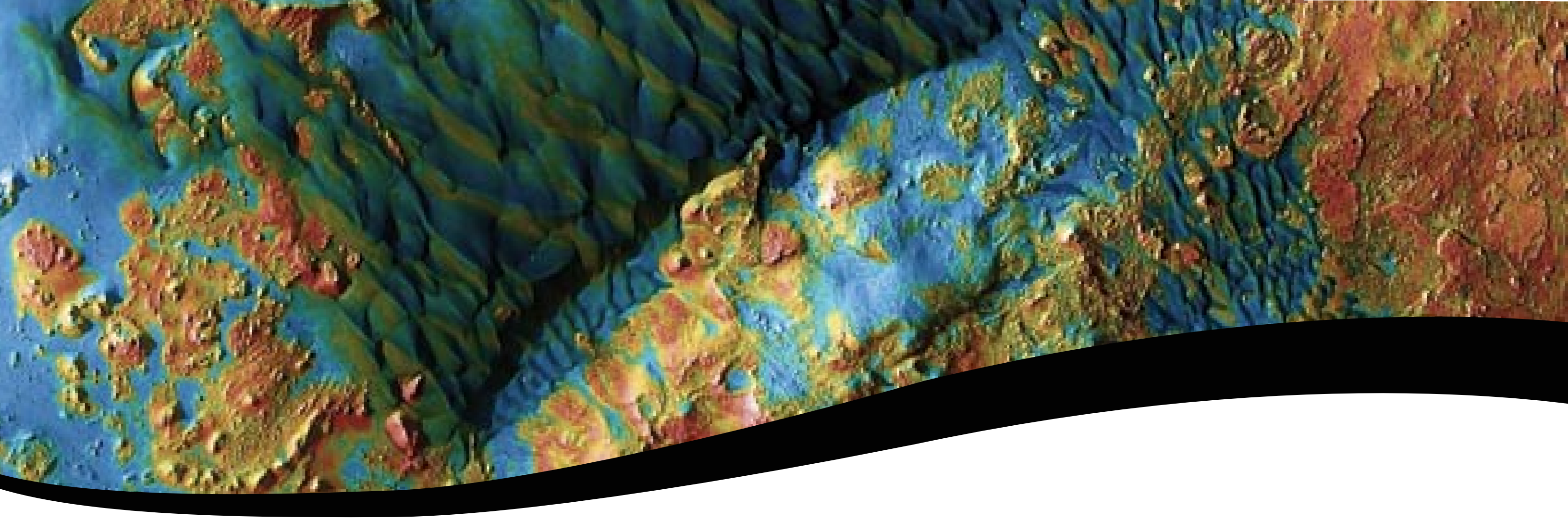
NASA begins in each science area with **the priorities defined in decadal surveys of the NRC**, then generally sponsors science **community-led teams to develop roadmaps to plan implementation** of survey research and mission priorities. The first Earth Science decadal survey is currently in progress; thus, future missions in Earth science are not prioritized. NASA will address Earth Science future mission prioritization once the decadal survey is available.

Tables 2.2.a-2.2.e provide lists of missions through 2016, prioritized for each major science area. The table includes all space and Earth science missions that NASA will initiate, design, develop, launch, or begin to operate from January 2007 through December 2016. The rationale is detailed in this section, and supporting information is presented in Chapters 4-7 on Earth Science, Planetary Science, Heliophysics, and Astrophysics, respectively. Currently operating missions are not included. Operating missions that have exceeded their prime mission lifetime are prioritized in periodic senior review processes led by members of the science community.

Priority has been assigned based on a combination of scientific and programmatic factors. Other things being equal, missions closer to launch are given higher priority for funding than missions further from launch. Other factors considered in the prioritization are technology readiness, mission science interdependencies, partnership opportunities, executive and legislative branch mandates, and programmatic considerations. Thus, assignment of high priority to a mission does not always mean it is developed for launch first; rather, it will be developed for launch as soon as it can be done well, implemented commensurate with the community's desire for a balanced program of small, medium, and large missions, and scheduled in accord with the phasing of available funding. The rationale for the priority order and the endorsement history of each mission are summarized in the table, with overarching considerations for each science area in the text preceding each table.

Table 2.1

Science Questions and Research Objective		
Science Area	Science Questions	Research Objectives [multiyear Outcomes, 2006 NASA Strategic Plan—Appendix 1]
Earth Science: Study planet Earth from space to advance scientific understanding and meet societal needs.	• How is the global Earth system changing? • What are the primary causes of change in the Earth system? • How does the Earth system respond to natural and human-induced changes? • What are the consequences for human civilization? • How will the Earth system change in the future?	1. Understand and improve predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition 2. Enable improved predictive capability for weather and extreme weather events 3. Quantify global land cover change and terrestrial and marine productivity and improve carbon cycle and ecosystem models 4. Quantify the key reservoirs and fluxes in the global water cycle and improve models of water cycle change and fresh water availability 5. Understand the role of oceans, atmosphere, and ice in the climate system and improve predictive capability for its future evolution 6. Characterize and understand Earth surface changes and variability of Earth's gravitational and magnetic fields 7. Expand and accelerate the realization of societal benefits from Earth system science
Planetary Science: Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space.	• How did the Sun's family of planets and minor bodies originate? • How did the solar system evolve to its current diverse state? • What are the characteristics of the solar system that led to the origin of life? • How did life begin and evolve on Earth and has it evolved elsewhere in the solar system? • What are the hazards and resources in the solar system environment that will affect the extension of human presence in space?	1. Learn how the Sun's family of planets and minor bodies originated and evolved 2. Understand the processes that determine the history and future of habitability in the solar system, including the origin and evolution of Earth's biosphere and the characteristics and extent of prebiotic chemistry on Mars and other worlds 3. Identify and investigate past or present habitable environments on Mars and other worlds, and determine if there is or ever has been life elsewhere in the solar system 4. Explore the space environment to discover potential hazards to humans and to search for resources that would enable human presence
Heliophysics: Understand the Sun and its effects on Earth and the solar system.	• How and why does the Sun vary? • How do the Earth and planetary systems respond? • What are the impacts on humanity?	1. Understand the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium 2. Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields 3. Develop the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers
Astrophysics: Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets.	• What are the origin, evolution, and fate of the universe? • How do planets, stars, galaxies, and cosmic structure come into being? • When and how did the elements of life and the universe arise? • Is there life elsewhere?	1. Understand the origin and destiny of the universe, phenomena near black holes, and the nature of gravity 2. Understand how the first stars and galaxies formed, and how they changed over time into the objects recognized in the present universe 3. Understand how individual stars form and how those processes ultimately affect the formation of planetary systems 4. Create a census of extrasolar planets and measuring their properties



Tables 2.2.a-2.2.d are largely comprised of two types of missions: strategic and Principal Investigator-led (PI-led). Strategic missions are the backbone of the science roadmaps in each area and are usually large and multi-purpose in scope. Strategic missions are generally assigned to a NASA Center to implement, with science instruments and many platform components selected in open competition. Competed missions are employed to meet focused science objectives via innovative mission proposals. Competed missions are generally solicited as complete missions via open Announcements of Opportunity, and each is led by a PI. Because the decadal surveys tend to group missions by size category, one significant challenge is to integrate small, medium, and large missions into a single list for each science area, creating a balanced portfolio that includes all three types of missions as well as suborbital and R&A programs.

The largest factors driving the variance between NRC decadal survey priorities and final implementation priorities are pecuniary. Within NASA, cost increases on missions in development limit the pace at which new and smaller missions can be initiated. Externally, outyear budget horizons are lower today than at the time NRC decadal survey priorities were set. Nevertheless, NRC decadal survey priorities remain the principal determinant of the priority order of space science missions in Table 2.2.

Overall, the mission set described in Tables 2.2.a-2.2.d is consistent with the budget projections through 2011 provided in the President's Fiscal Year 2007 request (1 percent growth through 2011) and inflationary growth (2.4 percent assumed) for 2012–2016. The NASA Authorization Act of 2005 authorized higher levels in FY2007 and FY2008, but final appropriations are not yet available. The outyear budget horizon is lower in the FY07 budget request than projected in prior years in this decade, making the task of prioritization both more important and more challenging.

The cost classifications of some missions ("large", "moderate", etc.) are those given in the endorsing document, and do not necessarily correspond to their current costs. Projected launch dates are shown in parentheses. The tables of mission priorities will need to be reconsidered with the release of new decadal surveys and other NRC reports and science task force reports, and with the selection of competed missions and other programmatic changes. They will be updated in each subsequent edition of this Plan, nominally every three years.

2.2.1 Earth Science Mission Priorities and Rationale

In Earth Science, a major challenge is to prioritize pathfinder missions that make new global measurements to address unanswered questions and reduce remaining uncertainties with systematic missions that maintain continuity of key measurements awaiting transition to operational systems managed by other agencies. The former enable researchers to probe the processes involved in global change via first-time global measurements. These often involve active remote sensing (via radars and lidars) that are more challenging to implement, and more in keeping with NASA's role as a research and technology agency. The latter build on past missions (often using newer technologies) to provide long-term continuity of measurement for those parameters that are indicators of variability and trends in global climate change and that aid in distinguishing natural from human-induced change.

Recognizing that both types of missions are crucial to the overall Earth Science effort, the priority list for missions currently in development assigns highest priority to missions that fulfill Legislative or Executive Branch mandates and interagency commitments. The major factors in systematic mission priorities are the importance of the measurement to global change research and the maturity of the operational transition plan. These are followed by missions that will make first-time global measurements. The two pathfinder missions, having been selected within the same competitive process, do not have a relative priority other than that inferred from their respective launch dates. The future representative measurements are not listed in priority order. The forthcoming first NRC decadal survey for Earth science will identify science community priorities for future measurements, as well as begin to address issues arising from recent changes in the NPOESS program. Also influencing the priorities are the U.S. Climate Change Science Program (CCSP), the

Table 2.2a

Earth Science Mission Priorities	
Missions	Priority Rationale
NPOESS Preparatory Project [2009] Strategic mission - Systematic measurement	Required for continuity of several key climate measurements between the Earth Observing System and NPOESS. Implementation of the NPOESS Presidential Decision Directive of 1994. Joint mission with the NPOESS Integrated Program Office
Landsat Data Continuity Mission (LDCM) [2010] Strategic mission - Systematic measurement	Required for continuity of long-term global land cover change data; post-LDCM land imagery acquisition by an operational agency is planned. Mandated by the Land Remote Sensing Policy Act of 1992. Joint mission with USGS
Ocean Surface Topography Mission (OSTM) [2008] Strategic mission - Systematic measurement	Required for continuity of ocean altimetry; planned as part of a transition to operational agencies. Joint mission with CNES, NOAA and EUMETSAT
Glory [2008] Strategic mission - Initializes a systematic measurement	Addresses high priority objective of the U.S. Climate Change Science Program. Measure global aerosols and liquid cloud properties and solar radiation. Mandated by the President's Climate Change Research Initiative of 2001
Orbiting Carbon Observatory (OCO) [2008] Competed mission - Earth System Science Pathfinder	Nearing completion of development. First global measurement of CO_2 from space; small Earth science mission
Aquarius [2009] Competed mission - Earth System Science Pathfinder	In advanced stage of development. First global measurement of sea-surface salinity from space; small Earth science mission. Joint mission with Argentina
Global Precipitation Measurement (GPM) [2012] Strategic mission - Initializes a systematic measurement	Recommended by 2005 interim report of decadal survey committee; extend spatial coverage to global and temporal coverage to every 3 hours with constellation
Earth System Science Pathfinder (ESSP) [2014] – TBD Competed mission	Could address one of the future representative mission elements below; focus and relative priority to be determined using 2007 decadal survey; solicitation no earlier than 2008 for 2014 launch
Future Representative Mission Elements *(unprioritized)*: Changes in Earth's Ice Cover Global Ocean Carbon, Ecosystems and Coastal Processes Global Soil Moisture Global Wind Observing Sounder Multi-spectral Atmospheric Composition Sea Surface and Terrestrial Water Levels Vegetation 3-D Structure, Biomass, Disturbance Wide-swath All-weather Geodetic Imaging	Mission concept definitions and priorities to be determined after the 2007 decadal survey is available. Mission concept studies will likely result in integrating several of these elements into a single mission based on common or compatible technologies and observing techniques. The resulting mission concept set is likely to be a mix of strategic and competed missions

Oceans Action Plan, and the U.S. Integrated Earth Observation Strategy, which plans the U.S. contribution to the Global Earth Observation System of Systems (GEOSS).

2.2.2 Planetary Science Mission Priorities and Rationale

While NASA conducts missions to a broad range of solar system targets, Mars remains the prime target for sustained science exploration because: (1) the ability to address all five planetary science objectives at Mars, coupled with its accessibility, make Mars a unique scientific target in the solar system; (2) Mars exploration has progressed to the level where scientific investigations require multiple assets that form a temporally and spatially interrelated infrastructure on the surface and in orbit; and, (3) SMD's Mars missions provide a foundation of scientific knowledge to enable future human exploration and Mars is specifically called out as a high-priority target in the President's Vision for Space Exploration. In addition, recent discoveries of atmospheric methane and a wet past have highlighted Mars' unique place in the solar system. Furthermore, the missions required to meet the goals of Mars exploration are highly interdependent. For example, science orbiters characterize landing sites and provide communications links for surface investigations.

The most recent NRC decadal survey in Planetary Science (*New Frontiers in Solar System Exploration*, NRC 2003) prioritized Mars missions independently from missions to other solar system bodies and this distinction is continued in this Plan. Thus, two prioritized lists of missions are maintained for Planetary Science. NASA seeks to maintain a balance in solar system exploration between detailed investigations of individual bodies and broader-based exploration of multiple bodies throughout the solar system.

Priorities for missions on both lists have been assigned based on development stage, strategic value and launch date. In general, missions in development are assigned higher priority than missions not yet initiated, with strategic missions given higher priority than PI-led missions within each phase of development. Missions to the outer planets tend to be strategic due to their cost. Orbital mechanics also influence launch order; delays of months in launch can translate into addition of years of transit time. All other considerations being equal, missions are prioritized according to launch date, unless a mission has significant heritage in a high-priority goal of the NRC decadal survey.

In the broader program of solar system exploration, the most recent NRC decadal survey in Planetary Science identified one large mission, a Europa geophysical explorer. Although funding resources have thus far been insufficient to begin implementation of an outer planets mission of this scale in the time frame of that survey (2003–2013), NASA is working toward that end. The decadal survey also identified five priority medium-class missions, and NASA designed the New Frontiers competed mission program to create opportunities to implement them. One, the New Horizons/

Table 2.2.b.1

Planetary Science Mission Priorities and Rationale—Mars

Missions	Priority Rationale
Mars Science Laboratory [2009] Strategic mission	High-priority medium mission in 2003 decadal survey in advanced stages of development; roving analytical laboratory to address questions of habitability
Phoenix [2007] Competed mission – Mars Scout	Small Mars mission in final stages of development; fixed lander in northern polar plains of Mars
Mars Science Orbiter [2013] Strategic mission	Provides science responsive to 2003 decadal survey and required communications services
Astrobiology Field Lab, Mid-Size Rovers, or Network Landers [2016] Strategic mission	Provides science responsive to 2003 decadal survey; choice to be determined in part based on Mars Science Laboratory and Mars Reconnaissance Orbiter results
Mars Scout-11 [2011] Competed mission – Mars Scout	Opportunity for a small Mars mission to capitalize on new science

Table 2.2.b.2

Planetary Science Mission Priorities and Rationale—Other Solar System Destinations	
Missions	Priority Rationale
Juno [2011] Competed medium mission - New Frontiers	High-priority, medium-class mission in 2003 decadal survey; also high priority in 2003 Heliophysics decadal survey. Jovian gravity, composition and magnetic fields
Dawn [2007] Competed small mission - Discovery	Small planetary mission in final stages of development; investigations of the two large asteroids Ceres and Vesta
Discovery 2006 [2013] Competed small mission	Next small planetary mission; three mission concepts selected to proceed to Phase A, down-select anticipated in 2007
Europa Explorer [beyond 2016] Strategic mission	Highest-priority large mission in 2003 decadal survey; probe habitability and accessibility
Titan/Enceladus Explorer [beyond 2020] Strategic mission	Second highest-priority strategic mission in the 2006 solar system exploration roadmap; survey Titan's atmosphere and surface; Enceladus portion TBD
New Frontiers 3 [2015] Competed medium mission	Opportunity for high-priority medium class missions in 2003 decadal survey; solicitation NET 2008 following assessment of the field of candidate missions
Discovery 2008 [2015] Competed small mission	Opportunity for a small planetary mission; more than one mission may be selected; solicitation NET 2008

Pluto Express, was launched in 2006; a second is the Juno mission to Jupiter now in development. In parallel, NASA is working on high-priority science that can be accomplished with small (Discovery) missions; the decadal survey recommended a launch rate of one such mission every 18 months. The Discovery 2006 and 2008 entries reflect planned solicitations and may represent more than one actual mission for each solicitation.

2.2.3 Heliophysics Mission Priorities and Rationale

The Heliophysics flight strategy is to deploy modest-sized missions, frequently, to form a small fleet of solar, heliospheric, and geospace spacecraft that function in tandem to understand the coupled Sun-Earth system. Operating this group of spacecraft as a single observatory (the Heliophysics Great Observatory) allows measurements across distributed spatial scales to be linked with a variety of models to fill observational gaps and provide predictions of tomorrow's space weather. Continuing and evolving this distributed asset to meet the needs of the Vision for Space Exploration are among the Heliophysics Program's highest priorities.

Resources are available to implement a portion of the NRC decadal survey for priorities set in heliophysics (*From the Earth to the Sun: A Decadal Survey for Solar and Space Physics*, NRC 2003), *albeit* on a longer time scale, which impacts the envisioned science synergies between missions. The Solar Probe, Ionosphere/Thermosphere Storm Probes, Inner Heliospheric Sentinels, Geospace Electrodynamic Connections, and Magnetospheric Constellation missions must necessarily be implemented outside the decadal time frame of the survey (2004–2014).

Mission prioritization has been determined by the Helio–physics roadmap process, which resulted in concept mission studies and mission priorities aligned with the available funding profiles based on the factors of scientific importance and strategic value to NASA's goals. The list includes also two Explorer missions, a Medium Explorer (MIDEX) and a Small Explorer (SMEX), that will be competitively selected through future Announcements of Opportunity to best meet heliophysics science objectives.

Considerable synergy exists between Heliophysics and other science areas. For example, the Solar Dynamics Observatory is a high priority in the astrophysics decadal survey, and Planetary Science's JUNO mission is the third mid-scale mission in the Heliophysics decadal survey.

Table 2.2.c

Heliophysics Mission Priorities and Rationale

Missions	Priority Rationale
Solar Dynamics Observatory (SDO) [2008] Strategic Mission: Living with a Star	#3 priority space-based moderate initiative in the astrophysics decadal survey (2001), nearing completion of development
Interstellar Boundary Explorer (IBEX) [2008] Competed Mission: Small Explorer	Nearing completion of development; image the 3-D boundary of the heliosphere
Magnetospheric Multiscale (MMS) [2013] Strategic Mission: Solar Terrestrial Probe	#1 priority mid-scale mission in 2003 decadal survey; study microphysics of three fundamental plasma processes: magnetic reconnection, energetic particle acceleration, and turbulence
Radiation Belt Storm Probes (RBSP) [2012] Strategic Mission: Living with a Star	#2A priority mid-scale mission in 2003 decadal survey; observe how radiation environments hazardous to satellites and humans form and change
Explorer/MIDEX [2013] Competed Mission: Medium Explorer	2008 solicitation for launch in 2013 for new science and vitality of the Heliospheric Great Observatory; the 2003 decadal survey endorsed continuation of a vigorous Explorer program
Explorer/SMEX [2015] Competed Mission: Small Explorer	2010 solicitation for launch in 2015 for new science and vitality of the Heliospheric Great Observatory; the 2003 decadal survey endorsed continuation of a vigorous Explorer program
Ionosphere/Thermosphere Storm Probes (ITSP) and Inner Heliospheric Sentinels (IHS); [beyond 2015] Strategic Missions: Living with a Star	#2B and #4 priority mid-scale missions in the 2003 decadal survey; order between these two missions not yet determined. Space weather missions in differing orbits to enable prediction
Solar Orbiter [beyond 2013] Strategic Mission: Living with a Star	#4 priority small-scale mission in 2003 decadal survey; partnership with ESA to measure properties and dynamics of solar wind
Solar Probe [beyond 2016] Strategic Mission	High priority flagship-scale mission in 2003 decadal survey to probe the processes controlling heating of the solar corona; requires new funding
Geospace Electrodynamic Connections (GEC) [beyond 2016] Strategic Mission: Solar Terrestrial Probe	#5 priority mid-scale mission in 2003 decadal survey to determine the fundamental processes coupling the ionosphere and magnetosphere

2.2.4 Astrophysics Mission Priorities and Rationale

The most recent NRC decadal survey *Astronomy and Astrophysics in the New Millennium* (2001) lists the James Webb Space Telescope as its top-ranked major space-based initiative. The recent NRC report *Assessment of Options for Extending the Life of the Hubble Space Telescope* (2005) strongly endorsed the fourth Hubble servicing mission. Table 2.2.d reflects the other top priorities of the decadal survey, as well as its endorsement of "the continuation of a vigorous Explorer program." Also of influence are the NRC report *Connecting Quarks with the Cosmos* (2003) and the National Science and Technology Council response *Physics and Astronomy in the 21st Century* (2004). The Beyond Einstein program is in part an implementation of these reports. NASA (in partnership with the DOE) has requested the NRC to form a committee to recommend which Beyond Einstein mission to implement in the first opportunity identified, and the NRC's report is expected by September 2007, in time for input to the FY2009 budget. The first Beyond Einstein mission is scheduled for a launch in approximately 2015–2016 (the exact date depends on which mission is selected to proceed first: Joint Dark Energy Mission, Constellation-X, Laser Interferometer Space Antenna, Inflation Probe, or Black Hole

Table 2.2.d

Astrophysics Mission Priorities

Missions	Priority Rationale
James Webb Space Telescope (JWST) [2013] Strategic mission	Top-ranked space-based "Major Initiative" in the 2001 decadal survey; infrared successor to Hubble to image first light from the Big Bang
Hubble Space Telescope – Servicing Mission 4 (HST-SM4) [2008] Strategic mission	Continued operation endorsed by 2001 decadal survey; Report of the HST-JWST Transition Panel (2003). Shuttle mission to replace instruments and equipment to extend HST life
Gamma-ray Large Area Space Telescope (GLAST) [2007] Strategic mission	Top-ranked space-based "Moderate Initiative" in the 2001 decadal survey; all-sky survey of high-energy gamma ray sources
Herschel Space Observatory (Herschel) [2008] **Planck Surveyor (Planck) [2008]** Instruments on international missions	ESA mission with NASA as partner; U.S. participation endorsed in the 2001 decadal survey; star formation and cosmic background radiation, respectively
Kepler [2008] Competed mission - Discovery	The 2002 solar system exploration decadal survey "endorses the fundamental importance of the Discovery line of missions." Survey 100,000 stars to search for Earth-size planets
Wide-field Infrared Survey Explorer (WISE) [2009] Competed mission - Explorer	2003 selection in MIDEX (Explorer) competition. The 2001 decadal survey "endorses the continuation of a vigorous Explorer Program". All-sky survey in infrared for a wide range of studies
Stratospheric Observatory for Infrared Astronomy (SOFIA) [2010 Initial Operating Capability] Strategic Mission	Endorsed as a "Moderate" program in the 1991 decadal survey; reaffirmed in the 2001 decadal survey. Observations of stellar and planet-forming environments.
Explorer/MIDEX [2013] Competed mission – Medium Explorer	2008 solicitation for launch in 2013. The 2001 decadal survey "endorses the continuation of a vigorous Explorer Program"

Astrophysics Mission Priorities—Continued

Future strategic missions planned for launch after 2015 (unprioritized)	*The priorities for those missions that launch after 2015 will be likely be re-established following the release of the next decadal report of the Astronomy and Astrophysics Decadal Survey (expected by 2010 or 2011).*
Space Interferometry Mission (SIM) Strategic Mission	Endorsed by the 1991 decadal survey as a new Moderate Program; re-endorsed in 2001 decadal survey. Characterize other planetary systems
Beyond Einstein-1	One of the five missions below, based on the recommendation of the NRC in a study now underway for this purpose:
Constellation-X (Con-X)	Second-ranked space-based "Major Initiative" in the 2001 decadal survey; x-ray observation to study black holes, dark matter and energy
Joint Dark Energy Mission (JDEM)	Endorsed by the NRC *Connecting Quarks with the Cosmos* report (2003); measure cosomological parameters of the expanding universe, joint mission with DOE
Laser Interferometer Space Antenna (LISA)	Second-ranked space-based "Moderate Initiative" in the 2001 decadal survey. Measure gravitational waves; joint mission with ESA
Black Hole Finder Probe (BHFP)	One potential implementation (the Energetic X-ray Imaging Survey Telescope) is the fourth-ranked space-based Moderate Initiative in the 2001 decadal survey; census of black holes
Inflation Probe (IP)	One potential implementation (Cosmic Microwave Background polarization) is endorsed by the NRC *Connecting Quarks with the Cosmos* report (2003); stringent test of inflationary cosmology and Big Bang physics
Terrestrial Planet Finder (TPF) Strategic mission	Third-ranked space-based "Major Initiative" in the 2001 decadal survey; characterize all components of other planetary systems, image Earth-like planets and search for signs of life
Beyond Einstein-2	One of the four missions not selected as the Beyond Einstein-1

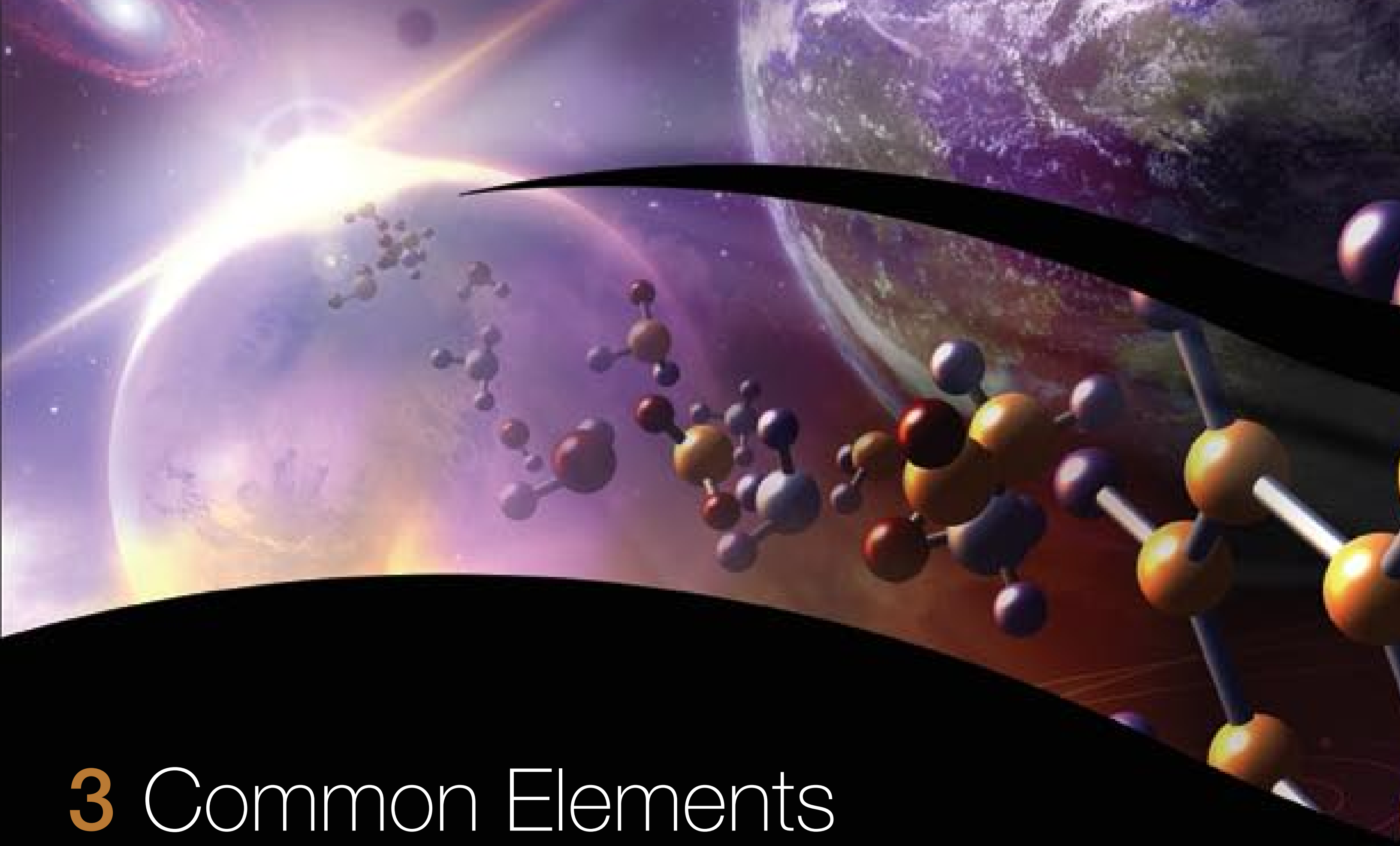
Finder Probe). A second Beyond Einstein mission will be one of the remaining four Beyond Einstein Program missions.

The President's Vision for Space Exploration also called for NASA to "conduct advanced telescope searches for Earth-like planets and habitable environments around other stars". The Navigator Program is NASA's implementation of this objective and is represented by the Space Interferometry Mission (SIM) and Terrestrial Planet Finder (TPF). Both the 1991 and 2001 decadal surveys endorsed SIM, and TPF was endorsed in 2001, to search for exo-planets and perform other groundbreaking astrophysics.

The Astrophysics list includes two new Explorer missions, a MIDEX and a SMEX; as these are to be competitively selected in future Announcements of Opportunity, their science goals are not yet defined. Because the Explorer and Discovery competitions cut across divisional boundaries, there is no guarantee that the Astrophysics Division will fly missions from any specific future solicitation. Their number and inclusion here are based on the statistics of previous awards amongst the SMD divisions in these programs.

The priorities for those missions that launch after 2015 will be likely be re-established following the release of the next astronomy and astrophysics decadal survey (expected by 2010 or 2011).

Night Launch of the Solar Terrestrial Relations Observatory (STEREO) is a Brilliant Sight



3 Common Elements of Strategy

Chapter 3

Common Elements of Strategy

Central to SMD's strategy for accomplishing NASA's science goals and objectives and meeting the multitude of challenges set forth in the guiding documents are our SMD principles. These principles have been foundational to SMD's accomplishments in the past and will lead to revolutionary advances in science in the future. Research and analysis (R&A) will also continue to be crucial to science discoveries in the coming decade. Our strategy places a strong emphasis on providing opportunities for the best minds and organizations to compete to accomplish the greatest science and technological advancement with reasonable risk. Toward these ends, SMD will continue to use proven strategies for program development and mission planning while investing wisely in advanced technology and in computation and information management. SMD will build on its network of partnerships and provide leadership in developing the workforce for the future through robust education and public outreach programs. The principles are listed below, and major program elements are described in greater detail in the following sections.

3.1 SMD Principles

- **Investment choices first consider scientific merit.** SMD will use open competition and scientific peer review as the primary means for establishing merit for selection of research and flight programs.
- **Active participation by the research community outside NASA is critical to success.** SMD will engage the external science community in establishing science priorities, preparation and review of plans to implement those priorities, analysis of requirements trade studies, conduct of research, and evaluation of program performance.
- **The pace of scientific discovery is fueled by prompt, broad, and easy access to research data.** SMD will ensure vigorous and timely interpretation of

mission data by requiring that data acquired be made publicly available as soon as possible after scientific validation.

- **Partnerships are essential to achieving NASA's science objectives.** Other nations and agencies are engaged in space and Earth science. NASA and SMD will partner with other national and international organizations to leverage NASA's investment and achieve national goals.

- **Partnerships are essential to realizing relevant societal benefits from NASA's research.** Beyond increasing scientific understanding, many NASA programs produce results with practical societal benefits. NASA and SMD will forge partnerships with other U.S. Federal agencies to facilitate their use of NASA research data and science results in their operational products and services.

- **The NASA mandate includes broad public communication.** SMD will convey the results and excitement of our programs through formal education and public engagement. SMD will seek opportunities to promote student interest in science, technology, engineering, and mathematics disciplines and careers.

- **Sustained progress in advancing U.S. space and Earth science interests requires investments across a broad range of activities.**

    - The range of activities include basic research to understand the scientific challenges, technology development to enable new capabilities, space mission development to acquire the vital new data, and supporting science and infrastructure systems to ensure delivery of high value scientific results to the science community and the general public.

    - NASA will consider the long-term sustainable health of the necessary scientific disciplines and communities that enable progress towards NASA's scientific objectives when determining the mix of research and mission investments.

    - SMD will establish mission lines that enable competitive selection, funding, and management of classes of missions based upon the focus of the science outcome. Some missions are focused on specific science questions, and some missions are focused on providing foundational data sets that researchers will be using for decades to come. In the first case, PI leadership has proven to be a successful strategy for maintaining science focus and technical discipline. In the second case, strategic missions with guidance from a representative science team is more appropriate.

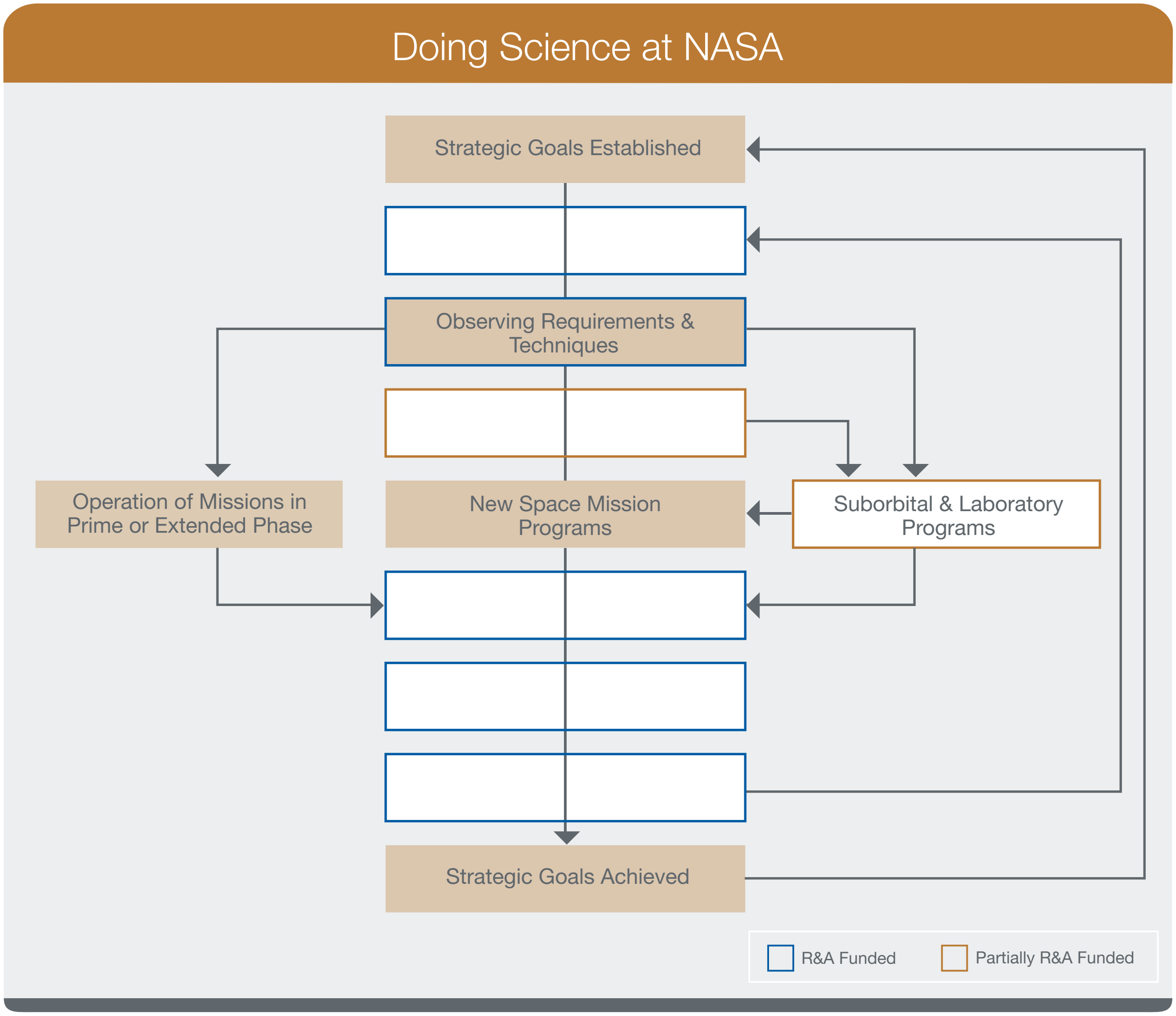
    - NASA and SMD will maintain essential technical capabilities at the NASA Centers to plan for the future, lead strategic missions, and assist NASA-sponsored community research and mission developments.

- **The Nation looks to NASA for innovation in space.** SMD will accelerate the pace of scientific discovery through advanced technologies that will enable and enhance new space missions; shorten the mission development cycle; and speed the use of observation, model, and research results in the planning of future and the operation of current missions and systems.

3.2 Research Planning and Implementation

Scientific research and analysis (R&A) is the core of NASA's science activity. The primary purpose of this Plan is to lay out a route to achieve NASA's science objectives. While much of this Science Plan describes space missions and their sequencing as the most visible aspects of NASA's science programs, the necessary stepping stones along that route are supplied by the scientific R&A programs. R&A programs provide not only the scientific foundation on which the rest of the science research enterprise is built, but much of the superstructure into which the individual mission efforts are integrated.

Figure 3.1



3.2.1 Role of Scientific Research and Analysis

Figure 3.1 shows the conceptual path of scientific progress in SMD, which is adapted as needed by each of the four science areas in this Plan. R&A programs develop the pioneering theories, techniques, and technologies that result in missions. These programs enable exploration of innovative concepts in sufficient depth to determine whether they are ready for incorporation in space missions. The results of R&A also inform and guide the scientific trades and other choices that are made during the development of missions. Sponsored researchers guide the operation of robotic missions, selecting targets for observation or sampling. R&A programs then capitalize on the new information obtained by the missions to advance understanding across the breadth of NASA science. It is R&A that turns the data returned from NASA missions into knowledge; it is this knowledge that addresses NASA's strategic objectives. NASA cannot accomplish its mission and the objectives of the Vision for Space Exploration without scientific R&A.

NASA-sponsored scientific R&A comprises an ever-evolving suite of individual PI-proposed investigations that cover the complete range of science disciplines and techniques essential to achieve NASA's science and exploration objectives. The diversity of the program is one of its critical components. NASA's R&A activities cover all aspects of basic and applied supporting research and technology in space and Earth sciences, including, but not limited to:

- theory, modeling, and analysis of mission science data;
- aircraft, stratospheric balloon, and suborbital rocket investigations;
- experiment techniques suitable for future space missions;
- concepts for future space missions;
- advanced technologies relevant to future space missions;
- techniques for and the laboratory analysis of extraterrestrial samples returned by spacecraft;
- determination of atomic and composition parameters needed to analyze space data as well as returned samples from the Earth or space;
- Earth surface-based observations and field campaigns that support science missions;
- interdisciplinary research to use findings from missions to answer science questions;
- integrated Earth system models;
- systems engineering approaches for applying science research data to societal needs (especially in Earth science and heliophysics); and,
- applied information systems research applicable to NASA objectives and data.

Once a NASA science mission launches and begins returning data, data analysis programs sponsor the analysis of scientific data returned by the mission with the goal of maximizing the scientific return from NASA's investment in spacecraft and other data-collection sources. The data analysis program is fundamental to achieving NASA's science objectives because it funds data analysis during and after a spacecraft's lifespan. NASA also funds data archiving and distribution services and partners with other Federal agencies to sustain these over the long term. Complementary investigations expand data analysis opportunites. For instance, laboratory measurements, suborbital observing campaigns, and ground-based field campaigns during and after missions greatly enhance the quality of the information that can be recovered from spacecraft data. Finally, they enable further exploration of unexpected results.

Open data policies and R&A funding enable research on space mission and related data by a broad range of researchers who publish their results in the open scientific literature. For those scientific investigations, such as weather and climate research and solar flare observation, that have practical societal benefits, scientific assessments and applications benchmarking assure their results are conveyed to agencies that can use them to improve the essential services they provide to the Nation. Results of NASA-sponsored research in areas such as the space environment, planetary atmospheres, and lunar surface composition become the scientific basis for decisions on human exploration systems and activities. As is the nature of science, answers to today's questions lead to new questions and goals for the future.

Achieving NASA's objectives requires a strong scientific and technical community to envision, develop, and deploy space missions and to apply results from these missions for the benefit of society. Such a community currently exists within the United States at universities, government facilities, and industrial laboratories. This robust U.S. research community is essential to the successful formulation, implementation, and exploitation of NASA missions.

Determining the optimal mix of investment among R&A programs, large and small missions, data management, and related activities is a challenge. Using advice from the NRC and the NAC, NASA makes that determination to best achieve its goals and objectives within the overall resource levels provided by the President and the Congress. As noted earlier, projected outyear funds are less than anticipated a year ago, and, as a result, R&A funds for data analysis and future instrument concepts are less than projected a year ago. As we move forward, NASA will work to assure an effective mix of investments across all the activities required to achieve its science goals.

3.2.2 Research Solicitation and Selection

To optimize quality and preserve scientific integrity, NASA uses open competition and scientific peer review as the primary means for establishing merit for its flight and research programs. Open and competitive merit selection is fundamental to all aspects of NASA's science programs. Participants are selected through a broadly advertised, open, competitive process. That is, opportunities are open to all proposers, within fixed rules, via public announcement, and selections are based primarily on scientific and technical merit as evaluated by independent peer review.

Proposals for R&A investigations are solicited, usually annually, through NASA Research Announcements (NRAs) developed by NASA research program staff. The majority of NASA's research investigations are solicited through the SMD's annual omnibus NRA, Research Opportunities in Space and Earth Sciences (ROSES). ROSES program elements span the types of science activities described above regardless of budget category, including R&A, supporting research and technology, suborbital investigations, data analysis from active missions, archival data analysis, guest investigator programs, science teams including participating scientists and interdisciplinary scientists, multimission science integration, modeling and assessment, Earth system science applications, and E/PO activities.

Proposals to participate in NASA's science missions are solicited through Announcements of Opportunity (AOs) developed by NASA mission program staff in collaboration with the appropriate program office at a NASA Center. Participation in a NASA space mission includes development of complete PI-led missions from concept to operation, development of instruments and other systems for NASA-led missions, participation in the mission science team responsible for the scientific success of a mission, and analysis of mission data.

3.2.3 Cross-cutting Research in Astrobiology

Questions about life in the solar system and the galaxy are central to the Vision for Space Exploration. The Vision directs NASA to explore Mars, Jupiter's moons, and other solar system bodies to search for evidence of life and to conduct advanced telescope searches for habitable environments on planets around other stars. Astrobiology is a new field, built by NASA a decade ago on the framework of its longstanding exobiology efforts. It brings together scientists from diverse disciplines including Earth and planetary science, astrophysics, heliophysics, microbiology, evolutionary biology, and cosmochemistry to develop the scientific foundation needed to pursue these space exploration goals.

Astrobiology and the missions it supports bring modern science to bear on questions that, in one form or another, are as old as humanity itself: How does life begin and evolve? Does life exist elsewhere in the universe? What is the future of life on Earth and beyond? NASA has developed the tools and capabilities that have brought these questions from the realms of speculation and philosophy to the realm of science. As seen in Table 2.1, relevant answers are pursued in the research programs and flight missions of all four SMD Divisions, with the Planetary Science Division providing the institutional home for the core Astrobiology Research and Analysis (R&A) program that serves to integrate these efforts.

The NRC's *An Assessment of Balance in NASA's Science Programs* (2006), describes well the role astrobiology plays in SMD's science portfolio:

"The decadal surveys for astrophysics and for solar system exploration both embraced astrobiology as a key component of their programs, with the questions encompassed by astrobiology serving as overarching themes for the programs as a whole. The missions put forward in the solar system exploration survey are all key missions in astrobiology, whether they are labeled as such or not. And issues and missions related to astrobiology represent one of the key areas of interest identified in the astronomy and astrophysics communities.

Astrobiology provides the intellectual connections between otherwise disparate enterprises. NASA's astrobiology program creates an integrated whole and supports the basic interdisciplinary nature of the field. Further, the Vision is, at its heart, largely an astrobiology vision with regard to the science emphasis. In developing the future of the program, the missions actually feed forward from the basic science. Astrobiology is just beginning the type of synthesis and integration that will allow it to provide science input for future mission development. Without it, the science and the scientific personnel will not be in place to support the missions when they do fly.

At a time of increasing desire for cross-disciplinary programs, astrobiology represents an outstanding example of the development of a successful new interdisciplinary area."

The Astrobiology R&A program is itself highly interdisciplinary. Among its subjects are research on how the ingredients of life may have been formed in space or in primitive planetary environments; how and where habitable environments form and what makes them habitable; how evidence of life may be detected, whether in rocks from Mars, from the ancient Earth, or on planets around other stars; how ecosystems function in extreme environments on Earth; and how habitable environments are affected by their interaction with the space environment, whether through radiation or through the infall of cosmic material large and small. To conduct this interdisciplinary research, A diverse community of scientists works together across discipline boundaries in search of a common understanding of nature, guided by an Astrobiology Roadmap (*http://astrobiology.arc.nasa.gov/roadmap/*) that identifies the context and connections with other space and Earth science activities. While the FY07 budget reduced the planned outyear budget for Astrobiology R&A, it remains one of SMD's largest research programs.

Through Astrobiology R&A graduate students and undergraduates in diverse disciplines are teaching each other the languages and concepts of their fields, and researchers at all career stages are conducting interdisciplinary collaborations that broaden their scientific perspectives, abilities, and aspirations. The excitement of this dynamic field is attracting many of the best students and researchers and has led to increased support for space exploration. The Astrobiology community is stitching together the fabric of Earth and space science to understand how it supports the formation and flourishing of life.

3.3 Mission Planning and Development

Flight Mission Planning

The National Aeronautics and Space Act of 1958 (Space Act) established NASA as an aerospace research and development agency that sponsors and conducts flight missions to obtain data in furtherance of its objectives. In SMD, flight missions range from suborbital projects—including balloons, sounding rockets, and airplanes—to interplanetary probes and flagship observatories. All investigations and missions selected and flown must respond to Agency goals and strategic objectives. Mission opportunities are open to all proposers, within fixed rules, via public announcement, and selections are based primarily on scientific and technical merit as evaluated by independent peer review. Foreign partners are frequent and valued participants in joint missions. The partnerships are generally conducted on a cooperative, no-exchange-of-funds basis. NASA also works closely with a number of other Federal agencies to implement and support our flight missions.

In planning missions, SMD uses two distinct models. “Strategic missions” are major undertakings whose goals and objectives are developed with significant community involvement and which are managed directly by a NASA Center. These missions are highly complex, with decade-long development phases and high cost ceilings. Strategic missions typically include focused technology development within the project structure. Instruments and other components of the mission are usually openly competed. Strategic missions generally address multiple science goals of high strategic value, and their science and technical requirements are broad and very challenging.

In contrast, “PI-led missions” are cost-capped missions, addressing narrowly focused science objectives that can be addressed by a single mission led by a single PI. Complete mission teams are assembled and led by the PI. In order to ensure that PI-led missions remain within or close to their cost cap, they must be technically mature when proposed. A wide range of organizations may manage a PI-led mission, such as a NASA Center, a university, a nonprofit organization, or a commercial entity. A NASA Center program office is assigned to provide management oversight (e.g., Marshall Space Flight Center for Discovery and New Frontiers missions, and the Jet Propulsion Laboratory for Mars Scout missions). Selection of a PI-led mission is through a rigorous process of scientific and technical peerreview. The missions proposed as PI-led missions are typically more responsive to recent discoveries than are strategic missions.

SMD meets many of its strategic objectives through “mission lines” which consist of a series of missions within a single program that address a specific set of programmatic and strategic objectives. Missions are implemented within the program on the basis of science priorities, technology readiness, and fiscal resources. These missions may be realized as either strategic or competed missions, as NASA-led or PI-led, and as large, medium, or small missions. Strategic mission lines include Solar Terrestrial Probes (STP), Mars Exploration, Navigator, Living With a Star (LWS), Earth Science Systematic Missions (formerly EOS), and Beyond Einstein. For strategic missions, competed components include instruments, science team, interdisciplinary science and data analysis, and other opportunities. Competed, PI-led mission lines include Discovery, Explorer, Earth Science System Pathfinder (ESSP), Mars Scout, and New Frontiers. The Directorate encourages broad participation in all of its flight missions by the academic community and outside industry.

Beyond the mission lines, where the scope, strategic objectives, and technology challenges require greater leadership and expertise by NASA Centers, SMD implements flagship class missions. Flagship mission costs are generally significantly higher than those of other mission classes, and flagship missions often involve multiple partners. Examples include the Cassini mission now operating at Saturn and the James Webb Space Telescope now in formulation.

Cost Estimation

Sound estimation and management of mission cost is essential to mission success. For both strategic and competed missions, SMD employs NASA-standard processes and independent reviews to ensure each mission’s readiness to proceed to the next stage, beginning with initial selection. As a part of the competed-mission proposal review process, NASA has multiple independent cost estimates and

Table 3.1

Program/Mission Lines

Mission Lines	Mission Class*	Objectives and Features	Example Missions
Earth System Science Pathfinder (ESSP)	Competed, PI-led small missions	Address focused Earth science objectives and provide opportunities for new science investigations.	OCO, Aquarius
Earth Science Systematic Missions	Strategic missions of all sizes	Make new global measurements to address unanswered questions and reduce remaining uncertainties with systematic missions that maintain continuity of key measurements awaiting transition to operational systems managed by other agencies.	NPP, LDCM, OSTM, Glory, GPM
Discovery	Competed, PI-led medium missions	Explore solar system bodies and/or remotely examine the solar system and extrasolar planetary system environments.	Dawn, Kepler
Mars Scout	Competed, PI-led medium missions	Provide regular opportunities for innovative research in support of Mars objectives.	Phoenix
New Frontiers	Competed, PI-led large missions	Explore the solar system with frequent missions that will conduct high-quality, focused scientific investigations designed to enhance our understanding of the solar system.	Juno
Mars Exploration (core)	Strategic medium and large missions	Maximize the scientific return, technology infusion, and public engagement of the robotic exploration of the Red Planet. Each strategic mission has linkages to previous missions and orbiters and landers support each other's operations.	MSL, MSO
Explorers	Competed, PI-led small missions	Provide flight opportunities for focused scientific investigations from space with the Heliophysics and Astrophysics science areas.	WISE, IBEX
Solar Terrestrial Probes (STP)	Strategic medium missions	Execute a continuous sequence of defined strategic projects to provide in-situ and remote sensing observations, from multiple platforms, for the sustained study of the Sun-Earth System.	MMS, GEC
Living With a Star (LWS)	Strategic medium to large missions	Strategic sequences of missions to resolve the highest-priority unknowns in the connected system from the Sun to the Earth.	SDO, RBSP, ITSP, IHS, Solar Orbiter, Solar Probe
Beyond Einstein	Strategic medium and large missions	Complete Einstein's legacy and lead to understanding the underlying physics of the very phenomena that came out of his theories.	Con-X, LISA, JDEM, BHFP, IP
Navigator	Strategic large missions	Interrelated missions to explore and characterize new worlds, enable advanced telescope searches for Earth-like planets, and discover habitable environments around neighboring stars.	SIM, TPF

* Small missions have life cycle costs less than approximately $300M. Mid-size missions have life cycle costs between approximately $300M and $750M. Large missions have life cycle costs in excess of $750M. Flagship missions, in contrast to Mission Lines, are individual strategic missions and are in excess of $1 billion.

schedule assessments made for each proposal using different models and methodologies for reasonability and realism comparisons. These estimates are part of the selection process, both at the initial step and following a concept study review. For directed missions, the projects prepare detailed grass roots estimates and schedules, which are then vetted by the cognizant NASA Center, before their initial confirmation. Concurrently, the NASA Independent Program Assessment Office prepares independent technical and schedule assessments, as well as a cost estimate for the project. SMD also obtains independent cost estimate and schedule assessment at this time. Furthermore, all projects approaching their confirmation review (the required authorization to proceed with implementation) prepare detailed grass roots cost and schedule estimates, again vetted by the cognizant NASA Center. Concurrently, SMD obtains an updated independent cost estimate and schedule assessment, and, on major projects, the Independent Program Assessment Office performs another detailed technical schedule assessment and cost estimate. All three estimates are compared in a cost and schedule reconciliation process to ensure all three are entities employ the same ground rules and assumptions. The estimates are then submitted to the appropriate decision authority. At the time of mission confirmation, these estimates are considered to be accurate to within 20 percent of actual final mission cost.

Space Communications

Spacecraft commanding, control, navigation and data transmission are critical to successful science operations. Early in the study and design phases, the flight mission must make trades in the specification and design of flight subsystems and instrumentation in order to communicate with ground or space relay tracking systems. In addition, the science investigation must be tailored to accommodate existing communications capabilities, or the mission will have included development of new, enabling capabilities as part of the investigation. Flight mission project leaders are responsible for the selection of communications providers whether NASA communications networks, commercial providers, university-resident capabilities, partner-supplied services, or combinations of these.

The conduct of future missions and research will also place an increasing demand on NASA's space communications resources. Improvements to NASA's space communications technologies will continue for both the Deep Space Network (DSN) and Ground Network (GN). Options under consideration include use of arrays of small antennas plus radio-frequency improvements (transmitters, inflatable antennas, transponders, for example), together with optical communications to provide orders-of-magnitude increases in science data rates. Advances in autonomy and onboard intelligence will provide opportunities for space-ground trade offs and alleviate downlink bandwidth constraints.

Launch Services

NASA's Space Operations Mission Directorate (SOMD) is responsible for ensuring access to space for all NASA requirements and conducting appropriate studies and industry coordination on behalf of the Agency. Consistent with law and national policy, NASA and NASA-sponsored payloads are primarily flown on launch vehicles manufactured in the United States. SOMD is responsible for acquiring and managing reliable and cost-effective services and for certifying launch vehicle configurations that are available from existing and emerging commercial providers as necessary to assure access to space for civil missions including cargo, robotic, science, and human space exploration requirements. Under special circumstances, SOMD may request the use of launch services from the Department of Defense subject to interagency concurrence, and/or foreign suppliers subject to approval by the Director of the Office of Science and Technology Policy, consistent with law and national policy. National policy also permits use of a foreign launch vehicle as part of an approved international cooperative mission with launch contributed on a no-exchange-of-funds basis.

To assure continued access to space for science missions planned for launch in the next decade, bold, innovative, and strategic actions must be initiated now, particularly for the medium performance class of launch vehicles. Beyond 2009, a budget threat exists for planetary and Earth science missions launching under the NASA Launch Services contract for the cost of sustaining the medium class launch capability. Cost projections for such missions could seriously jeopardize access to space for NASA's highest priority science missions. The SOMD is examining the launch services marketplace to determine the existence, credibility, and maturity of Alternate Launch Providers (ALP) to satisfy NASA's requirements and priorities. The initial study is complete with a follow-on study in progress to look at cost, technical and schedule risk characterization.

3.4 Advanced Technology

Advances in science are often preceded and enabled by advances in technology. In many cases, fundamentally new tools and techniques are needed to enable new missions. Technology activities in the SMD are, by definition, science-driven—measurement goals, science objectives, and mission requirements drive technology development efforts—and include open, peer-reviewed, competitive solicitations, active management of technology projects, and energetic communication with the full breadth of the technology community.

Technology challenges are identified to bolster capabilities in areas that are crucial to scientific progress at NASA. Currently, key challenge areas are shown in figure 3.2.

SMD's technology program is built on the principle of maintaining a well-balanced, relevant, and sustained program of investments. It consists of the following primary program elements:

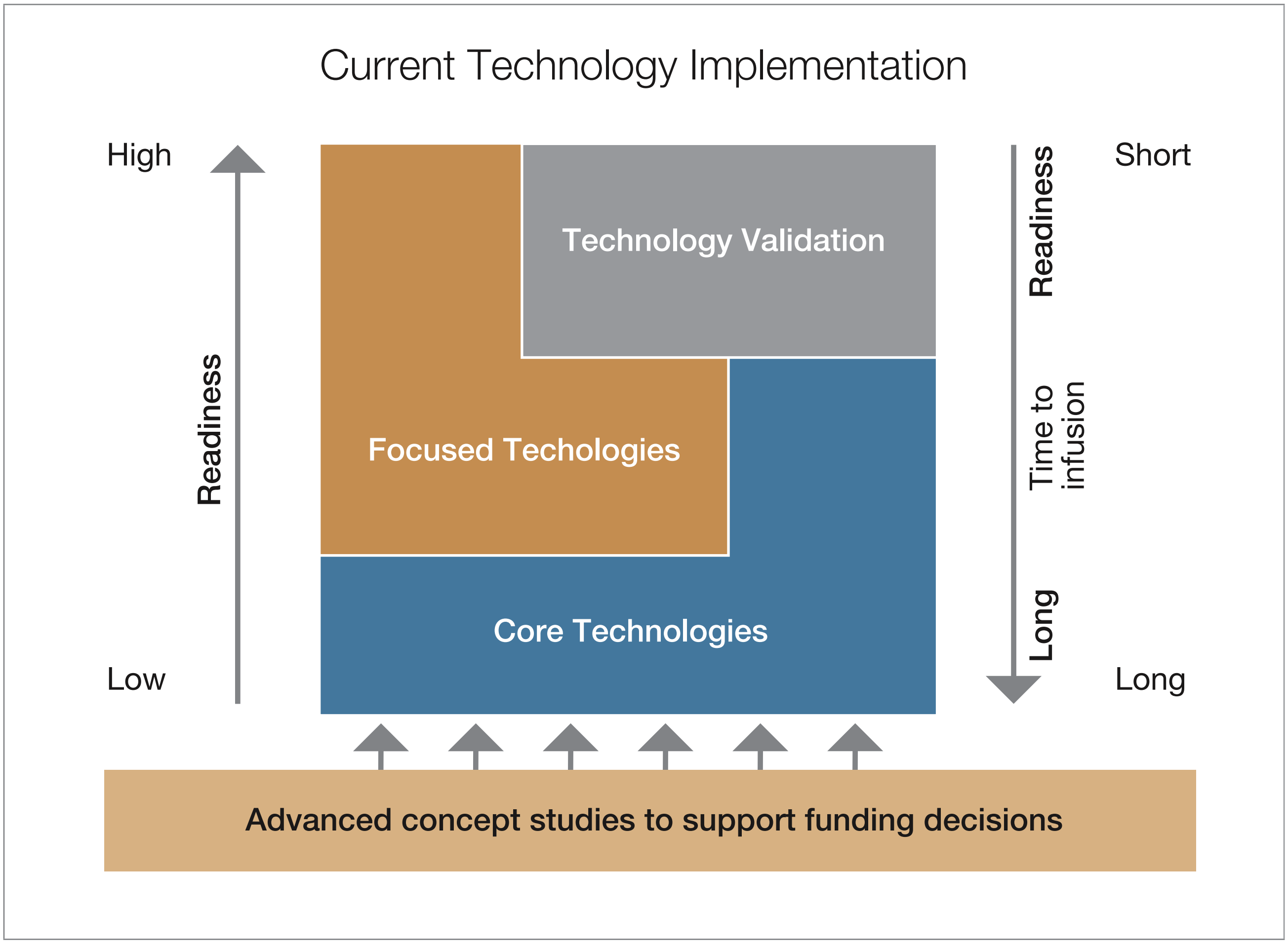
- An aggressive, long-range *core technology program* to enable the next generation of high-performance

Figure 3.2

Selected Key Technology Challenges/Priorities

- New remote sensing technologies to better see, detect, and measure the Earth, the sun, the solar system, and the universe
- Large, lower-cost, lightweight mirrors and space-Deployable Structures for the next generation of large telescopes and antennas
- Novel platforms, including power and propulsion technologies, that can take instruments to new vantage points
- Intelligent distributed systems that enable advanced communications, efficient data processing and transfer, and autonomous operations of land- and space-based assets
- Information synthesis to derive useful knowledge from extremely large data sets through visualization, advanced simulations, analysis, and seamlessly linked models

Figure 3.3

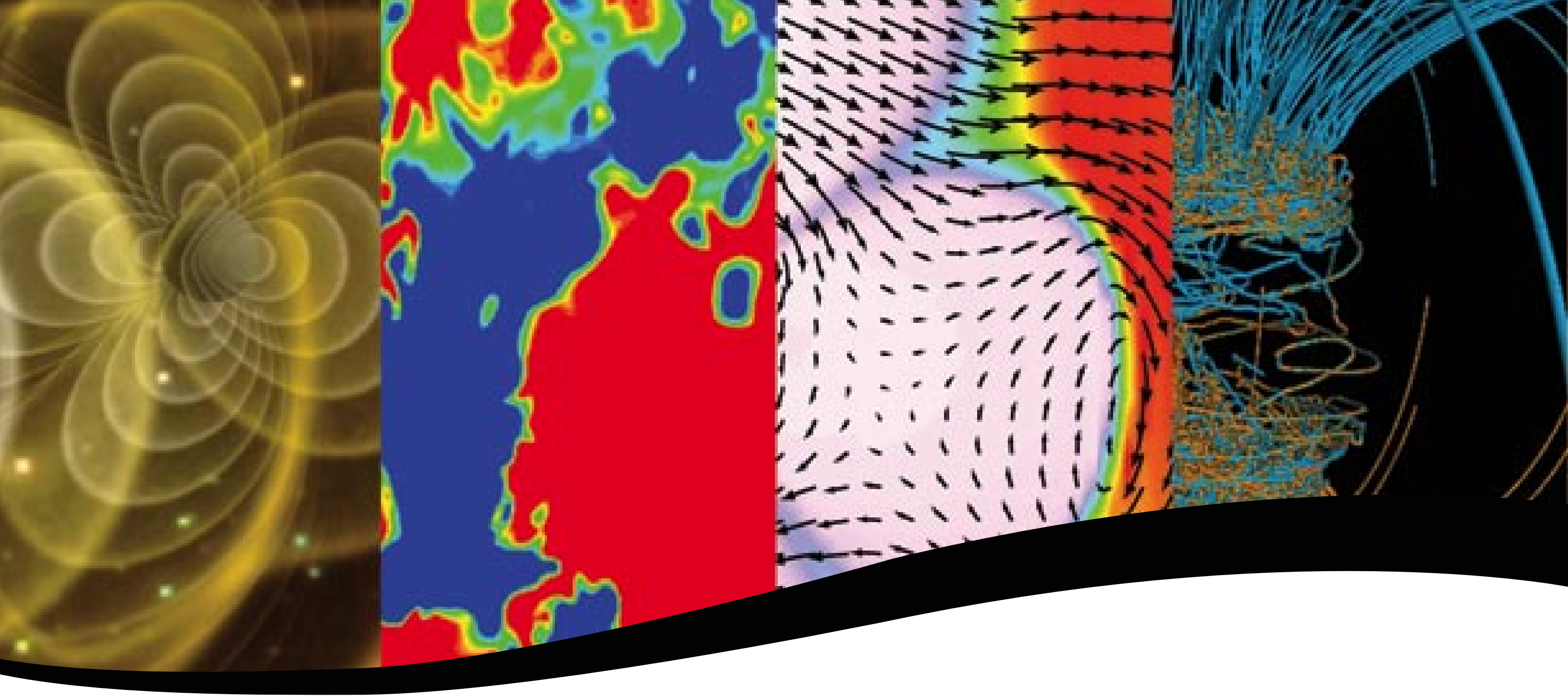


and cost-effective missions, coordinated across the four science areas to minimize gaps and overlaps. This program targets lower technology-readiness levels (TRLs; a maturity scale of 1-10) and a class of missions, not any specific mission technology developments are all competed through ROSES.

- A set of *focused technology programs* to enable near-term emerging missions, led within each science area and tailored to their specific missions. This program provides the mid-to-high TRL technologies targeted to a specific mission and is structured to accelerate and tailor already identified technologies to fit a project. The focused technology program is implemented primarily through competed solicitations. Directed work is done by exception.

- A *technology validation program* serving all of SMD, complemented by high TRL advanced development, to bring laboratory technologies to flight readiness. This program has the responsibility to validate, verify, and certify selected technologies as ready for flight. This program selects and applies the most appropriate certification approach for each specific technology and consists of ground-based validation, airborne-based demonstrations, and, if necessary, in-space validation.

- Ongoing *advanced technology studies* to explore technology options and to establish technology priorities for future mission options. These studies are a necessary element of planning a technology program. These studies require adoption of specific mission concept baselines to draw comparative conclusions. Even though based on specific mission concepts, these are not mission studies. Rather, they are studies to evaluate the effectiveness of projected capabilities of new technologies. These studies also include technology-development plans and cost estimates to reach the projected levels of technology performance, for the purpose of identifying the most cost-effective approaches for satisfying future mission needs.



Critical technologies are developed in core technology programs and transitioned to focused technology programs that are closely tied to specific mission infusion. Flight validation programs are used when deemed necessary. Core technology is developed 3-6 years before mission formulation. Focused technology is developed 3 years before formulation. Resources required are dependent on the current state of the technology and the timescale for which the technology is required; urgent needs require greater resources.

3.5 Computational Information Management

Vast quantities of data already result from science missions, with substantial growth expected in volume, complexity, and multiplicity of sources. But data acquisition is only the front end of the information pipeline. Once acquired, the data are processed, analyzed, and often transformed into visual products to yield increased knowledge and scientific understanding. The overall context for the science information pipeline has evolved dramatically from a single spacecraft or instrument perspective to a much more multimission, systems science perspective. Mission data flows into a coherent archive environment for retrieval and analysis, as well as combination, comparison, and cross-correlation with other observations, datasets, theoretical models, simulations, etc. The goal of the next-generation science data and computing environment is to provide a comprehensive and robust infrastructure of data, computing, and modeling resources to maximize scientific productivity and knowledge enhancement.

The future environment will build upon the “virtual observatory” concept to allow for exploration and data mining across widely distributed datasets and sources. The emerging linkage of rich datasets, state-of-the art models and simulations, and high-performance computing capabilities, through high-bandwidth networks and middleware transparent to the user, will lead to much greater scientific understanding and predictive capability. Provision of these capabilities will rely heavily on advances in a broad range of computer science and technologies. Key actions that guide the vision and strategy for realization of the future data and computing environment include:

- Secure strong stewardship of the integrity and long-term preservation of science data and ensure the broadest possible use of these assets as a national resource, often through partnerships with other Federal agencies. Each science division sponsors a data management program to carry out these responsibilities.

- Provide the science community robust and reliable access to the data resources and analysis capabilities sufficient to meet their research needs. Federate the data and computing efforts across SMD to provide a coherent perspective to the science users and promote interconnection and sharing.

- Evolve the infrastructure in response to science needs through infusion of advanced capabilities and enhanced services. Innovative elements and capabilities, tailored information products, advanced software tools, algorithms, computational methods, etc. will be openly solicited to promote strong collaborations involving the space, Earth, and computer science and technology communities.

- Coordinate the evolution of the virtualized environment with those of other Federal agencies and international partners to ensure interoperability and sharing of technology, best practices and experiences.

SMD has made considerable progress over the past year to stabilize planning for high-end computing capability as a key strategic asset for realization of its science objectives. For example, the computing power made available with the acquisition of the Project Columbia supercomputing system at NASA's Ames Research Center has already proven to be a vital resource for producing significant science results in a number of areas. System performance for these unique capabilities will continue to be refined and tuned to deliver maximum service to a broader spectrum of science users in a distributed, multi-tiered computing architecture. A longer–term plan for the continued evolution of the high-end computing environment will developed over the next 18 months in close conjunction with the science disciplines, as well as with related endeavors with partners in other Federal agencies. We will also maintain close alignment with complementary research in relevant technology areas such as distributed computing, intelligent data exploration, and reliable and robust software development.

3.6 Strategic Partnerships

SMD pursues partnerships with a wide variety of NASA, national, international, academic, and commercial organizations. These partnerships enable SMD to leverage others' resources to accomplish common scientific goals. Partnerships also serve to fulfill national policy objectives, including reducing unnecessary overlap among agencies, and pursuing the peaceful use of space for the benefit of all. Such partnerships enable more of humanity to participate in scientific exploration and discovery.

The Space Act provides our authority to enter into agreements with foreign and international organizations, other U.S. government agencies, commercial entities, academic institutions and other organizations. In particular, the Space Act authorizes and encourages NASA to enter into partnerships that help fulfill our mission. As a result, SMD engages in a wide variety of strategic partnerships, grouped broadly into cross-NASA, interagency, and international collaborations of various types.

SMD's major interagency partners include the Department of Defense (DoD), DOE, NSF, NOAA, and the USGS. Some examples include collaboration with NSF on meteorite collection and curation, working closely with DOE on space missions that explore fundamental physics, and partnering with NOAA and DoD in developing the next generation of weather and environmental satellites. A complete list of SMD's interagency partnerships is long, totaling over 60 major agreements.

SMD's international partnerships are numerous and diverse. SMD currently manages over 240 active international agreements, with several dozen more agreements or extensions of existing agreements being developed in any given year. These agreements range from ESA's provision of instruments and launch services for the James Webb Space Telescope to SMD's provision of science instruments on the Japanese Suzaku and Hinode spacecraft to the Dutch and British providing science instruments for SMD's Aura spacecraft. SMD's most frequent international partners, in alphabetical order, are Canada, Europe (both the multinational European Space Agency and individual national space agencies), Japan, Russia, and South America. SMD has also collaborated with India and with Latin American universities and space agencies and is exploring opportunities to partner with China.

The aerospace industry plays a central role in the design, engineering, manufacture, construction, and testing of both large and small space missions; in the design, development, testing, and integration of advanced instruments; and in the development of advanced spacecraft, instrument, mission operations, and information system technologies. Many industry capabilities have been developed for commercial applications with NASA core technology support. The resulting extensive space industry infrastructure is available for use for SMD purposes.

Establishing and maintaining partnerships requires management discipline. Partnerships involve dependencies and risks that need to be properly managed. Partnerships may also involve significant policy and/or legal issues, such as international relations, export control, intellectual property, or potential liabilities, that can complicate the development process. SMD remains committed to strategic partnerships that enhance our programs and their scientific or technological return. Our approach is to assess each potential partnership in terms of whether it will reduce NASA cost, enhance the science return of the mission, or make possible discoveries that would otherwise go unmade. Our goal is to partner with organizations that offer unique expertise, services, or materials that we could not acquire internally or otherwise afford. Strategic partnerships will continue to play important roles in making possible the scientific discoveries that lie ahead.

3.7 Workforce Development, Education and Public Outreach (E/PO)

SMD programs implement NASA's three major education goals in coordination with the NASA Education Office:

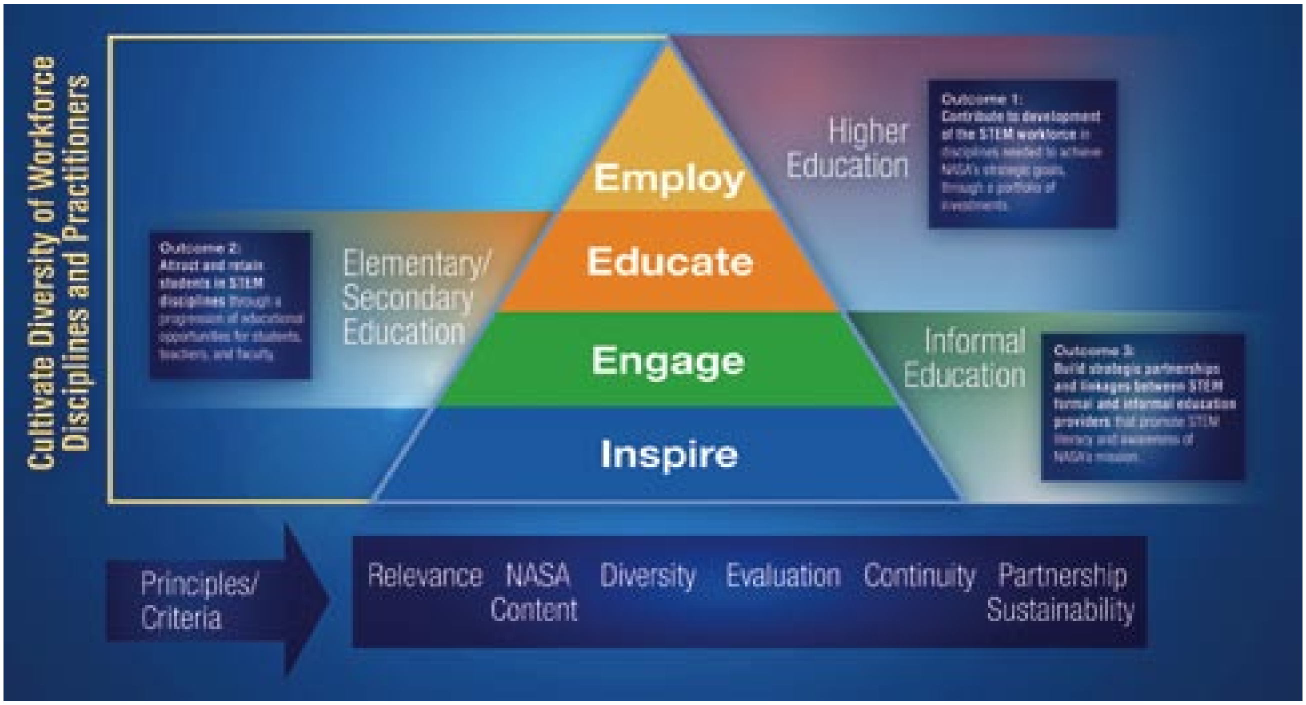
- Strengthen NASA and the Nation's future workforce;
- Attract and retain students in science, technology, engineering, and mathematics (STEM) disciplines; and,
- Engage Americans in NASA's mission.

SMD plays an essential role in NASA's Strategic Education Framework to "inspire, engage, educate and employ" (Figure 3.4). The discoveries and knowledge generated by NASA science missions and research programs consistently engage the public, inform teachers, and excite students. Using programmatic tools and resources, SMD is building strategic educational and public outreach partnerships to enhance the Nation's formal education system and contribute to the broad public understanding of science, technology, engineering, and mathematics (STEM). SMD's Education Program sponsors both formal and informal educational opportunities that promote STEM literacy through the dissemination and application of unique NASA resources.

Workforce Development Approach

SMD aids in workforce development through student support at the undergraduate, graduate, and post-doctoral levels embedded in its research, technology, and flight projects, as well as distinct educational opportunities. The university-based research and technology projects sponsored by SMD allow students and post-doctoral researchers to gain invaluable NASA science program work experience as part of their education and professional training. The suborbital programs (airplanes, unmanned aerial vehicles (UAVs), 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 lead to experiences in problem solving and increased understanding of the systems engineering that is the underpinning of successful science missions. In addition, the NASA Postdoctoral Program, NASA Earth and Space Science Fellowship Program, and other early-career programs (e.g., Early Career Fellowships, New Investigator Program in Earth Science) ensures the continued training and nurturing of a highly qualified workforce to help NASA continue the scientific exploration

Figure 3.4 - NASA's Strategic Education Framework



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.

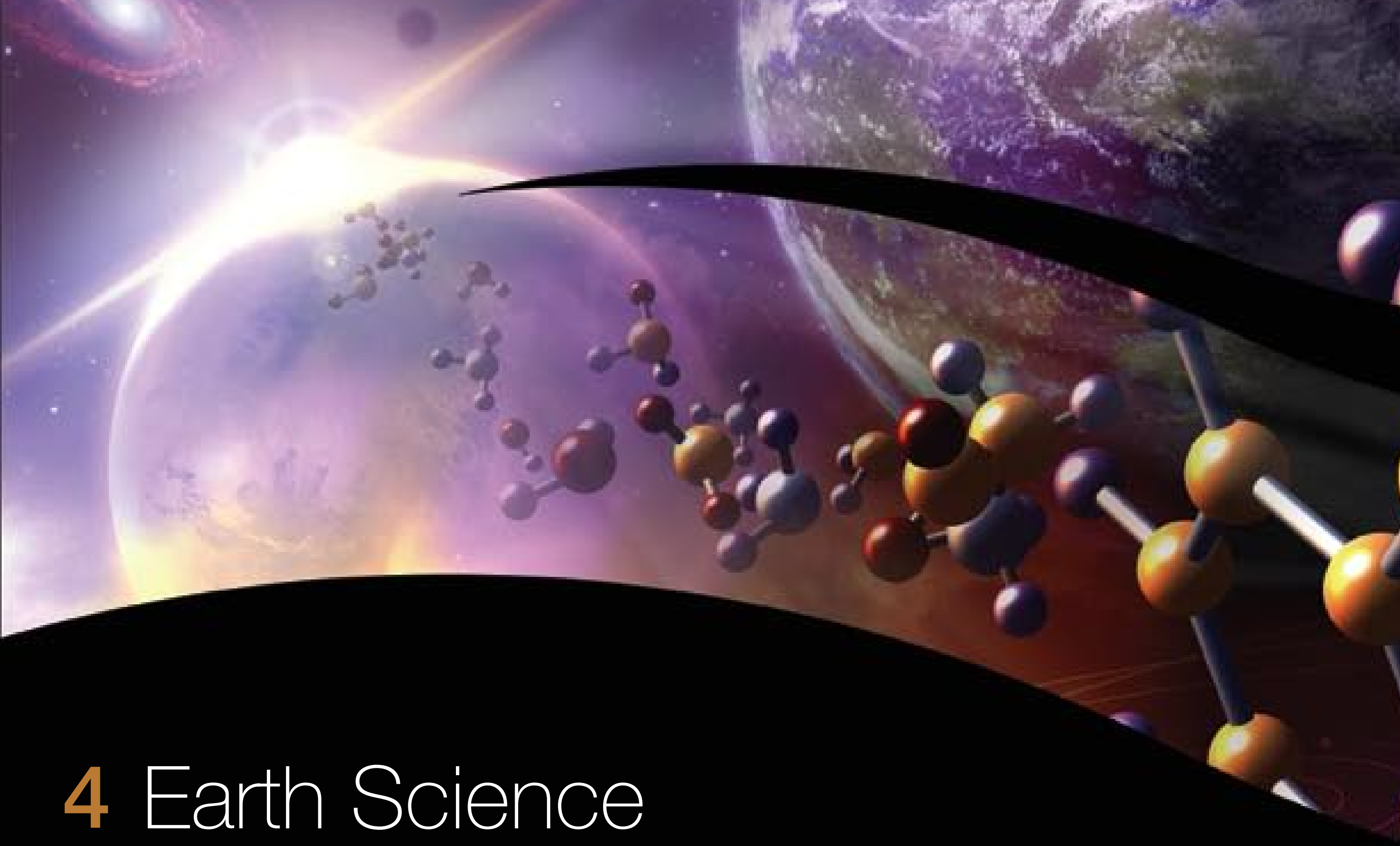
E/PO Implementation Approach

SMD's E/PO programs share the results of our missions and research with wide audiences, both formally and informally. These E/PO programs aim to attract and retain students in STEM disciplines by energizing science teaching and learning. In addition, E/PO programs promote inclusiveness and provide opportunities for minorities, students with disabilities, minority universities, and other target groups to compete for and participate in science missions, research, and education programs. The combined emphasis on pre-college/pre-workforce education, diversity, and increasing the general public's understanding and appreciation of science, technology, engineering, and mathematics encompass all three major educational goals.

SMD integrally incorporates E/PO into flight missions and research programs. Science mission researchers and other personnel are encouraged to become active participants in various education and outreach activities. PIs can propose augmentations to their research grants for this purpose. A prime focus remains on identifying and meeting the needs of educators and on emphasizing the unique contribution NASA science can make to education and to the public's understanding of science. To assist educators in preparing NASA's future workforce, many professional development opportunities are available that are firmly rooted in the science and technology of NASA missions.

Collaboration is key to building nationwide programs that contribute to improving teaching and learning at the pre-college level and to increasing the scientific literacy of the general public. The Directorate achieves this leverage in pre-college education 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. Informal education alliances are well established with science centers, museums, and planetariums, as well as public radio and television program producers. SMD works to enrich the STEM education efforts of community groups such as the Girl Scouts, 4-H Clubs, and the Boy's and Girl's Clubs of America. The strength of each of these partnerships relies on the combination of the science-content knowledge and expertise of the SMD and the educational expertise and context of each partner.

Most educational products created under the auspices of SMD are readily available to educators through online directories (*http://teachspacescience.stsci.edu/cgi-bin/ssrtop.plex* and *http://science.hq.nasa.gov/education/catalog/index.html*). In addition, direct links are provided from these sites to other NASA sites, as well as other national educational materials databases. Finally, mechanisms are in place to solicit and evaluate expert feedback on the quality and impact of all E/PO programs.



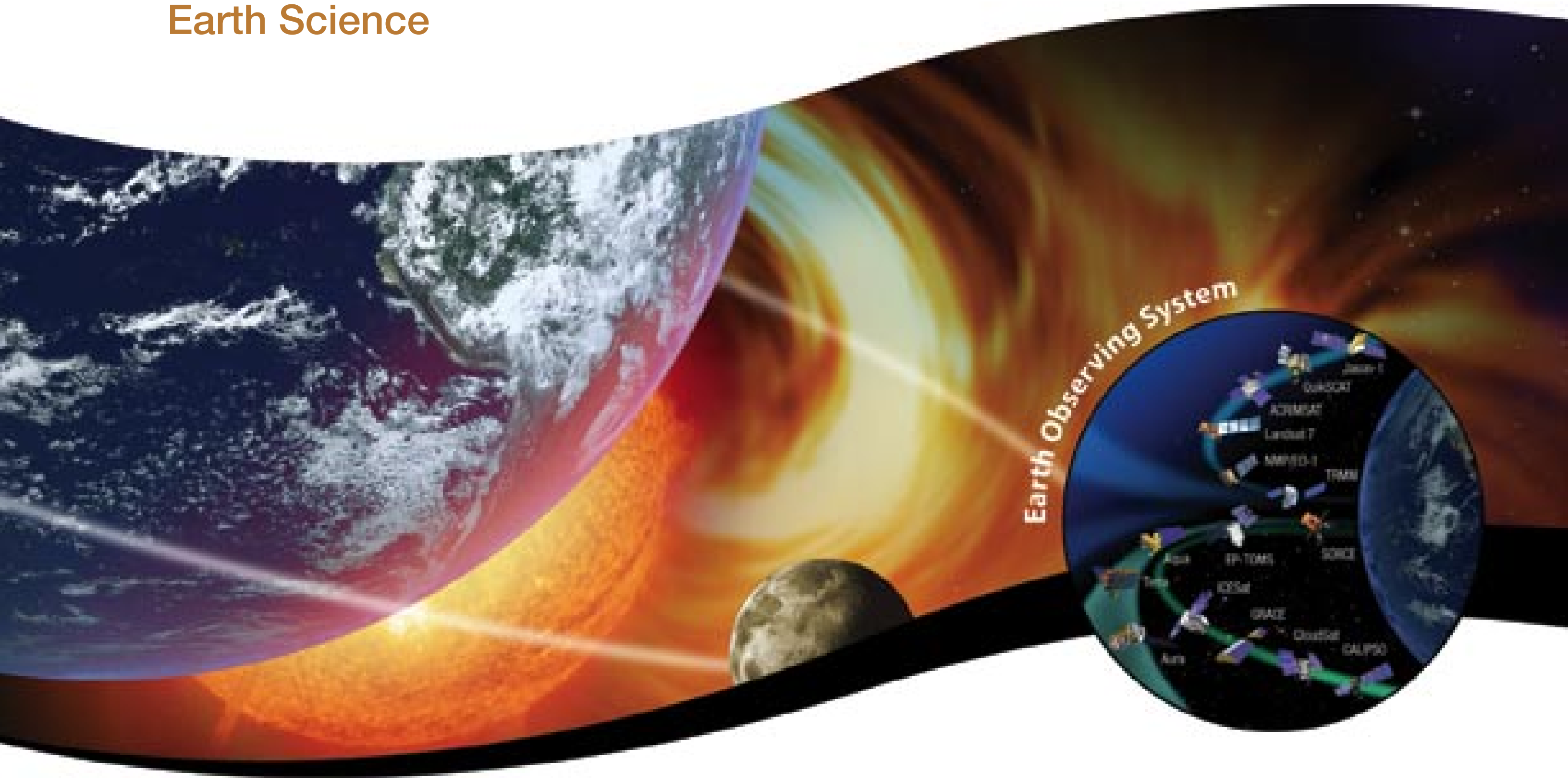
4 Earth Science

Strategic Goal:

Study Earth from space to advance scientific understanding and meet societal needs.

Chapter 4

Earth Science



NASA's Earth Science Program is dedicated to advancing Earth remote sensing and pioneering the scientific use of global satellite measurements to improve human understanding of our home planet in order to inform economic and policy decisions and improve operational services of benefit to the Nation. The program is responsive to several Congressional mandates and Presidential initiatives.

4.1 Intellectual Foundation

The Earth is the only known harbor for highly diversified life in the universe. In contrast to Mars and Venus, Earth's atmosphere, vast quantities of surface liquid water, and internally generated magnetic field maintain an environment conducive to life and human civilization.

Perhaps more than any other human activity, a half-century of progress in Earth observation from space has steadily changed our perception of the Earth as our home planet. Satellite measurements of essential characteristics have enabled human understanding of the Earth as a system of interconnected parts. It is now clear for example that the characteristics of Earth's atmosphere so critical to human habitability are maintained by complex and tightly coupled circulation dynamics, chemistry, and interactions with the oceans, ice and land surface; all of which are driven by solar radiation and gravitational forces.

From the vantage point of space we see at continental and planetary scales the vast extent and complexity of human activities. Over the past 50 years, world population doubled, world grain supplies tripled, and total economic output grew sevenfold. From space, we see that expanding human activities now affect virtually the entire land surface and are altering world oceans and ice masses, as well. Over the next 50 years, the world population is likely to grow to 11 billion, exerting ever more demands for habitable land and natural resources and greater influences on climate. Natural variability in the Earth system occurs in many temporal and associated spatial scales, from very short-term weather (such as tornadoes), through the diurnal cycle, longer-period weather phenomena like frontal systems, then through the annual cycle (El Niño Southern Oscillation) and even longer oscillations (like the Pacific Decadal Oscillation). These are punctuated with episodic events such as volcanic eruptions and accompanied by longer-term change. Spatial scales vary from global processes such as changes in thermohaline circulation to regional such as melting of polar ice sheets to local-scale processes such as those manifested by floods and droughts. Understanding of these varying scale processes and their interaction enables predictive capability of the Earth system to inform resource management decisions and multiple level policies.

Thus, we live on a planet undergoing constant change due to natural phenomena and our own activities. To maintain and improve quality of life on Earth (e.g., support sustainable development), we need global information about the state of the environment and its future evolution. Continuous global observations of variability and change are required to reveal natural variability and the forces involved, the nature of the underlying processes, and how these are coupled within the Earth system.

NASA's strategic goal in Earth science is motivated by the fundamental question: **"How is the Earth changing and what are the consequences for life on Earth?"** NASA's mission in Earth science, as mandated by the Space Act, is to "... conduct aeronautical and space activities so as to contribute materially to ...the **expansion of human knowledge of the Earth** and of phenomena in the atmosphere and space" [emphasis added]. Therefore NASA's role is unique and highly complements those of other Federal agencies such as NOAA, NSF, USGS and EPA by continually advancing Earth system science from space, creating new remote sensing capabilities, enhancing the operational capabilities of other agencies, and collaborating with them to advance national Earth science goals. For example, NASA and the USGS are long-time collaborators in the Landsat program, and that partnership is evolving in keeping with the maturity of land-cover remote sensing. NASA and NOAA are also long-time collaborators in satellite systems for use in weather prediction. Today's civilian weather satellite system was built and launched by NASA under a reimbursable arrangement with NOAA, and NOAA operates the system and manages the data for use in its operational forecasting role. The next generation polar-orbiting satellite system is being developed by NOAA and DoD with NASA as a technology provider and aims to make key climate measurements as well. However, this program is currently undergoing a restructuring due to cost and technical challenges, and the outcome may have significant implications for NASA's future Earth Science Program.

From the 1960s through the 1980s, space and airborne observations allowed the first global view of the Earth and led to important discoveries such as the processes behind Antarctic ozone depletion, the Earth's response to incoming solar radiation, and the extent, causes, and impacts of land use and land cover change.

In the 1980s and 1990s, NASA's comprehensive suite of global measurements together with the associated temporal scales of observation led to the development of the interdisciplinary field of Earth System Science. NASA deployed the first set of platforms in the Earth Observing System (EOS) and promoted research focused on the Earth as a system—a dynamic set of interactions among continents, atmosphere, oceans, ice, and life.

In this decade, NASA has begun to deploy new types of sensors to provide three-dimensional profiles of Earth's atmosphere and surface. Emphasis is placed into linking together multiple satellites into a constellation, developing the means of utilizing a multitude of data sources to form coherent time series, and facilitating the use of the extensive data in the development of comprehensive Earth system models.

In the decade 2007–2016, NASA will develop and demonstrate new sensors and interacting constellations of satellites to address critical science questions and enable advances in the Nation's operational capabilities. Expanded operational capabilities will be complemented with the delivery of reliable data products from the space observing system and the continual improvement of predictive models based on emerging scientific research. In the future, as more data is collected and analyzed from a multidisciplinary viewpoint and as predictive model development moves toward increased coupling of Earth system components, there will be increasing requirements for scientific research. Likewise, the number of space-based observations required for assimilation into the coupled models will also grow with the complexity of the system. In order to meet the increasing demands of data volume and model complexity within a constrained budget and while maintaining a healthy program balance, NASA will pursue the following strategies:

- Work with the scientific community to create interdisciplinary teams that help focus research and resources on key uncertainties and model deficiencies;

- Develop, in concert with commercial partners, new, decentralized approaches to data archiving and management that emphasize broad, creative uses of multidisciplinary datasets;

- Develop, launch, and operate a cost-effective suite of spaceborne missions that observe multiple key Earth system parameters; and,

- Coordinate with other U.S. and international partners to ensure that a core set of key measurements is made on a sustained basis.

NASA's Earth science programs are essential to the implementation of three major Presidential initiatives: Climate Change Research (June 2001), Global Earth Observation (July 2003), and the U.S. Ocean Action Plan (December 2004). The first is the subject of the U.S. CCSP, combining the congressionally mandated Global Change Research Program (USGCRP) with the Climate Change Research Initiative. The second is related, and focuses on national and international coordination of Earth observing capabilities to enhance their use in meeting important societal needs. An Earth Observation Summit in Brussels, Belgium, in February 2005 adopted a 10-year plan for a Global Earth Observation system of systems. The third is the U.S. Government response to the Congressional Commission on Ocean Policy of 2002 and its final recommendations report, *An Ocean Blueprint for the 21st Century*. NASA's unique role in these coordinated efforts is to advance remote sensing technology and computational modeling for scientific purposes, and facilitate the transition of mature observations and technologies to partner agencies that provide essential services using Earth science information. Earth Science at NASA contributes to the Vision for Space Exploration by providing leverage of observing technologies and knowledge of Earth as a planet to aid in the Nation's exploration of worlds beyond.

The NRC is just now completing its first decadal survey for Earth science and applications from space. This survey will be used to set priorities for future missions and research. The missions, programs and research objectives in this section are based on heritage roadmaps developed with the science community in each of the science focus areas defined below. The most recent Earth Science Research Plan can be found at *http://science.hq.nasa.gov/strategy/past.html*.

4.2 Science Objectives and Outcomes: The Six Earth Science Focus Areas

The complexity of the Earth system, in which spatial and temporal variability exists on a range of scales, requires that an organized scientific approach be developed for addressing the complex, interdisciplinary problems that exist, taking good care that in doing so there is a recognition of the objective to integrate science across the programmatic elements towards a comprehensive understanding of the Earth system. In the Earth system, these elements may be built around aspects of the Earth that emphasize the particular attributes that make it stand out among known planetary bodies. These include the presence of carbon-based life; water in multiple, interacting phases; a fluid atmosphere and ocean that redistribute heat over the planetary surface; an oxidizing and protective atmosphere, *albeit* one subject to a wide range of fluctuations in its physical properties (especially temperature, moisture, and winds); a solid but dynamically active surface that makes up a significant fraction of the planet's surface; and an external environment driven by a large and varying star whose magnetic field also serves to shield the Earth from the broader astronomical environment.

The resulting structure is comprised of six interdisciplinary Science Focus Areas:

- Atmospheric Composition
- Weather
- Carbon Cycle and Ecosystems
- Water and Energy Cycle
- Climate Variability and Change
- Earth Surface and Interior

These six focus areas include research that not only addresses challenging science questions, but drives the development of an Earth observing capability and associated Earth system models. In concert with the research community, NASA developed a hierarchy of science questions. The fundamental question: **"How is the Earth changing and what are the consequences for life on Earth?"** leads to five associated core questions, representing a paradigm of variability, forcing, response, consequences and prediction, leading in turn to the 24 detailed Earth science questions in Table 4.1. NASA strategy for linking the six interdisciplinary science focus areas is to solicit and fund research addressing combinations of these science questions.

The following sections describe each Science Focus Area. Each section describes the scientific field, NASA's current contribution, and next major steps in the period 2007-2016. The last addresses the interdisciplinary and integrative nature of the program.

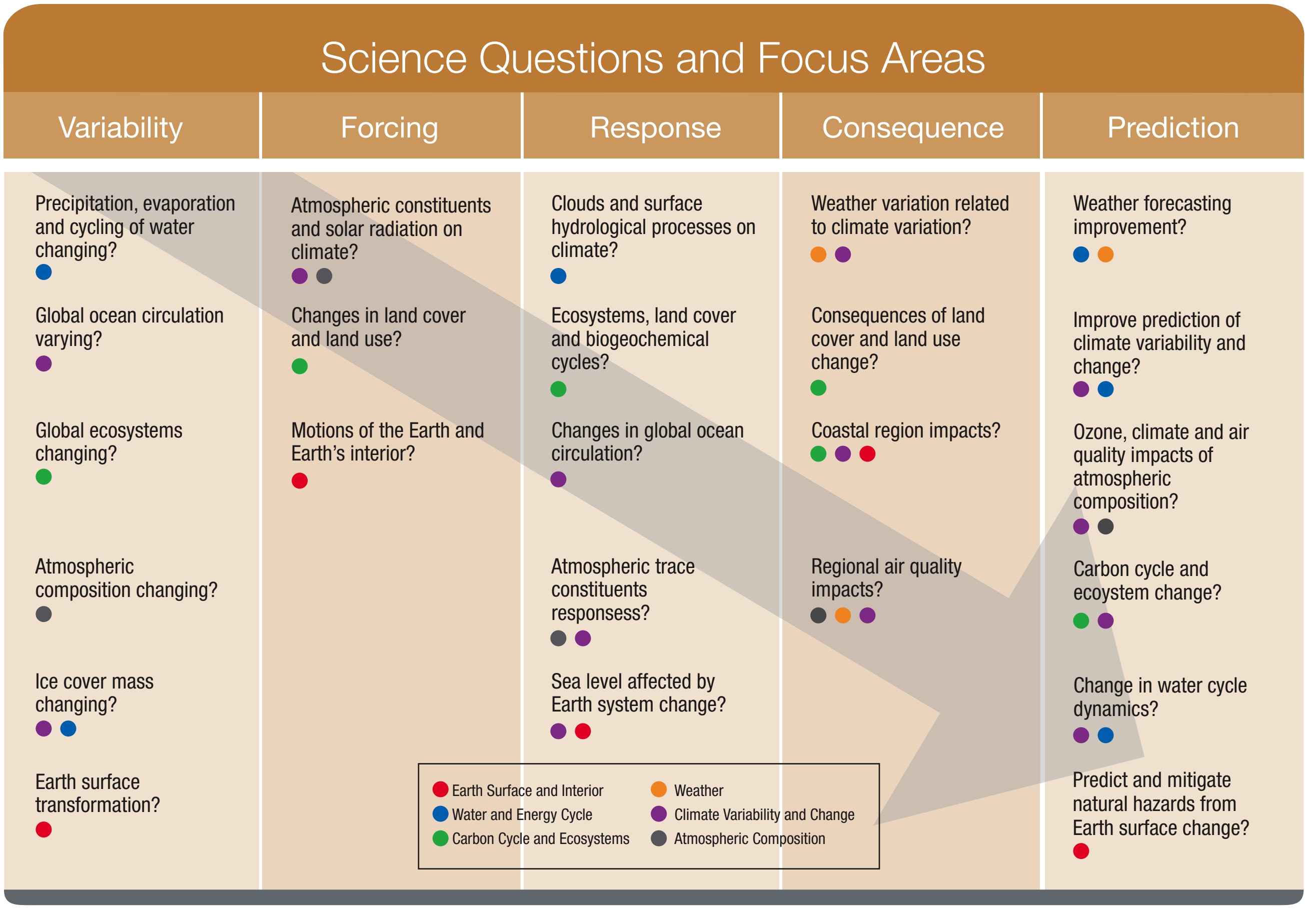
Table 4.1 - Links and Interrelationships between Science Focus Areas and Science Questions

Earth Science Questions
Overall: How is the Earth changing and what are the consequences for life on Earth?
How is the global Earth system changing? (Variability)
How are global precipitation, evaporation, and the cycling of water changing? How is the global ocean circulation varying on interannual, decadal, and longer time scales? How are global ecosystems changing? How is atmospheric composition changing? What changes are occurring in the mass of the Earth's ice cover? How is the Earth's surface being transformed by naturally occurring tectonic and climatic processes?
What are the primary forcings of the Earth system? (Forcing)
What trends in atmospheric constituents and solar radiation are driving global climate? What changes are occurring in global land cover and land use, and what are their causes? What are the motions of the Earth's interior, and how do they directly impact our environment?
How does the Earth system respond to natural and human-induced changes? (Response)
What are the effects of clouds and surface hydrologic processes on Earth's climate? How do ecosystems, land cover and biogeochemical cycles respond to and affect global environmental change? How can climate variations induce changes in the global ocean circulation? How do atmospheric trace constituents respond to and affect global environmental change? How is global sea level affected by natural variability and human-induced change in the Earth system?
What are the consequences of change in the Earth system for human civilization? (Consequences)
How are variations in local weather, precipitation, and water resources related to global climate variation? What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems? What are the consequences of climate change and increased human activities for coastal regions? What are the effects of global atmospheric chemical and climate changes on regional air quality?
How will the Earth system change in the future, and how can we improve predictions through advances in remote sensing observations, data assimilation and modeling? (Prediction)
How can weather forecast duration and reliability be improved? How can predictions of climate variability and change be improved? How will future changes in atmospheric composition affect ozone, climate, and global air quality? How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future? How will water cycle dynamics change in the future? How can our knowledge of Earth surface change be used to predict and mitigate natural hazards?

4.2.1 Atmospheric Composition

Understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition. Earth's atmosphere is 99.9 percent nitrogen, oxygen and argon, but the trace gases and aerosols comprising the remaining one-tenth percent play a critical role in human welfare and global change. The atmosphere links all of the principal components of the Earth system interacting with the oceans, land, ice sheets, as well as terrestrial and marine plants and animals. Emissions from natural sources and human activities enter the atmosphere at the surface and

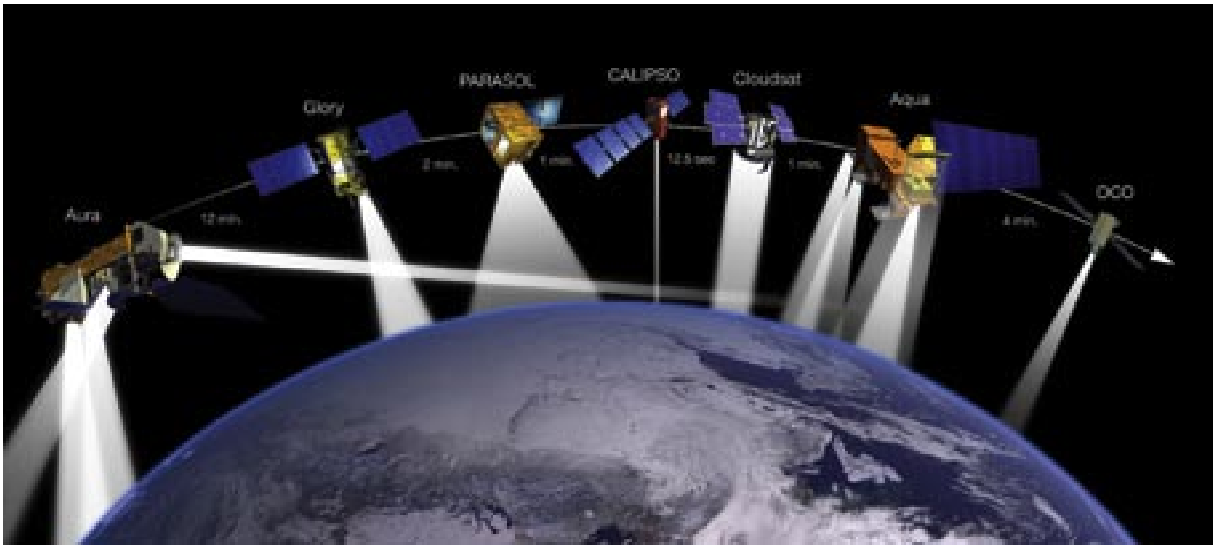
Figure 4.1 - Links and interrelationships between Science Focus Areas and Science Questions



are transported to higher altitudes and around the globe. Changes in atmospheric composition affect the Earth's energy balance, the stratospheric ozone layer, the climate and weather system, and surface air quality, which in turn create multiple environmental effects that influence human and ecosystem health. Exchanges with the atmosphere link terrestrial and oceanic pools in the carbon cycle as well as other biogeochemical cycles.

Understanding atmospheric composition in the Earth system requires an integrated approach including a hierarchy of space-based, suborbital, and pathfinder observations, laboratory and field studies, and modeling, with periodic assessments of understanding and significance to decision making. Recent advances in atmospheric remote sensing from low Earth orbit (LEO) with instruments on NASA satellites such as Terra, Aqua, Aura, CloudSat and CALIPSO, as well as those on international partner satellites, have demonstrated the value of using satellites for both scientific studies and environmental applications. Research results are integrated into periodic international scientific assessments, most notably the Intergovernmental Panel for Climate Change (IPCC) for climate and the World Meteorological Organization/United Nations Environment Programme's (WMO/UNEP) for ozone.

In the coming decade, space-based measurement capabilities for ozone, water vapor, CO, NO_2, HCHO, SO_2, aerosols and other constituents must be continued from LEO and, at the same time, instrument capabilities and measurement algorithms for these species improved. In addition to continuing and improving our current LEO observations, the next-generation scientific and observing framework for atmospheric composition will likely also include multispectral sentinel missions in geostationary (GEO) or Sun-Earth Lagrangian (L-1) orbits that have high spatial and temporal resolution, as well as measurements in the planetary boundary layer. The combination of LEO and GEO observations for atmospheric composition will enable substantial improvements in "chemical weather" forecasting, determination of sources and sinks of greenhouse gases and aerosols, and a better understanding of atmospheric transport enabling characterization of the processes that control water vapor and other species in the upper troposphere and of the influences of long-range transport of emissions on air quality. Advanced technological capabilities will allow affordable



The A-Train

NASA, with international partners (Canada, France, Netherlands, Finland, United Kingdom, and Japan), has put into orbit a

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lites orbiting the Earth which are carefully choreographed by NASA ground controllers to observe the same portion of the Earth over the time span of twenty three minutes. The Earth's land, oceans, ice packs, and atmosphere are now being observed by five of the six satellites using fourteen instruments which observe the Earth radiation from the ultraviolet to the millimeter wavelength region including polarization properties of clouds and aerosols.

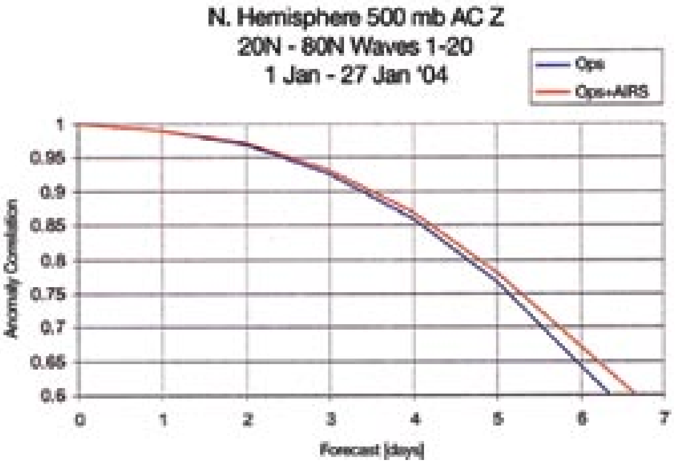
The five satellites now in orbit include Aura, Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL), CALIPSO, Cloudsat, and Aqua. The instruments include spectrometers, radiometers, polarimeters, and lasers, which map or determine vertical distributions beneath the A-Train. A particular target is the composition of the Earth's atmosphere, which is being studied by a full range of A-Train instruments, resulting in tremendous synergy by combining datasets. For example, simultaneously measured cloud and trace gas properties can be studied to better understand the formation of clouds and aerosols and their interactions with gases from near the ground into the stratosphere. This will be valuable in understanding the connections between atmospheric chemistry and climate. The launch of OCO, the sixth satellite, in 2008 will complete the constellation and make the first global measurements of CO_2 sources and sinks.

continuation of long-term systematic observations of the profile abundance of a wide range of trace gases on rides of opportunity.

4.2.2 Weather

Enable improved predictive capability for weather and extreme weather events. Improvements in weather prediction have great social and economic value. NASA contributes to better prediction capability by providing new or improved space-based observations and by providing new models and methods to assimilate these observations into the models. To enable weather prediction, we need satellite-based measurements of temperature, moisture, wind, clouds, and precipitation. Weather prediction is the determination of the future state of these variables and their interpretation in terms of storm properties. Recent satellite observations of lightning are also contributing to the understanding of storm properties and early detection of tornado activity. NASA and NOAA collaboration over decades has enabled the transition of NASA observing capabilities and research to improve operational environmental satellites and weather forecasting models. The origin of almost all instruments that have ever flown on weather satellites operated by NOAA can be traced back to NASA programs.

The latest NASA sensor for the measurement of temperature and moisture is the Atmospheric InfraRed Sounder (AIRS) instrument on the Aqua satellite. Radiance data



Impact of AIRS on Global Forecast Skill

Experimental weather forecasts at the Joint Center for Satellite Data Assimilation using AIRS data indicate significant improvements in global forecast skill compared to the operational system without AIRS data. The improvement in forecast skill at six days is equivalent to gaining an extension of forecast capability of several hours. While this may seem small, it is quite significant when compared to the rate of general forecast improvement over the last decade. A several hour increase in forecast range at five or six days normally takes several years to achieve at operational weather centers.

from the AIRS/AMSU (Advanced Mircowave Sounding Unit) combination has made significant positive impact in global forecast skill and is currently being used by NOAA in operational weather prediction. Increasingly, operational Numerical Weather Prediction (NWP) centers around the world are using or developing the capability to assimilate precipitation observations to improve the forecasting of weather and severe storm events. Research based on Tropical Rainfall Measuring Mission (TRMM) data has demonstrated the benefits of assimilating precipitation data into NWP models. The GPM mission and the associated constellation satellites will considerably extend the spatial and temporal measurement of precipitation. A key component of the Weather Focus Area is a set of core efforts to assimilate new NASA satellite data into numerical forecast models and to assess the associated forecast improvement. Two groups are currently working on this problem, the NASA-NOAA-U.S. Air Force (USAF) Joint Center for Satellite Data Assimilation and NASA's Short-term Prediction Research and Transition Center.

Looking ahead, a new satellite mission to accurately measure the three-dimensional global wind field needed to optimally specify global initial conditions for numerical weather forecasts. The wind field plays a unique dynamical role in forcing the mass field to adjust to it at all scales in the tropics and, at smaller scales, in the extratropics. Advanced imaging and sounding from GEO or Medium Earth Orbit (MEO) is required to complement advanced polar orbit observations with time resolution necessary to fully observe and understand weather scale processes. Current GEO imager/sounder instruments operate at infrared wavelengths. Instruments operating at these wavelengths cannot "see" below the clouds, which are generally present whenever interesting meteorology is taking place. In order to take full advantage of GEO observations, it is necessary that the infrared instrument suite is complemented with microwave cloud-penetrating instrumentation. AIRS and AMSU have reached the maximum vertical resolution attainable with passive sounding. Improvements in the vertical resolution will be necessary to satisfy the requirements of the numerical weather prediction models of the next decade. Further improvements in vertical resolution may require the development of active (lidar and/or radar) sounding techniques.

4.2.3 Carbon Cycle and Ecosystems

Quantify global land cover change and terrestrial and marine productivity, and improve carbon cycle and ecosystem models. Earth's carbon cycle and ecosystems both influence and respond to global environmental changes. Major uncertainties in climate science stem from uncertainties in the global carbon cycle. Two garner special attention in NASA's program. First, at present the difference between the total release of carbon dioxide (CO_2) to the atmosphere from known sources and the total amount of CO_2 removed from the atmosphere by known carbon sinks does not equal the change in CO_2 concentration of the atmosphere. Approximately one quarter of this carbon (about 1.9 Petatons per year) is unaccounted for, but there is accumulating evidence that this "missing sink" is in Northern Hemisphere terrestrial systems. Second, how terrestrial and marine ecosystems may respond to changes in climate in combination with other contemporary environmental changes, such as changes in land use and management, invasions of exotic species, nitrogen deposition, and acidification of the surface ocean, is unclear. What is clear is that these environmental changes are occurring on an unprecedented scale, in both rate and geographical extent. Resolution of these uncertainties is needed because of the profound implications for future climate, food production, biodiversity, sustainable resource management, and the maintenance of a healthy, productive environment.

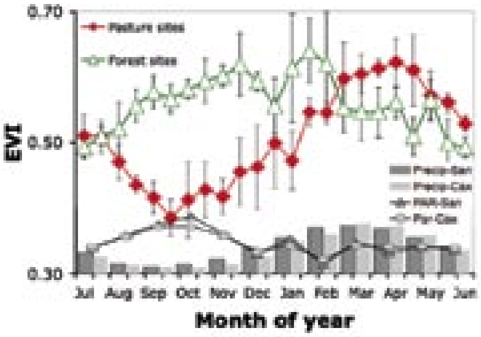
Thus, three objectives are identified for Carbon Cycle and Ecosystems research: (1) document and understand how the global carbon cycle, terrestrial and marine ecosystems, and land cover and use are changing; (2) quantify global productivity, biomass, carbon fluxes, and changes in land cover; and (3) provide useful projections of future changes in global carbon cycling and terrestrial and marine ecosystems for use in ecological forecasting and as inputs for improved climate change predictions.

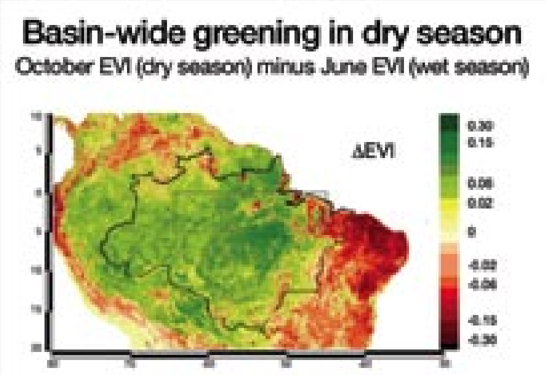
In the current decade, key missions now in development address these objectives. Well-calibrated and validated systematic observations of moderate-resolution ocean color, vegetation biophysical properties, fire, and land cover as well as high-resolution land cover form a critical foundation for focus area research. The NPOESS Preparatory Project (NPP) and Landsat Data Continuity Mission (LDCM) are intended to provide near-term continuity as these observations transition into the U.S. operational remote-sensing domain. The focus area depends on the continued availability of these climate-quality systematic observations and informs NASA investment in the development of advanced technologies to improve these observations and make them more economical in the future. The OCO will measure atmospheric carbon dioxide concentrations and advance our ability to locate and quantify regional carbon sources and sinks by dramatically increasing the number of global measurements over what can be provided with ground-based networks and aircraft.

Priority new observations are: (1) measurements of vegetation height and profiles of three-dimensional ecosystem structure to estimate above-ground biomass and carbon stocks with greatly reduced uncertainties and to characterize species habitats in ways that will enable exploration of fundamental controls on biodiversity; (2) well-calibrated measurements of the coastal ocean that allow discrimination and quantification of dissolved and particulate organic matter, phytoplankton pigments, and sediments in order to deduce the fate of carbon in the coastal ocean and quantify its role as either a source of sink for carbon; and (3) measurements of the distribution, abundance, and variability of plant groups with important ecological and physiological functions (e.g., nitrogen-fixing species, invasive species, plants with differing photosynthetic pathways or growth rates) to be used to improve process characterizations in predictive models and develop more refined land-cover analyses. In addition, following the completion of a successful OCO mission, advanced, high-resolution measurements of atmospheric profiles of carbon dioxide and methane will be needed to further refine our ability to quantify global sources and sinks, providing accuracy sufficient to balance the global carbon budget and monitor carbon-management activities.

Amazon Rainforests Green Up with Sunlight in Dry Season

- MODIS-derived Amazon vegetation phenology from 2000-2005 shows Enhanced Vegetation Index (EVI) increase of 25% during the dry season across intact forests. Pastures show decline.
- Forest behavior is opposite of what had been thought and portrayed in current models, and is consistent with new observations from flux towers.



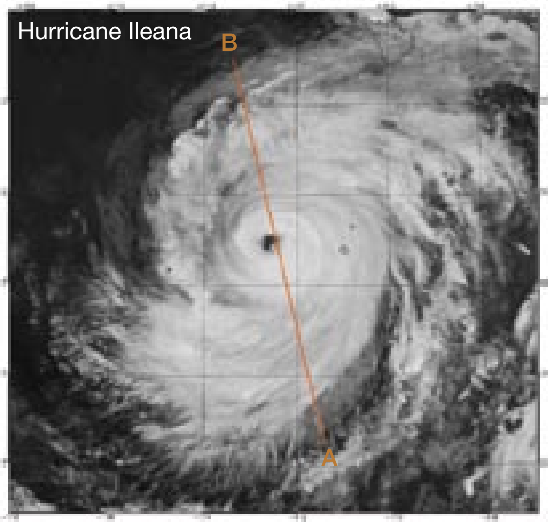


Huete, A. R., K. Didan, Y.E . Shimabukuro, P. Ratana, S. R. Saleska, L. R. Hutyra, W. Yang, R. R. Nemani, R. Myneni. 2006 Amazon rainforests green up with sunlight in dry season. GRL 33.

4.2.4 Water and Energy Cycle

Quantify the key reservoirs and fluxes in the global water cycle and improve models of water cycle change and fresh water availability. Water is paramount for humans, the environment, and their interaction and co-existence. Water is a critical component of societal sectors such as agriculture, energy, commerce, and recreation. The movement, availability, and quality of water on Earth impact human and ecosystem health and viability in many ways. Yet, global water quantity and quality information is sparse at the spatial and temporal resolutions and accuracies needed to allow effective, efficient management of current and future water resources. Scientific understanding of the movement and stores of water is not sufficient to provide reliable forecasts of seasonal precipitation or extreme events, such as droughts and floods, and how these three phenomena might be altered by climate change. Since solar energy drives the water cycle and phase changes of water either release or require energy, NASA couples the study of water and energy within the Earth System.

The following are current major components of SMD's Water and Energy cycle research program. Precipitation is currently measured by TRMM, and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E instrument, Aqua). Coarse estimates of monthly changes of groundwater are derived from the Gravity Recovery and Climate Experiment (GRACE) satellite system. Atmospheric water vapor is well monitored by the AIRS instrument (Aqua). Aspects of the energy balance, including upward short- and long-wave radiation, are measured by Cloud and the Earth's Radiant Energy System (CERES) instruments on multiple platforms. High-resolution profile measurements of clouds and cloud properties will be available from the recently launched CloudSat and CALIPSO. These measurements, together with the backbone of systematic measurements of NASA, NOAA, and *in situ* monitoring (from many agencies and countries), enable improved understanding and modeling

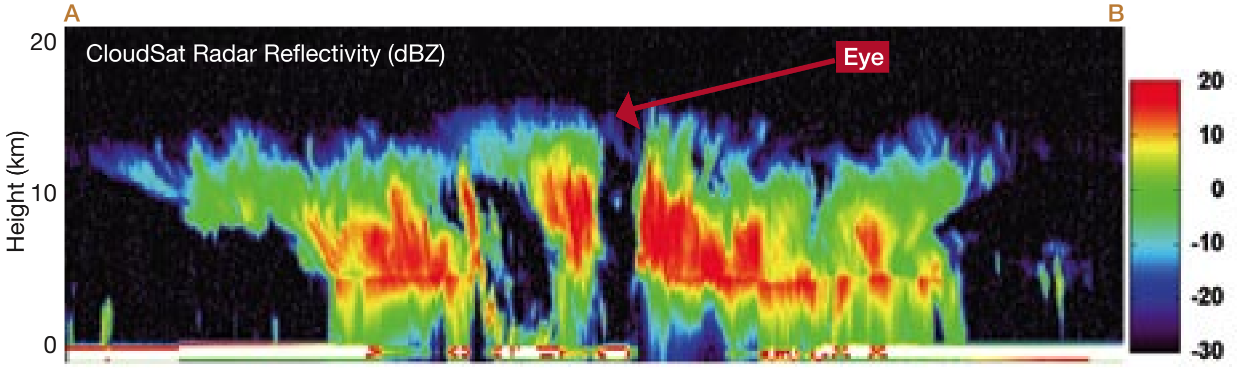


CloudSat Pioneers Cloud Observations

The cloud structures observed by CloudSat contain valuable information about the storm and its intensity. In fact, a theory exists linking cloud top height, temperature and sea surface temperature to the maximum low level wind speed. CloudSat observations are currently being adapted to determine this wind speed (referred to as a measure of hurricane intensity).

This CloudSat image below is especially unique revealing for the first tine the structure of clouds and precipitation through the storm including the eye.

MODIS 12 µm
(Channel 32)
23 Aug 2006
2100 UTC



capabilities. The above measurements also provide a good, initial, large-scale estimate of most fluxes and stores of the water and energy budgets. In order to answer challenging science questions and provide necessary information to decision and policy makers, efforts must go beyond simple compilation of observations and integrate across different streams of information to create a more coherent view of the global environment. This approach is being implemented by the NASA Energy and Water cycle Study (NEWS), for which a draft community-generated multiyear implementation plan is available (*http://wec.gsfc.nasa.gov/*).

Future satellites will enable dramatic increases in resolution of the water and energy cycles. For example, the GPM mission will extend remote sensing of precipitation globally, with more temporal completeness, allowing better estimation of this term in the Earth's water budget. Currently, direct measurement of evaporation is not feasible, but it can be estimated by fusing various observations using models. The Aquarius satellite will soon provide a key variable, sea-surface salinity, for computation of ocean evaporation. The critical missing information pertains to enhanced observation of soil moisture, snow, and river discharge. Soil moisture is especially important because it strongly influences land evaporation rates, a prominent intersection of the water and energy cycles. Other future mission concepts are being scoped and scientifically evaluated specifically for determining river discharge and the liquid water content of the snow pack. Also, research is exploring employment of current ocean characteristics remote-sensing technology to assess inland water quality.

4.2.5 Climate Variability and Change

Understand the role of oceans, atmosphere, and ice in the climate system and in improving predictive capability for its future evolution. Climate change can have tremendous consequences for the lives and livelihoods of individuals as well as for entire civilizations. While favorable climate is believed to have facilitated the "cradle of civilization" that sprang from the fertile lands of Mesopotamia, past climate change has displaced or even eliminated cultures and societies. One of the most notable climate changes displaced the Vikings, who in the late twelfth century abandoned villages and towns in Greenland and Iceland after temperatures cooled by only a few degrees centigrade. Society's ability to mitigate, adapt to, or capitalize on climatic change depends critically on understanding the processes at work and our ability to predict their future behavior. Climate variability and change research incorporates comprehensive observations into models that can accurately predict climatic change over seasonal, interannual, decadal, and longer time periods.

NASA's role in characterizing, understanding, and predicting climate variability and change focuses on global observations of the major components of the system, the naturally occurring processes and human activities that affect climate, and their interactions within the Earth system. To this end, NASA deployed the EOS and is seeking to extend key EOS measurements through partnerships with Agencies managing operational systems, such as the for the NPOESS Preparatory Project which will provide continuity of selected measurements from the Terra, Aqua, and Aura satellites. SMD is also pursuing first-time measurements of parameters driving important climate processes, including aerosol properties (Glory), sea surface salinity (Aquarius) and global carbon dioxide (Global Carbon Observatory).

In the future, as in the EOS era, research in Climate Variability and Change will draw heavily on the observations generated by missions important to the other Science Focus Areas. Of particular importance to climate, however, are observations of ocean circulation and heat storage, ice-sheet mass balance and change processes, and the solar irradiance, cloud properties, and aerosols that govern climate forcing. Thus, advanced ocean radar altimetry and scatterometry and continuity of measurement of climate-forcing agents will be high on the agenda for research in Climate Variability and Change.

4.2.6 Earth Surface and Interior

Characterize and understand Earth surface changes and variability of the Earth's gravitational and magnetic fields. Our planet is a restless one, subject to earthquakes, volcanic eruptions, destructive floods, landslides and other natural hazards arising from processes deep in the planet's interior as well as to the complex suite of interactions among the solid Earth, atmosphere, oceans, hydrosphere, and biosphere. The Earth Surface and Interior (ESI) focus area seeks to provide international leadership through the development of space-based techniques and their associated interpretive models.

The *Solid Earth Sciences Working Group (SESWG) Report* (SESWG, 2002) endorsed by the NRC's *Review of NASA's Solid-Earth Science Strategy* (2004; available at *http://solid-earth.jpl.nasa.gov/* and *http://www.nap.edu/*) recommends measurement and analysis strategies to understand: (1) the nature of deformation at tectonic plate boundaries and the implications for earthquake hazards; (2) the interaction between tectonics and climate to shape the Earth's surface and create natural hazards; (3) the interactions among ice masses, oceans, and the solid Earth and their implications for sealevel change; (4) the evolution of magmatic systems and the conditions of volcanoes eruptions; (5) the dynamics of the mantle and crust and the response of the Earth's

GRACE

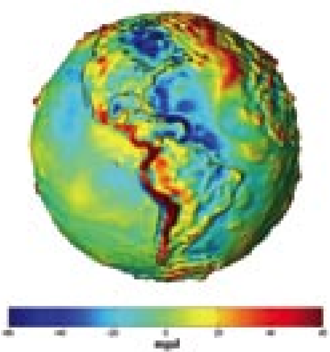


Figure 1: GRACE Gravity Field from Tapley, B, Ries, J, Bettadpur, S, Chambers, D, Cheng, M, Condi, F, Gunter, B, Kang, Z, Nagel, P, Pastor, R, Pekker, T, Poole, S, Wang, F GGM02 - An improved Earth gravity field model from GRACE, JOURNAL OF GEODESY, NOV 2005, Vol. 79, Iss. 8, PP. 467-478

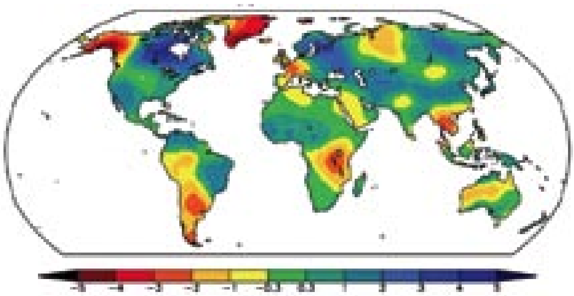


Figure 2: Scale is equivalent mass of surface water layer change in cm/yr. Rodell, M., J. S. Famiglietti, H. Kato, B. Zaitchik, and L. Gulden, Estimating Seasonal to Interannual Groundwater Variability Using GRACE, American Geophysical Union Fall Meeting, San Francisco, 11-15 December 2006.

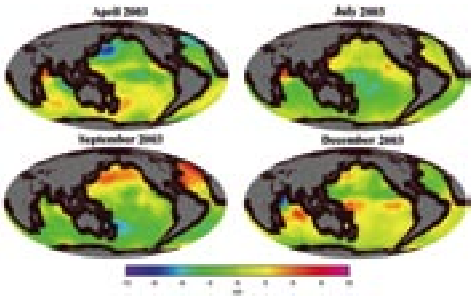


Figure 3: Scale is sea level change in cm. From D.P. Chambers, Observing Seasonal steric sea-level variations with GRACE and satellite altimetry, J. Geophys. Res., 2006, vol 111, C03010, doi:10.1029/2005JC002914

The Gravity Recovery and Climate Experiment (GRACE) is the first Earth System Science Pathfinder Mission. The goal of the GRACE mission is to provide measurements of the Earth's gravity field with sufficient accuracy to measure the transport of mass within the Earth's system on a monthly basis. GRACE is meeting that goal with over two-hundred publications relating to climate and geohazards related applications of its gravity field measurements. The GRACE gravity field has improved the accuracy of our knowledge of Earth's average gravity field by over 100 times, sufficient accuracy to verify the Lense-Therring Effect a component of the theory of General Relativity. Seasonal averages in the gravity field are being used to measure changes in seasonal ocean-heating patterns and water storage in continental river basins. Longer term averages are being used to study changes in mass distribution and their response to global climate change. Figure 1 displays the GRACE gravity field representing the cumulative measurements of the first three years of the GRACE mission.

If we examine the GRACE data for trends in gravity field over the 3.5 years of GRACE observations we find examples of changes in water storage and the long-term response of the solid Earth. Mass increases around Hudson's Bay in Canada and near the Scandinavian peninsula are caused by glacial rebound of the solid Earth due to the long term melting of the polar ice caps during the past 100,000 years. Melting of the ice sheet in Greenland and glaciers in Alaska, seen here as declines in water storage, have been documented using GRACE and other observations. It will become easier to distinguish real water-storage trends, caused by climate change or other anthropogenic influences, from normal variability in the water cycle as the data record from GRACE grows.

In Figure 3, the combined measurements of total sea level change measured by the Jason-1 radar altimeter and ocean mass change from GRACE are used to estimate the change in sea level due to ocean warming during 2003. The maximum in the northern hemisphere tends to occur in September and the minimum in April. This is the first direct measurement of the global scale effect of ocean warming on sea level, a significant driver and response to of the Earth's climate change.

Go to *http://gracetellus.jpl.nasa.gov* for more information on the GRACE mission results.

surface; and (6) the dynamics of the Earth's magnetic field and its interactions with the Earth System.

The SESWG report's strategy is carried out in three distinct elements:

- Space Geodesy: NASA developed Space Geodesy, the determination of the size and the shape of the Earth from space and continues to provide global leadership in its advancement leading to numerous significant discoveries, such as understanding mass transport within the Earth system (relevant to sea level change and crustal deformation) and the development and maintenance of the terrestrial and celestial reference frames (relevant to precision navigation of spacecraft). The principal components of NASA's Global Geodetic Observing Network include both ground observatories (Satellite Laser Ranging stations and Very Long Baseline Interferometry stations) and space-based assets such as the Laser Geodynamic Satellites (LAGEOS) and GRACE satellites.

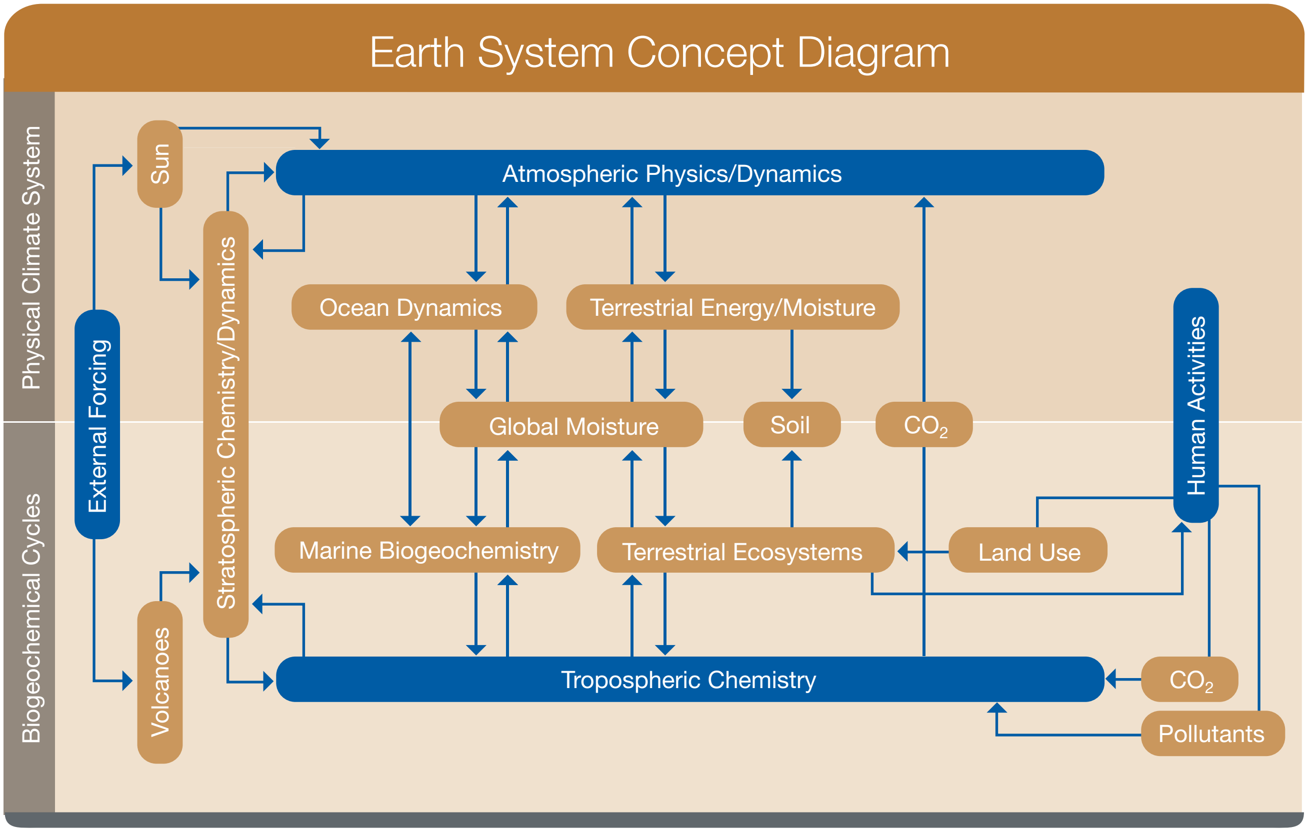
- Natural Hazards: This program element aims at capability to assess, mitigate and forecast natural hazards, such as earthquakes, landslides, coastal and interior erosion, floods and volcanic eruptions. Space-based geodetic and optical-imaging technology using radar, lidar, and hyperspectral visible and thermal imaging are evolving technologies to enable measurement of the slow subsidence of river deltas, the pre-eruptive inflation of volcanoes, and the buildup of strain along earthquake prone faults.
- The Earth's Planetary Interior: The dynamics of the Earth's interior are important to human existence as the driver of natural hazards and disasters. NASA's missions for the past several decades provided order-of-magnitude improvement in the development of advanced gravity and geomagnetic field models. Most notably GRACE enabled the first-ever determination of time-varying gravity field, which led and continues to lead to discoveries related to mass transport in the Earth system.

NASA's principal partners in this focus area are the USGS, the NSF, the National Geospatial-Intelligence Agency (formerly NIMA), U.S. Naval Observatory, and NOAA, as well as a broad array of international space agencies and organizations.

4.2.7 Interdisciplinary Science

NASA initiated its Interdisciplinary Science Program (EOS/IDS) more than a decade ago to advance understanding of the Earth system (Figure 4.2). EOS/IDS investigations have been focused primarily on developing understanding

Figure 4.2 - Earth System Concept Diagram derived from *Earth System Science: A Program for Global Change* (NAC, 1988). This report led to the development of EOS.



of interactive Earth system processes, Earth system model development, training the next generation of interdisciplinary scientists, and developing the necessary infrastructure to take full advantage of EOS data as they become available. Prior to the launch of EOS satellites, many of these investigations made use of precursor datasets. Together, these interdisciplinary projects were intended to establish a scientific foundation for exploitation of data from EOS satellite sensors and to make progress toward developing interactively coupled Earth system models that capture atmosphere-ocean-land-biosphere interactions across a range of space and time scales.

At present, the focus of the program is to: (1) exploit the vast wealth of new data from EOS and related satellites relevant to interdisciplinary research on interactions among components of the Earth system; (2) promote interdisciplinary research in topic areas of continued interest, particularly those identified as emerging science areas in the *Strategic Plan of the U.S. Climate Change Science Program* (*http://www.climatescience.gov*); and (3) pursue innovative interdisciplinary research in new topical areas. Results of research activities also provide inputs for, or promote the development of, models that advance predictive capability of important aspects of the Earth system.

Earth Science Opportunities Enabled by Human Exploration of the Moon

The return of human explorers to the surface of the Moon by 2020 creates additional opportunities for realizing Earth science priorities. During the period of time covered by this Science Plan, NASA will establish a “Lunar Exploration Architecture”—a baseline plan for the types of missions and the types of facilities that will be developed to support the Nation’s exploration goa
as well as the timescale in which those capabilities will be available to support Earth science activities.

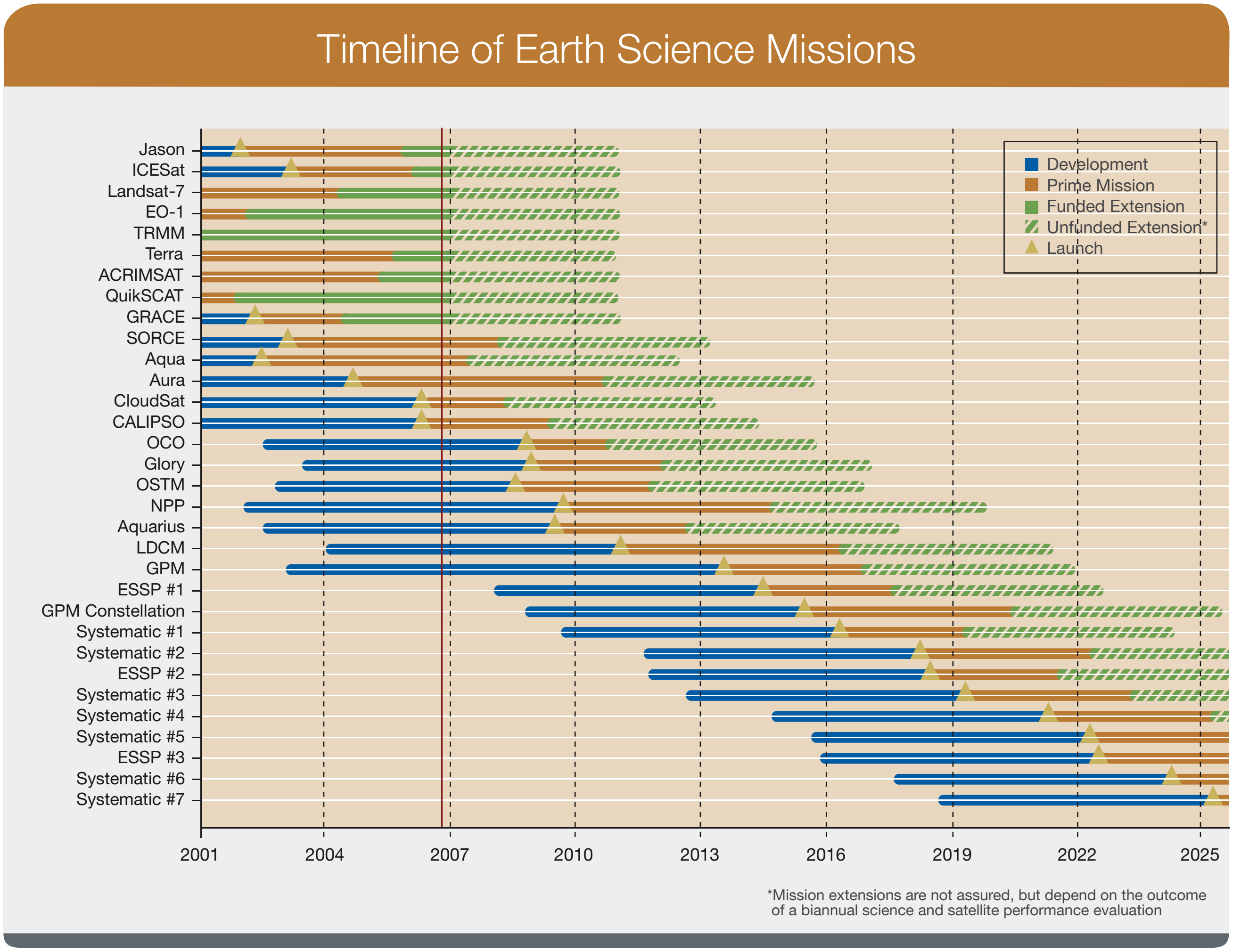
At the same time, NASA will conduct studies to identify potential investigations and projects that can realize priority Earth science objectives from the Moon. The interim report on *The Scientific Context for the Exploration of the Moon* (NRC, 2006) identifies “utilizing data from the Moon to characterize Earth’s early history” as one priority and suggests that better understanding of lunar cratering flux may help establish the history of impacts on early Earth. The report also identifies “determining the utility of the Moon as a platform for observations of Earth” as a priority and recommends that NASA evaluate the Moon’s potential as an observation platform for scientific observations of Earth. NASA is sponsoring an NRC study to identify those Earth science objectives that can be realized from the lunar surface and to determine the additional studies necessary to establish their cost and benefit. In 2007, NASA will select several concept studies for science investigations that can be realized on the short sorties that will be the first human exploration missions. Also in 2007, the NASA Advisory Council will sponsor a lunar science workshop aimed at establishing science objectives for the lunar exploration program.

In identifying Earth science mission concepts that can be realized from the surface of the Moon and in establishing the priorities for those potential missions, SMD will use the same community-based processes that have been used to establish priorities in the current Earth science program. Recognizing that newly enabled candidate missions must compete with other miss
science objectives in Earth science.

4.3 Mission Summaries

Beginning with the launch of the Terra satellite in December 1999, NASA began to deploy an EOS with the objective of collecting systematic, well-calibrated and validated, long-term measurements to characterize and detect change in the Earth system. A suite of polar-orbiting and low-inclination satellites, each carrying multiple sensors, linked to a data system for acquisition, processing, and distribution, provides numerous science data products with global coverage and repeated measurements of sufficient frequency and accuracy to address key aspects of global change. With the launch of Aura in July 2004, NASA completed the deployment of the observing system that now provides a core set of data products to characterize the Earth system and to identify and elucidate changes. In addition, satellites like GRACE, launched in March 2002, probe key Earth processes globally for the first time. The CloudSat and CALIPSO satellites, launched in April 2006, are recent additions to these highly focused exploratory measurement missions. Figure 4.3 provides the timeline of Earth science systematic and exploratory missions, including placeholders for future missions according to budgetary assumptions discussed in section 4.3.3.

Figure 4.3 - Earth science mission timeline (includes placeholders for future missions)



*Mission extensions are not assured, but depend on the outcome of a biannual science and satellite performance evaluation

4.3.1 Mission Classes

The hallmark of NASA's Earth Science Program is the synergy between different classes of observations, basic research, modeling, and data analysis, as well as field and laboratory studies. In the recent past, three types of space flight missions were distinguished: systematic observation missions, exploratory missions (PI-led), and operational precursor or technology demonstration missions. The identification of these categories represents a significant evolution of the original architecture of the EOS, which combined studying basic processes, assembling long-term measurement records, and introducing innovative measurement techniques. The distinction between these classes of missions facilitates a sharper definition of primary mission requirements and clearer selection criteria, ultimately leading to a shorter development cycle and more cost-effective implementation.

4.3.2 Missions in Formulation and Development

NASA plans to complete all missions that have been initiated prior to the Decadal Survey. Table 4.2 below provides a summary of the Earth Science missions presently in development and formulation phase and their connection to the Earth science objectives.

4.3.3 Planning for Future Missions

Several different options exist for developing future mission portfolios. In the course of maximizing the science return from Earth Science missions, SMD seeks to design the most cost-effective mix of mission sizes and types over

Table 4.2

Earth Science Future Mission Summary

Program	Mission	Objective (See Table 2.1)							Mission Objectives and Features
		1	2	3	4	5	6	7	
Systematic	NPOESS Preparatory Project (NPP)	●	●	●		●		●	Extension of key Aqua and Terra measurements supporting long-term climate observations. Partnership with the NPOESS Integrated Program Office; dependence on Integrated Program Office (IPO) for key instruments.
Systematic	Landsat Data Continuity Mission (LDCM)			●		●	●	●	Extension of multi-spectral moderate resolution land surface imaging. Partnership with USGS; NASA develops the observatory, USGS operates the satellite and distributes the data.
Systematic	Ocean Surface Topography Mission (OSTM)					●		●	Measurement of global sea surface height via radar altimetry. Partnership with France/CNES in development; partnership with NOAA and EUMETSAT for operations.
Systematic	Glory	●				●		●	Global measurement of aerosol and liquid-cloud properties, and total solar irradiance. NASA mission; migration to NPOESS is TBD.
ESSP	Orbiting Carbon Observatory (OCO)	●		●		●		●	Measurement of global column carbon dioxide. Competitively selected PI-led mission.
ESSP	Aquarius				●	●		●	Global measurement of sea surface salinity. Competitively selected PI-led mission; partnership with Argentina.
Systematic	Global Precipitation Measurement (GPM)		●		●	●		●	Frequent, high spatial resolution, microphysically detailed global precipitation. Constellation of satellites; partnership with Japan on core satellite; other satellites contributed by a variety of partners.

time. Three examples are provided of approaches to far-term planning, 2012 through 2025 below:

- Mission Profile with an ESSP every two years results in (1) medium-class systematic missions every other year starting in 2017 (five missions through 2025) and (2) an ESSP mission every other year starting in 2014 (six through 2025).
- Mission Profile with an ESSP every four years (see Figure 4.4) results in (1) medium-class systematic missions starting in 2016 (six through 2025); and (2) an ESSP mission every four years starting in 2014 (three through 2025).
- Mission Profile with an ESSP every four years including a large mission results in (1) a large mission in

2021 (one through 2025); (2) a medium-class mission starting in 2016 (four through 2025); and (3) an ESSP mission starting in 2014 (three through 2025).

Among the above options, it is likely that the most cost effective is secured by launching medium-class missions (~$500M) every 1-2 years with an additional ESSP mission (~$250M) every four years. Given the current budget projections, six medium-class missions and three ESSP missions can be implemented through 2025. Medium-level missions in general are cost-effective, provide a diversity of datasets to serve broad constituencies of the Earth science community, and can constitute the backbone for building a NASA strategic vision for Earth Science. ESSP missions offer opportunities to infuse new ideas and are widely competed. Large missions have the benefit of offering simultaneous observations of a large number of variables, but at the expense of management complexity and increased risk, often resulting in launch delays and unanticipated costs.

4.3.4 Representative Future Mission Elements

This section describes representative future mission elements, which may be implemented depending on the content of the Earth Science Decadal Survey conducted by the NRC. The elements discussed here are representative for each Science Focus Area (SFA) and have been among the top priorities for the respective SFAs as shown in the Earth Science SFA legacy roadmaps, representing longstanding science community perspectives. The overall priorities across the SFA are shown in the table below and have been discussed at community meetings, including the Earth Science Subcommittee of the NASA Advisory Council, as ideas for their consideration. Mission concept studies are currently underway by NASA Centers, guided by science working groups to further develop these ideas and establish cost baselines. Once the NRC Decadal Survey mission concepts and priorities are available, these mission elements will be adjusted accordingly. Furthermore, integrated mission studies will be conducted across the above elements to develop optimal implementation by considering crosscutting and complementary technologies and platforms. NASA will engage the science community in developing a mission roadmap to implement the science priorities of the Decadal Survey while achieving optimal implementation efficiency.

To further illustrate the kind of representational mission elements under study, the following descriptions are provided for the first entry in each SFA.

Changes in the Earth's Ice Cover

The Earth's ice sheets play a critical role in the Earth system primarily through their contributions to sea level, but also through their potential impacts on ocean and atmospheric circulation. Recently, the ice sheets of Greenland and West Antarctica have been showing dramatic ice losses in outlet glaciers near their margins, but, at the same time, the East Antarctic ice sheet and the central parts of Greenland have been growing. The extent of these changes and the mechanisms that control them are expressed in the change of surface elevations and topography. As a result, a mission that accurately measures ice-sheet elevation changes is critical to determining their current and likely future contributions to sea level. Because the ice sheets are so large (millions of square kilometers), even small vertical changes are of great significance. The ability to measure their surface elevation change at centimeter-scales is essential.

Sea ice is also a key component of the global climate system because of its effects on ocean and atmospheric circulation patterns. Its importance is amplified by the positive albedo feedback whereby, as sea ice cover diminishes, the exposed ocean absorbs more solar energy, which further warms the ocean and further melts the sea ice. Arctic sea ice has been shrinking significantly during the satellite era, and some estimates suggest the Arctic may be ice free in the summer in a matter of decades. The Antarctic sea ice is not showing similar losses, but it does exhibit local changes

Figure 4.4

Notional Future Mission Portfolio for Optimal Implementation

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
ESSP			OCO	Aquarius				ESSP				ESSP				ESSP			
Systematic Mission		Glory OSTM	NPP		LDCM		GPM		GPM Const	SYSP		SYSP	SYSP		SYSP	SYSP		SYSP	SYSP

Table 4.3

Potential Mission Elements/Measurements for Each Focus Area

Focus Areas	Potential Element / Measurements	Implementation Approach
Atmospheric Composition	Sentinel multispectral atmospheric composition	GEO or L1 spectrometers ultraviolet (UV)/visible, near-Infrared (IR), thermal IR
	Next Generation Aerosol Measurements	Multi-angle multi-spectral imaging polarimeter + High sensitivity backscatter lidar
	Atmospheric Composition for Climate and Transport	Advanced microwave sounder mid-earth orbit
	Systematic Upper Trop/lower Strat Composition	Micro-FTS Solar Occultation
Carbon Cycle and Ecosystems	Vegetation Three-Dimensional (3-D) Structure, Biomass and Disturbance	In priority order: 1) Profiling lidar; 2) P-band Synthetic Aperture Radar (SAR); 3) Interferometric Synthetic Aperture Radar (InSAR) Optimal: Combination of 1 and 2 or 3
	Global Ocean Carbon, Ecosystems, and Coastal Processes	LEO spectrometer and aerosol instrument; 20 aggregate bands in 350-1400 nm region with 5nm resolution from UV to 800nm (longer wavebands for atmospheric correction); 1km spatial resolution; SNR greater than 1000 for UV and visible aggregated bands, greater than 500 in near infrared
	Physiology and Functional Groups	Polar-orbiting imaging spectrometer(s) (~340-2500 nm)—with aerosol lidar for atmospheric correction. over ocean
Climate Variability and Change	Sea surface and terrestrial water levels	radar altimeter/ wide swath/ delayed Doppler
	ICESat Follow-on (Detailed Ice elevation, ice sheet mass)	Advanced laser altimeter
	Next Generation Ocean Surface Winds	Advanced scatterometer
Earth Surface and Interior	Wide Swath All Weather Geodetic Imaging	L-Band InSAR
	Land Surface Imaging	Spectrometers UV/visible, near-IR, thermal IR
	Advanced Gravity Measurements	GRACE-like satellite pairs, gradiometer constellation
	Geodetic Observing System	SLR/VLBI/GNSS ground networks
	Ionospheric Dynamics and Atmospheric Surface Pressure	GNSS Remote Sensing/Magnetometry

Potential Mission Elements/Measurements for Each Focus Area—Continued

Focus Areas	Potential Element / Measurements	Implementation Approach
Water and Energy Cycle	Global Soil Moisture	Active and Passive L-band (microwave) remote sensing system
	Surface Water Runoff	Dual Ka-band SARs
	Measurement of Snow and its Water Equivalent	Active Ku-band SAR + passive microwave radiometer (K or Ka band)
	Changes in Groundwater Storage	Constellation of GRACE satellite pairs
Weather	Global Wind Observing Sounder	Hybrid (coherent and direct detection) Doppler wind lidar
	Geostationary Synthetic Thinned Aperture Radiometer	Synthetic aperture microwave radiometer
	Active Temperature and Humidity Sounder	Combination active (i.e., lidar) and passive IR sounder
	Geostationary Precipitation Radar	Precipitation radar
Crosscutting	Advanced Remote-sensing Imaging Emission Spectrometer	Hyperspectral, high horizontal resolution IR and visible grating spectrometer imager sounder

that are of great importance to global ocean circulation and climate. Understanding the interactions between sea ice and the rest of the climate system now and in the future, requires detailed large-scale knowledge of how the thickness is changing. The most effective means of making such measurements is through observations of sea ice freeboard height (i.e., the height that the ice extends ice above water), which can then be converted to ice thickness. Because freeboard uncertainty translates to an order-of-magnitude greater thickness uncertainty, centimeter-scale elevation measurement precision is required.

For both sea ice and ice sheet changes, the required measurement is the same: accurate and precise surface elevation, which can best be achieved through an active laser altimetry approach. The feasibility of the approach has clearly been demonstrated by the ICESat dataset, and a tremendously valuable baseline against which future measurements can be compared has already been achieved. An advanced ice-elevation change mission will build on the groundbreaking achievements of the current ICESat mission, and enable continuous measurements of changes of ice sheet elevations as well as sea ice thickness and its changes. Moreover, ICESat has also demonstrated its utility for atmospheric measurements of cloud and aerosol vertical structure, hydrology, and vegetation structure, showing a clear applicability that extends beyond ice.

Global Ocean Carbon, Ecosystems, and Coastal Processes

How do carbon and other elements transition between ocean pools and pass through the global Earth system, and how do biogeochemical fluxes impact the global ocean and Earth's climate over time? How do hazards and pollutants impact the hydrography and biology of the global coastal zones? How (and why) is the diversity and geographical distribution of global and coastal marine habitats changing?

While the key biogeochemical stocks and fluxes in the ocean (e.g., particulate organic carbon, phytoplankton carbon, net primary production, organic carbon export) and their interactions are understood, their accurate quantification remains the primary uncertainty in global ocean biogeochemical cycles across environments ranging from clear open ocean waters to optically complex coastal waters. In order to derive particulate and dissolved carbon pools, detect physiological variability in phytoplankton, and quantify carbon source and sink sizes as well as key transformation rates, new space-based global observations are needed over an expanded spectral range and with finer resolution to utilize the rich information in ocean water-leaving radiances from the mid-UV wavelengths to the near infrared. These observations will allow for the accurate separation of in-water constituents (e.g., colored dissolved organic material, particle abundance, functional groups) by supporting the evolution of advanced ocean color algorithms (e.g. spectral matching approaches) and represent a maturation of ocean remote sensing science that learns from and builds upon the capabilities of current sensors and recent discoveries in carbon cycle and ecosystem (e.g., coastal fisheries, coral reefs, harmful algal blooms) research.

Observational requirements to meet the science goals involve a new mission to characterize ocean constituents and make supporting aerosol observations to effectively use the new spectral ocean color information. This mission would provide global coverage of continental shelves and near-shore environments, along with key polar regions particularly susceptible to climate variability (e.g., warming). The specification of an aerosol requirement for an ocean mission addresses the current limitations of the aerosol atmospheric correction in global ocean-color observations and supports functional linkages between atmosphere and ocean biological processes (e.g., iron fluxes to phytoplankton; biogenic aerosols and gases to the atmosphere).

Global Soil Moisture addresses the following two questions

How will water cycle dynamics change in the future? How are the variations in local water resources related to global climate variation?

Soil moisture estimates are required over the Earth's land surface to estimate the amount of water that is stored in and moved through the top layers of soil. Characterization of soil moisture is important because of its role in the exchange of water, energy, and carbon between the land and the atmosphere. Soil moisture is a critical component in determining the evaporation rates from the land surface (both from bare soil and through vegetation), making it an important quantity to measure accurately for weather forecasts and short-term (seasonal) climate prediction. Soil moisture observations have practical application, as well, for agriculture, water resource planning, disaster management (potential for floods, droughts, landslides), and for military trafficability determination.

Soil moisture measurements done *in situ* are difficult, time consuming, and expensive, making a global network of sufficient coverage and temporal frequency prohibitively expensive and logistically challenging. A future soil moisture mission using active and passive microwave remote sensing instruments would provide the needed observations. Assimilation techniques employing both *in situ* and current (non-optimal) satellite data have demonstrated the potential of such observations.

Global Wind Observing Sounder

Measurement of global wind profiles is recognized as the greatest unmet observational requirement for improving weather forecasts by the World Meteorological Organization, the large collection of nations planning the Global Earth Observation System of Systems, the NPOESS IPO, and NASA in its Weather Research Roadmap. The wind field plays a unique dynamical role in forcing the mass field to adjust to it at all scales in the tropics, and at smaller scales in the extratropics. Because of this, direct wind field measurement will have a much greater payback than improving accuracy and resolution of the mass field measurements already provided by advanced sounders, e.g., AIRS.

For extended vertical observations of global wind profiles, active remote sensors with range resolving capability are required. Doppler lidar techniques, which measure the change in wavelength of radiation backscattered from atmospheric molecules and aerosol particles, provide the best approach for full atmospheric coverage. No other viable alternative exists. Although Doppler radars can measure movement of cloud droplets and raindrops, only a small fraction of the volume in the troposphere and lower stratosphere contains clouds and rain at any given time. Molecules, however, are present in predictable amounts and aerosol particles abound in the boundary layer and clouds throughout the troposphere, providing a satellite-based lidar with continuous availability of scatterers. Preliminary analysis suggests that an optimum approach might consist of a hybrid instrument involving coherent as well as non-coherent methods.

Multispectral atmospheric composition addresses the following overarching questions

What effects do gaseous and particulate emissions have on global atmospheric composition in a variable and changing climate? How will future changes in atmospheric composition affect ozone, climate, and regional/global air quality?

The ability of the atmosphere to integrate surface emissions globally, on time scales from weeks to years and spatially from the surface to space, couples several environmental issues, including:

- Quantifying local sources and regional air pollution and the consequences of international and intercontinental transport of pollutants;
- Detecting and understanding stratospheric ozone depletion, its anticipated recovery, its interaction with a changing climate, and its impact on surface ultraviolet radiation; and,
- Quantifying climate forcing by radiatively-active gases and aerosols, particularly effects of reactive trace gases on aerosol/cloud formation and properties.

Increasingly, atmospheric research and observations are directed at the troposphere. Progress has been made possible by the development of high-resolution infrared and laser techniques, increasingly sensitive microwave detectors, and innovative analyses of ultraviolet data. The key issues are the variability and trends in surface emissions of ozone and aerosol precursors, the degree to which such precursors can be transported long distances, and the extent to which they undergo chemical transformations during their transport that effect downstream air quality. A multifaceted observational approach is needed, especially given the challenges of observing tropospheric gases and aerosols from space. For long-range transport and transformation of ozone, aerosols and their precursors, measurements of ozone, CO, NO_2, hydrocarbons (or their oxidized proxies such as CH_2O), and aerosols are needed with global-scale spatial coverage and high vertical resolution. In addition, water vapor is a key constituent for both chemical and radiative processes. Vertically resolved global distributions of water vapor are a critical ongoing need. A continuous, high-temporal and high-spatial measurement approach is needed to investigate the variability and trends in surface emissions. The key gases of interest are the same as those listed above. Aerosol precursor emissions of interest are SO_2, hydrocarbon, mineral dust, sea salt, and black carbon.

To properly address some of the scientific challenges summarized above requires two satellite missions: (1) an active or imaging system in LEO that enables high vertical resolution with global coverage; and (2) a high-temporal resolution mission in geostationary orbit or at the Sun-Earth Lagrange point L1 to observe atmospheric composition and transport on diurnal time scales to capture the interaction between climate and air quality.

Sea surface and terrestrial water levels

Sea surface levels are a critical climate variable in the Earth system, one that is tightly coupled to other parameters including sea ice extent, land ice mass, sea surface temperature, and so on. Sea level rise has the potential to impact the lives of hundreds of millions of Earth's inhabitants who live in the coastal zones. Conventional nadir-pointing radar altimetry as expected for the OSTM, and similar to the TOPEX/Poseidon and Jason-1 measurements, provides excellent continuity for measurements of global sea level. In addition, continued nadir altimeter measurements are needed for studies of basin-scale ocean circulation, heat transport, and El Niño/La Niña.

An enhanced type of radar altimeter, known as a wide-swath altimeter, can achieve the continuity needed for sea-level change measurements, while also providing greatly enhanced science return. A wide-swath altimeter uses radar interferometry to separate returns in one spatial dimension (across-track) and delay-Doppler processing to separate returns in the orthogonal dimension (along-track). This capability provides enhanced spatial resolution and temporal revisit time to allow measurement of mesoscale activity, including fronts, eddies, and boundary currents; eddy mean-flow interactions, eddy transports, and the role of eddies in climate; physical-biological interactions and the role of eddies in the carbon cycle; coastal tides and open ocean internal tides; and coastal currents.

High spatial resolution, wide-swath radar altimetry can resolve individual water bodies such as rivers, lakes and reservoirs on land. Measurements of the variability of terrestrial water levels over such bodies are one of the critical missing pieces in the terrestrial water budget. Such measurements will enable hydrologists to determine surface water storage change and discharge to predict the land surface branch of the global hydrologic cycle; measure flood hydraulics; and enable scientists to assess the role of fresh water storage as a regulator of biogeochemical cycles such as carbon and nutrients. A wide-swath altimeter can also improve our understanding of marine gravity field and global bathymetry at scales sufficient to resolve roughness that drives ocean mixing, internal wave generation, and tidal generation and would allow determination of the heights of seamounts accurately enough for navigation and habitat considerations.

Vegetation Three-Dimensional (3-D) Structure, Biomass, and Disturbance

How are the Earth's carbon cycle and ecosystems changing, and what are the consequences for the Earth's carbon budget, ecosystem sustainability, and biodiversity?

Measurements of vegetation structural characteristics over the Earth's land surface are needed to estimate biomass and carbon stocks and to quantify biomass recovery following disturbance in order to reduce uncertainties in the global carbon budget. These measurements are vegetation height, the vertical profile of canopy elements (i.e., leaves, stems, branches), and/or the volume scattering of canopy elements. A major source of uncertainty in global carbon budgets derives from large errors in the current estimates of above-ground carbon storage in terrestrial vegetation. Disturbance by natural phenomena, such as fire or wind, as well as by human activities, such as forest harvest, and any subsequent recovery complicate our ability to quantify carbon storage and release. As a result, terrestrial biomass and carbon in vegetation are very difficult to estimate with uniformity over large areas. A vegetation 3-D structure, biomass, and disturbance mission will enable critical estimates of changes in vegetation carbon stocks, thereby substantially reducing uncertainties about major factors affecting atmospheric concentrations of CO_2 and CH_4.

Vegetation vertical profiles and disturbance recovery patterns are also required to assess ecosystem health and characterize habitat. The 3-D structure of vegetation provides habitats for many species and is a control on biodiversity. Canopy height and structure variables influence habitat use and specialization, two fundamental processes that modify species' richness and abundance across ecosystems. Accurate and consistent 3-D measurements of forest structure at the landscape scale are needed for assessing impacts to animal habitats following disturbance. New understanding of relationships between vegetation structure and underlying processes, especially disturbance, will enable more effective management and utilization of natural resources and will likely lead to the discovery of fundamental processes that control biodiversity.

The satellite mission requires an active remote sensing approach to make continuous or repeated measurements of vegetation height and the vertical distribution or volume scattering of above-ground biomass.

Wide Swath All-Weather Geodetic Imaging

Geodetic imaging is the newly emerging capability to precisely measure via remote sensing the Earth's topography and its change over large regions. The land surface deforms both vertically and horizontally as a result of a number of geological and geophysical processes, many of which have significant implications for natural hazards. Episodic deformations arise from earthquakes and volcanic activities whose measurements are essential to understanding and mitigating these natural hazards. Aseismic deformation before and after earthquakes can now be measured as a result of space technologies. Timely measurement of this deformation is considered key to understanding earthquakes and the Earth's internal dynamics. Postglacial rebound occurs by slow, large-scale deformation that provides great insight into the mechanical properties of the solid Earth and influences the measurements of sea level changes at tide gages. Local land subsidence due to groundwater withdrawal, river and coastal erosion and deposition, landslides, and debris flows all impact the land surface and affect human livelihood. Continuous perturbation of the land surface arises from solid-Earth tides and loading by variations in atmospheric pressure, oceanic circulation, and the distribution of water and ice.

An Earth surface deformation mission is the highest priority for the Earth Surface and Interior focus area as presented in the strategic vision of the Solid Earth Science Working Group (SESWG) report and endorsed by the NRC review of 2004. Interferometric synthetic aperture radar (InSAR) is the most likely candidate technology to provide all-weather, wide-swath geodetic imaging capable of resolving millimeter scale deformation of the Earth's surface.

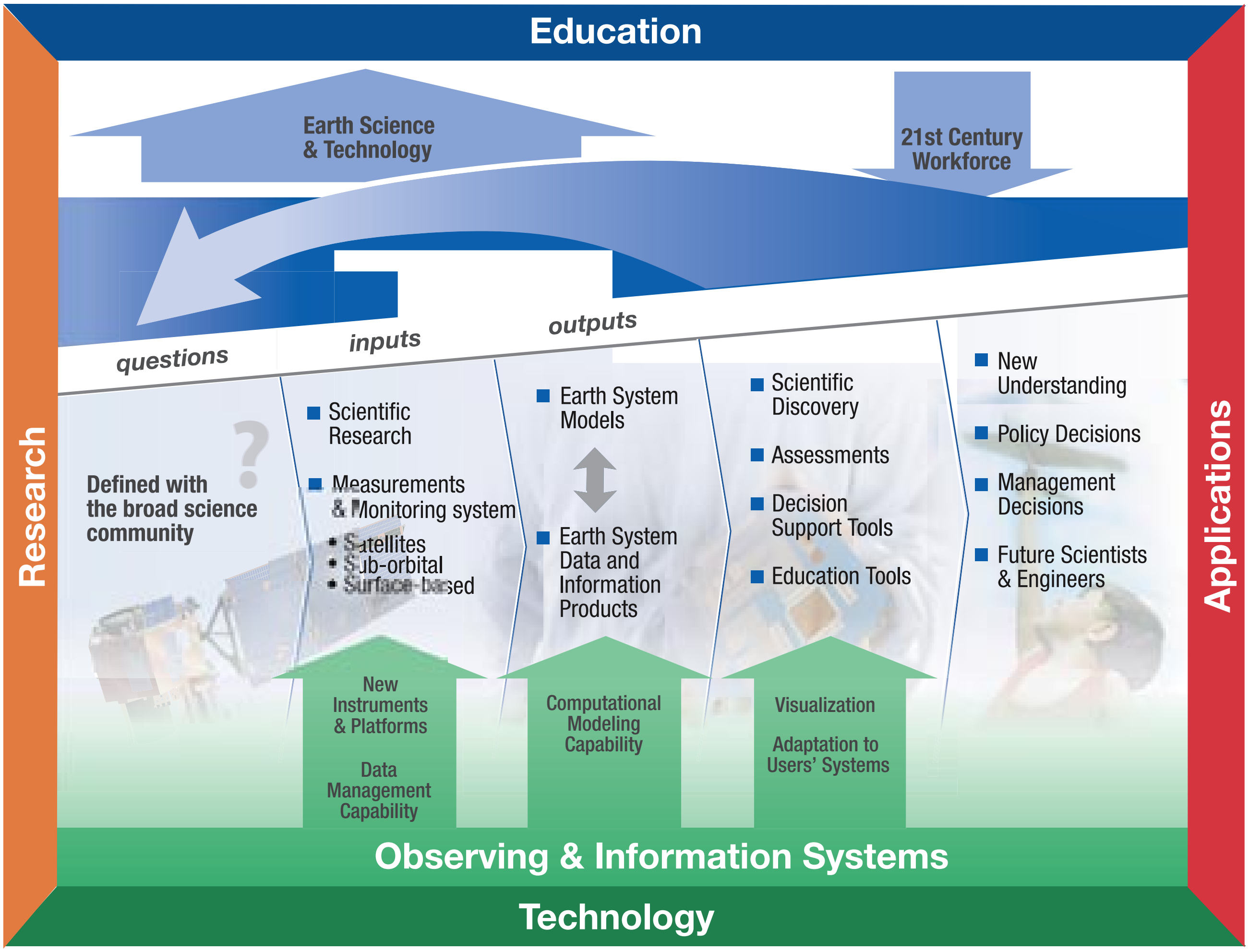
4.4 Program Elements

NASA's Earth Science Program is an end-to-end one that starts with the development of observational techniques and the instrument technology needed to implement them; tests them in the laboratory and from an appropriate set of suborbital (surface, balloon, aircraft) and/or space-based platforms; uses the results to increase basic process knowledge; incorporates results into complex computational models that can be used to more fully characterize the present state and future evolution of the Earth system; and develops partnerships with other national and international agencies that can use the generated information in environmental forecasting and in policy and resource management. Figure 4.5 illustrates this end-to-end framework and how the following program elements contribute.

4.4.1 Research and Analysis Program

The Earth Science Research Program is built around three related components—R&A, mission science teams, and EOS science. The R&A program serves as the "scientific base" for the overall Earth science endeavor. It is where

Figure 4.5 - Earth Science for Society Framework



basic scientific questions are recognized and addressed, where techniques (laboratory, field observations, modeling, and data integration) are developed, and where much of the infrastructure (especially for the instrumentation and scientific capability for calibration, validation, and modeling) is supported. The R&A program is organized around a recognized set of scientific disciplines and works to assure both present-day capability and longer-term innovative potential for the entire Earth science program. The open nature of the R&A program makes it the home for much of the training of future Earth system scientists. The mission science teams are the entities that work to most directly provide scientific results for NASA's Earth science missions. They focus on the development of retrieval algorithms and the quantitative use of NASA satellite data, both alone and in context of other satellite missions and suborbital activity, to address NASA's scientific questions. The EOS science program provides for enhanced calibration and validation activities that support the entire Earth science flight program and for a modeling and analysis program that emphasizes interdisciplinary scientific questions of broader scope than those addressed in the R&A program.

Earth system science is inherently interdisciplinary, and much of the cutting-edge science requires integration of techniques from multiple disciplines and data from multiple satellites, as well as that of space-based and suborbital data. In addition, the exacting requirements for calibration and validation for Earth science satellite products require the maintenance of an extensive set of surface-, aircraft-, and balloon-based observational capabilities that can be used to support satellite validation, as well as provide complementary observations that can be integrated with them. In meeting these challenges, the Earth Science research program both draws heavily on and contributes to, related activities in high end computing, suborbital science, applied sciences, and data management described below. This program is closely coordinated with those of its national and international partners, through domestic interagency activities (such as those under the Climate Change Science Program, the U.S. Group on Earth Observations, and the Ocean Action Plan) and international scientific partnerships (e.g., the World Climate Research Program, the International Geosphere-Biosphere Program, and the International Polar Year).

4.4.2 Applied Sciences Program

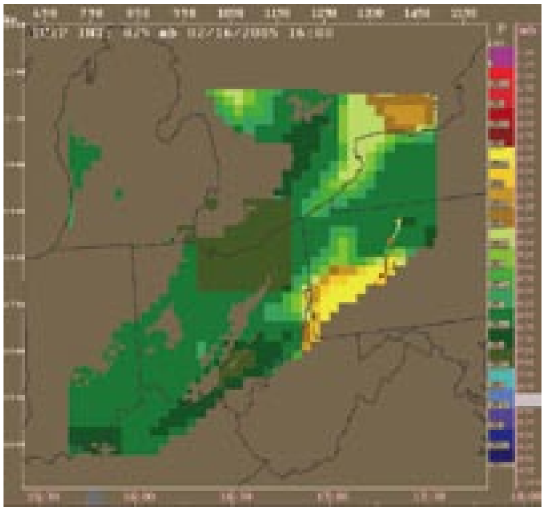
In pursuing the answers to fundamental science questions about the Earth system, many important results are achieved that can be of near-term practical benefit to society. The Applied Sciences Program's role is to extend the benefits of the scientific activities results achieved. These results take the form of NASA's:

- Observations from research satellites;
- Predictive capabilities from Earth system models;
- Outcomes from investments in mission enabling technology;
- Information products from data-management systems;
- Simulated sensor experiments for future spacecraft instruments;
- Capability from high-performance scientific computational and networking systems; and
- Knowledge gained from investments in research activities in the Science Focus Areas.

The Applied Sciences Program extends the usefulness of these results for societal benefit by working in partnership with entities that have operational decision-making responsibility. Joint activities benchmark the uses of NASA research results for decision support, quantifying the improvements our partners make in their decision-support systems by incorporating these results. To optimize the value of the societal benefits, the partners are typically Federal agencies or others that have regional- or National-scale responsibilities. The program is organized in two interrelated elements:

- The National Applications Element currently expands and accelerates the use of the results from NASA Earth science research through twelve applications of national priority: Agricultural Efficiency, Air Quality, Aviation, Carbon Management, Coastal Management, Disaster Management, Ecological Forecasting, Energy Management, Homeland Security, Invasive Species, Public Health, and Water Management. NASA engages public, private, and academic organizations in innovative approaches for using science information enabled by spacecraft observatories to provide decision support to serve society in these national applications. The program's National applications mirror most of the areas of interest for domestic initiatives, such as U.S. Group on Earth Observations (USGEO), and international initiatives, such as the Group on Earth Observations (GEO).
- The Crosscutting Solutions Element extends the benefits of the spectrum of observations from current and future NASA missions. These activities are intended

Aviation National Application



CIP Severity product original estimate at 825 hPa. Severity index increases from bottom to top of scale. Areas outside the colored pixels have negligible icing potential at this level. (16 Feb 2005)

The Current Icing Potential (CIP) Severity product is an automatically generated index of icing severity developed by the In-Flight Icing Product Development Team (IIPDT) sponsored by the Federal Aviation Administration's Aviation Weather Research Program. CIP Severity is scheduled to become an operational product of the NOAA/National Weather Service Aviation Weather Center in December 2006. This product will be available on the Aviation Digital Data Service (ADDS—*http:// www.aviationweather.gov/*).

Icing severity is incorporated into the CIP product using cloud microphysical data currently available from the Rapid Update Cycle (RUC) Model and advanced NEXRAD and Terminal Doppler Weather Radar algorithms. They are concurrently being integrated and tested by the FAA IIPDT to produce the seamless CIP Severity coverage needed over the continental U.S., Alaska, and Canada.

to demonstrate the usefulness of all NASA research results, including the results that will be achieved by current and future missions, such as CloudSat, CALIPSO, OCO, Aquarius, GPM, and others. To accelerate the use of future research results, this element invests in a crosscutting capability to (1) create candidate configurations of NASA observations and predictions with operational decision support systems; and (2), rapidly prototype experiments to test the viability of these candidate configurations.

4.4.3 Earth Science Technology Program

The Earth Science Technology Program is designed to foster the creation and infusion of new technologies into Earth Science activities, to enable new science observations, or reduce the cost of current observations. Requirements for advanced-technology development are based on requirements articulated in the *Earth Science Research Plan*.

Technology requirements are identified using a collaborative process of dialog between scientists, engineers, and technology experts that is recorded and made available through a widely accessible database. This provides a basis for the management of the technology-investment portfolio. Implementation is performed through open-competition solicitations in three distinct, but related, elements:

- Advanced Technology Initiatives (ATI)—Concept studies and component and subsystem technologies serving as the building blocks for instruments, platforms, and information systems;

- Instrument Incubator Program (IIP)—Instrument technology investments include passive and active sensing techniques, such as radar systems, large lightweight antennas, and active optical sensors using lasers; and

- Advanced Information Systems Technologies (AIST)—Technology developments include onboard processing, space communications, mission automation for self-tending spacecraft and instruments, and information synthesis to derive information from extremely large, complex data sets.

Remote sensing, computing, and communications technologies play a crucial role for the Science Focus Areas. Sustained technology developments are needed to provide future remote-sensing improvements and new capabilities that support advanced Earth-science research activities.

4.4.4 Modeling and High-End Computing

Effective use of Earth observations challenges the capabilities of the world's high-performance computing systems. Our ability to predict changes in the Earth's environment depends critically on simulating biogeochemical cycles, climate, weather, and natural hazards with fully coupled Earth system models constrained by observations. Beyond being the means for prediction, models enable analysis and optimal design for future observational schemes, thus guiding the science requirements for future satellite missions. Such Earth system simulations, based on accurate representation of a diverse set of interacting physical, chemical, and biological processes over time scales from days to centuries, are among the most demanding computational challenges facing scientists today.

NASA modeling efforts couple current observations with models through data assimilation, to support elements of Earth System Science. Reanalysis of data utilizing state of the art model-data assimilation over the satellite data record provide a test bed for climate models in the short term and also provide 'data' for considering sensor design of future investigations. Associated with reanalysis and assimilation are Observing System Simulation Experiments (OSSE) which, again, use model-data assimilation systems to evaluate potential value of next-generation observations.

The requirements imposed by the challenge represented by model representation of the Earth system provide a significant challenge given the multiplicity of modeling approaches, the range of implementation methods and systems, and the need to support innovation in implementing model components while facilitating comparisons of the different approaches. In response to this challenge, NASA has led development of the interagency development Earth System Modeling Framework (ESMF). The ESMF provides an improved ability to test and integrate model elements and verify that model results and differences are the result of new physics/chemistry/ecosystems elements, not mechanical interface issues, interpolation assumptions, etc. NASA model development with ESMF has allowed evolution of its core capability to new models that support analysis from weather to climate temporal and spatial scales. These new models are coupled to jointly developed NASA-NOAA assimilation systems and joint development of next generation assimilation.

The computational demands of Earth-observing systems extend from the acquisition of data from platforms in space to comprehensive Earth system simulations. The volume of remote sensing data products makes their routine production, storage, and distribution major computational requirements with unprecedented network and storage demands. Fully

Table 4.4

Remote Sensing Technology Needs by Science Focus Area

Remote Sensing Technologies	Science Focus Areas					
	Atmospheric Composition	Earth's Surface and Interior	Climate Variability and Change	Carbon Cycle & Ecosystems	Weather	Water and Energy Cycle
Advanced Broadband Spectrometer			●		●	●
Advanced Imaging Spectrometry	●	●	●	●	●	●
Advanced Microwave Sounder	●		●		●	●
Inspace Multi-frequency Lidar	●	●	●	●	●	●
Inspace differential Absorption Lidar (DIAL)	●			●	●	●
Inspace Doppler Lidar			●		●	
Multiangle Imaging Spectroradiometry	●	●	●	●	●	●
Advanced Radar and Laser Altimetry		●	●	●		●
Advanced Thermal Radiometry	●	●		●		●
Advanced Microwave Radiometry	●		●		●	●
Large Aperture Antenna Radiometry			●		●	●
Interferometric Synthetic Aperture Radar		●	●	●		●
Advanced Scatterometry			●		●	●
Large, Lightweight Antennas		●	●	●	●	●
Advanced Hyperspectral Radiometry	●	●		●		
Laser Interferometry		●	●			●
Quantum Gravity Gradiometer		●	●			●
Computing and Communications Technologies						
Standards and Interface Protocols	●	●	●	●	●	●
Data Mining and Data Fusion	●	●	●	●	●	●
High, Sustained Computational Throughput	●	●	●	●	●	●
High-Volume Data Management	●	●	●	●	●	●
Onboard Data Processing	●	●	●	●	●	●
Data Grids	●	●	●	●	●	●

coupled Earth system modeling further exemplifies the computational demands of Earth system analyses. Due to the nonlinear interaction between physical, chemical, and biological processes, an ensemble of model simulations must be performed to achieve statistically significant results. When satellite observations are assimilated into these simulations, the combined computational demands of data handling and ensemble model solution constitute a grand challenge in computing.

NASA is addressing these challenges by deploying advanced computing systems at several levels as well as research and development to derive, test, and implement the algorithms and other software systems required to make effective use of the emerging hardware architectures best suited to each research task. During the acquisition and deployment of computing systems, special attention will be paid to the computing and computational requirements to understand the nonlinear interactions between physical, chemical, and biological processes.

4.4.5 Data and Information Systems

With its focus on observations, NASA Earth science research depends on advanced data systems to acquire measurements, produce data products, provide active archives, and distribute data to research investigators. The Earth Science Data and Information Project provides scientific users, as well as a large and diverse general user community, with access to NASA's Earth science data, primarily through the EOS Data and Information System (EOSDIS). EOSDIS was developed as an end-to-end system, including command and control of satellites, management of data from satellites and field measurement programs, active archive, distribution, and information management. EOSDIS has been operating since 1999, and has evolved to incorporate emerging technology and changing research needs.

Currently, NASA Earth observing satellites provide about 500 Gbytes/day (500 x10^9 bytes/day) of instrument data from space, producing approximately 3 Tbytes/day (3 x10^{12} bytes/ day) of data products. Each year, NASA's space assets contribute about 1.2 Pbytes (1.2 x10^{15} bytes) of data to Earth science research. This enormous data stream is the primary resource for Earth science research with NASA and fuels a broad range of research, application, management, and decision activities worldwide. NASA manages these data with its user communities' advice, deleting or moving to lower levels of service products no longer considered useful or where more accurate observations become available.

Currently managing more than 2,800 data sets and distributing data to more than 185,000 users, EOSDIS continues to serve as the primary active archive and distribution system infrastructure for Earth observations obtained by NASA. Eight Distributed Active Archive Centers (DAACs), representing core Earth science disciplines, process, archive, and distribute NASA Earth observation data. Many science data products are produced on Science Investigator-led Processing Systems under the direct control of instrument teams while a few use the science data processing systems within the DAACs. In either case, the algorithms and quality assurance are provided by instrument teams. NASA's strategy is to continue to evolve and streamline this core infrastructure, while adding competed and peer-reviewed innovative elements needed to fully develop and access Earth science data records needed to answer the science questions.

4.4.6 Suborbital Science Program

Measurements on land and within the Earth's atmosphere and oceans are required to calibrate and validate measurements from space and are an integral part of a complete Earth observing system. Suborbital measurements and sensors on the Earth's surface augment observations from space with higher spatial and temporal resolutions that can be targeted at specific regions or focused on specific processes. Additionally, major experiments and field campaigns provide detailed information on processes observed from space, therefore playing a critical role in NASA's end-to-end program implementation frame work as the link between space-based observations and Earth system models. Thus, NASA recognizes that a comprehensive Earth observing system requires a global, integrated approach combining observations from spacecraft, suborbital platforms such as aircraft and balloons, surface instruments such as carbon-flux towers and ocean buoys, as well as major experiments and field campaigns engaging multiple surface and suborbital measurements, carefully coordinated with satellite observations.

Aircraft and other suborbital platforms provide laboratories for testing new approaches and sensors. Experience with suborbital observations is important for determining the value of sensors for space missions. Data collected by prototype sensors or simulators for sensors intended for satellite deployment are crucial for algorithm development and testing. In addition to their critical role in calibration, validation, and sensor development, suborbital remote sensing data complement satellite observations with higher resolutions and less interference that are often critical for characterizing heterogeneity in space or time or for understanding complex processes. In addition, aircraft data are critical for successful data assimilation into models as correlative measurements not obtainable from space and by providing error characterization and scale bridging among satellite observations, surface sites and model grids.

The Suborbital Science Program supports the infrastructure that supplies the suborbital-based data streams. This consists mostly of the aircraft (both traditional and unmanned) that are used as airborne laboratories and the aeronautical engineering base needed to modify and develop aircraft as Earth-observation platforms. Also included are design and engineering services for airborne sensors and field mission support. The program works closely with the managers of the R&A and EOS programs to determine what platforms should be supported, technology directions, and the schedule for suborbital missions and field campaigns. Priorities for the program are driven by the need to integrate the new data streams coming from satellite missions into the interdisciplinary R&A studies.

4.4.7 Earth Observation and Science Partnerships

NASA conducts Earth science research within a complex national and international context. While there are 13 participating agencies in CCSP, NASA continues to be the largest contributor to CCSP (appromately 60 percent) and provides active leadership and support of several CCSP interagency working groups. NASA's EOS and ESSP satellites now in orbit comprise the Nation's space-based research observing system for climate change. As described earlier, NASA has partnered with operational agencies in the U.S. (e.g., DoD, NOAA, USGS) and elsewhere to ensure the long-term continuity of key environmental measurements in the future. To that end, NASA's participation in NPOESS is actively aiming at continuing research data needs for systematic observations, share the cost of new developments, and develop precursor instruments and spacecraft technologies for future operational missions. The recent restructuring of NPOESS is a setback to this strategy, and NASA, NOAA, and OSTP are working to define a new way forward.

More broadly, NASA and NOAA have established a Joint Working Group (JWG) on Research and Operations. The JWG will identify near-term NASA research capabilities that can be transitioned to support NOAA operational use, and identify NOAA operational capabilities to support NASA research activities. Thus far, the JWG has outlined the transition process and recommended several near-term opportunities under five categories of activities: observing capability transition, mission extension, data record development and stewardship, data utilization, and tools and standards transition.

NASA's space assets, data management, and distribution systems and Earth science applications constitute significant contributions to each of the nine societal benefit areas highlighted in the *Strategic Plan for a U.S. Integrated Earth Observation System* (IEOS, 2005) and the *10-Year Plan for a Global Earth Observation System of Systems* (2005). GEOSS is designed to benefit from the full scope of the results of NASA research and development programs, flight missions and applied sciences partnerships on benchmarking enhancements to integrated system solutions for the nine societal benefit areas. NASA leadership contributed to developing and refining the framework and architecture of the U.S. IEOS and international GEOSS plans. The plans provide guidance in the direction for evolving research capacity (including NASA contributions) to enable improved future operational systems. NASA contributes to the national interagency activity through participation in the USGEO, a subcommittee of the interagency Committee on Environment and Natural Resources (CENR). SMD senior officials serve in the roles of Co-Chair and other positions of the USGEO and on the committees of the international Group on Earth Observations.

The Earth science program also has over 130 agreements with 55 countries' space agencies and Earth science research agencies, ranging from simple data-sharing arrangements to joint space missions. As described earlier, NASA's Earth science program is a key contributor to important international research programs and scientific assessments of global change.

4.4.8 Earth Science Education and Public Outreach

NASA Earth science is in a unique position to inspire, engage and educate the public about Earth system science by administering E/PO activities, which instill a passion for understanding and appreciating the complexity of the many aspects of the Earth system.

Inspiration of the next generation of Earth explorers begins at the K-12 level. Nationally and internationally recognized programs serve to enhance our Nation's talent pool in the areas of STEM. By funding programs that allow students to conduct grade-level appropriate environmental research, develop microsets of Earth science data from NASA satellite missions, and investigate migratory patterns of land and marine animals using data relayed from satellite transmitters, the Education Program assures that young students are actively engaged in dynamic, relevant, highly technological Earth science activities. Additionally, the K-12 Earth Systems Education Portfolio includes innovative educator professional development and classroom support materials as well as student summer intern activities and competitions.

Educational efforts at the undergraduate, graduate and post-doctoral levels intentionally shift focus toward the anticipated employment of those students within the environmental research and applications community. Grant money is available to allow educators and NASA scientists to collaborate on course and curriculum development. Opportunities are provided to use NASA data and technology in a variety of applications by awarding short term and long term fellowships. Several programs at this level target underserved and underrepresented student populations. The Earth System Science Fellowship Program (now a part of the new NASA Earth and Space Science Fellowship Program) and the New Investigator Program in Earth Science, designed to strengthen NASA's and the Nation's future workforce, are focused on training interdisciplinary Earth scientists.

Beyond and outside formal settings, there exist other opportunities to educate the public. Because the public experiences the direct effects of weather, climate and natural hazards events (such as hurricanes, earthquakes, droughts), there is an inherent level of interest and engagement in the underlying science. Informal education institutes, such as museums and science centers, are supported with a variety of outstanding Earth science programs, many of which provide rapid access to the latest NASA imagery and serve to sustain public lifelong learning. These partnerships not only promote an awareness of NASA's resources, but also continue to support STEM literacy beyond formal education. A primary near-term focus will be to engage, inform, and inspire diverse public audiences by broadly communicating recent advances in the Arctic and Antarctic research and climate science to correspond with the upcoming International Polar Year (2007–2008).

4.5 Earth Science Beyond 2016

The longer-term future for Earth science at NASA is focused on (1) providing to both provide dramatic advances in the type and availability of global environmental information through advances in observational and information science and technology; and (2) informing a significantly broader class of users of environmental information to make policy, management, and forecasting decisions.

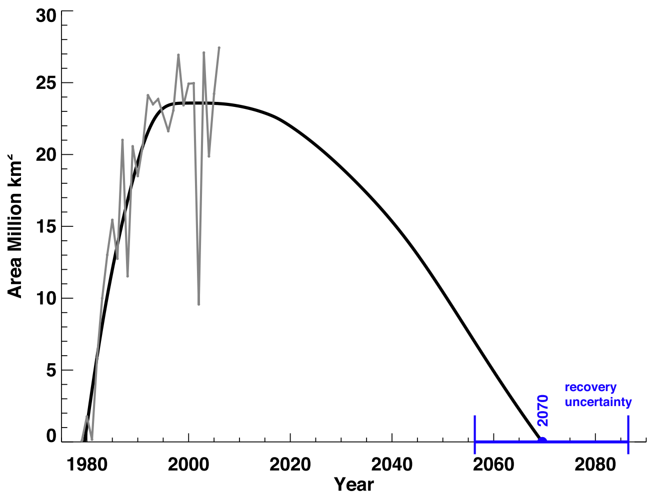
Developments in observational and information science and technology to be made over the next decade should enable fundamental changes in the nature, quality, resolution, and availability of global environmental information in succeeding decades. In particular, significant advances are seen in a number of areas, the combination of which will facilitate use of global environmental data in new ways:

- Advances in sensor and platform technology will enable new classes of environmental observations to be made with spatial and temporal resolution exceeding that previously available;

- Advances in information-systems technology, artificial intelligence, and onboard processing will allow for rapid and efficient identification of phenomena of interest and optimizing information to facilitate efficient transfer to the ground of the most useful results;

Figure 4.6

The Antarctic Ozone Hole



The appearance of the Antarctic Ozone Hole took the world by surprise even though ozone depletion from anthropogenic sources was predicted. Once it was discovered, NASA led the way in providing accurate tracking of its size and depth and the scientific explanation of its development. This leadership was enabled by an in-place robust supporting research capability throughout NASA's Earth Science Program. The diagnosis and response to global ozone depletion is an instance of how an environmental catastrophe was averted through careful observations, modeling, assessments and subsequent policy implementation. NASA research continues to make a major contribution in the international assessments of ozone depletion.

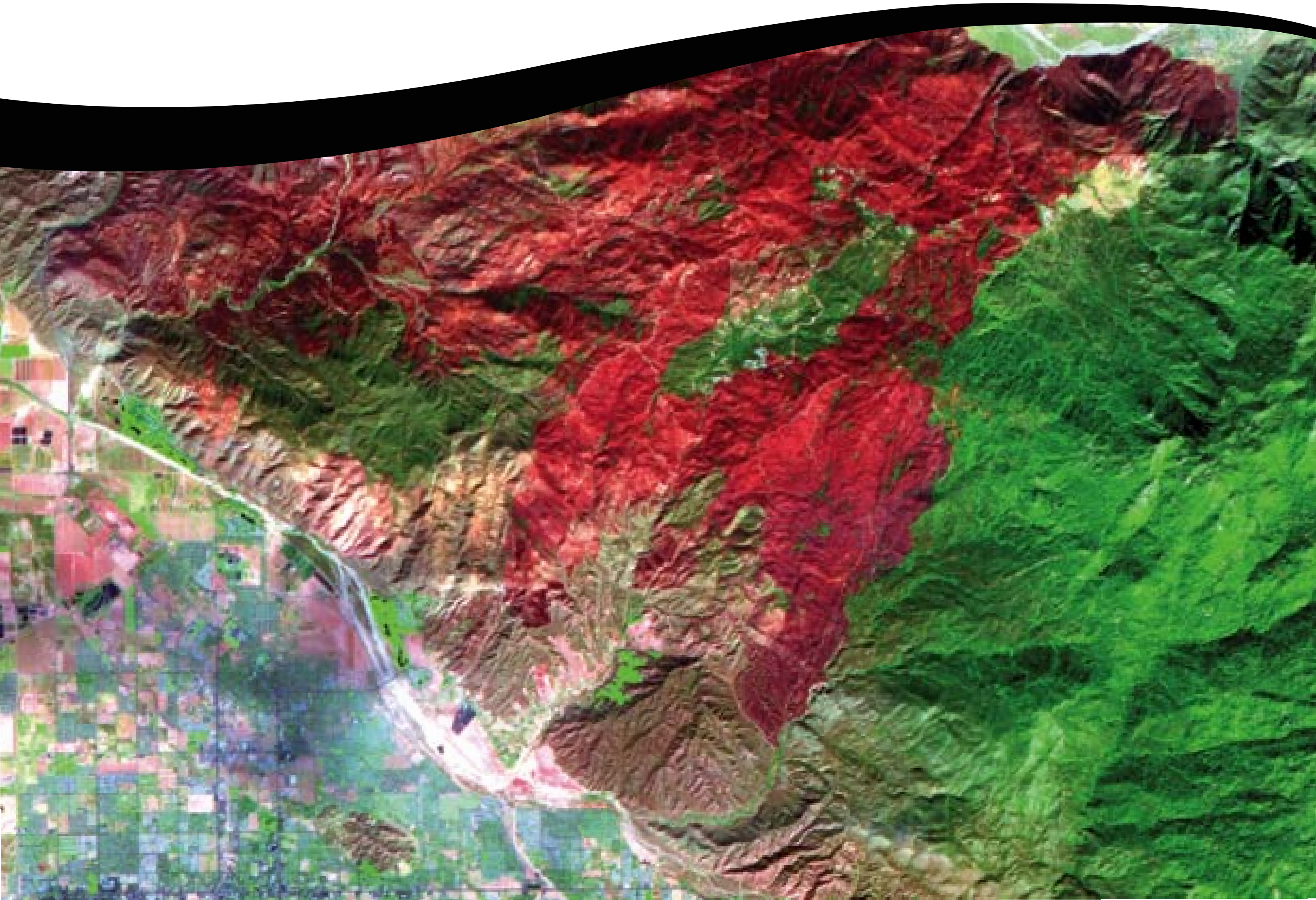
Model calculations by Paul Newman at NASA's Goddard Space Flight Center

- Advances in computing, networking, and visualization will allow for the delivery of needed data products in desired forms to end users in the appropriate time frame for maximum usefulness; and,

- Advances in science will assure the availability of algorithms designed to capitalize on technological advances, the accurate representation of geophysical and biogeochemical processes in models that are used to assimilate new observations and their use in initializing predictions, and the availability of models that add value to the observations.

As the nature, quality, resolution, and availability of the data are increasing, so will the set of users utilizing it to make policy, management, and forecasting decisions. While a variety of users already exist for NASA's global satellite information, and the scope of such users has been increasing (e.g., through partnerships between NASA and other Federal agencies with decision-support systems that can be informed by NASA data, as has been done through the Applied Sciences Program), in the longer-term future, we see an ever-increasing group of users ranging from the Federal government, through state and local governments, all the way to industry and non-governmental organizations. Their goals may range from long-range policy development (as has been demonstrated by the use of NASA-provided data in contributing to the scientific basis for regulation of halocarbon production and emission under the Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments), through resource management and near-term forecasting applications, to industrial use for guiding investment decisions that have multidecadal implications.

Earth system science and space-based observations will continue to be essential tools in national and international efforts in avoidance, adaptation, and mitigation of global change. As the Nation's civil space agency, NASA will be a leading innovator of those tools.



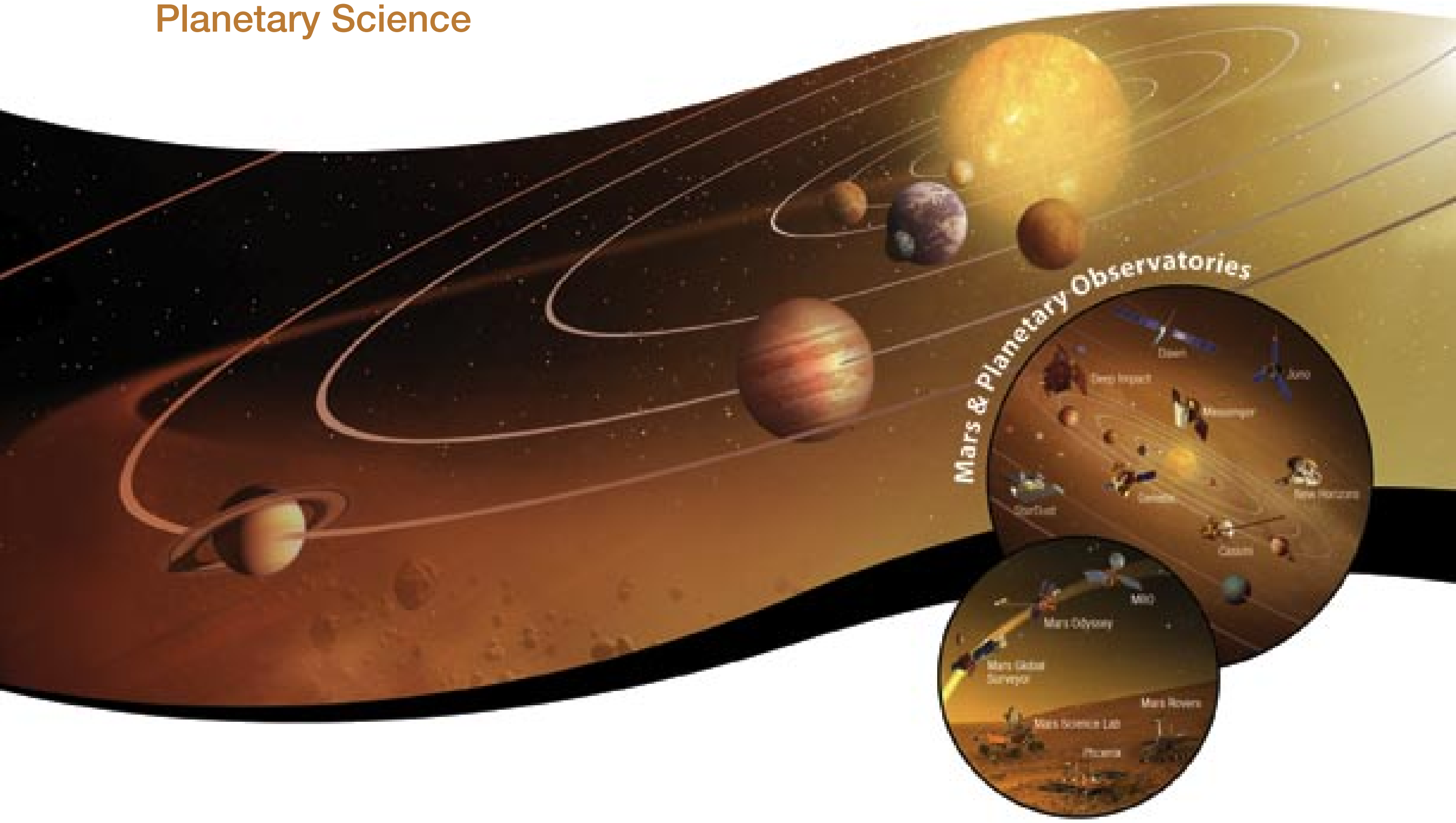
5 Planetary Science

Strategic Goal:

Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space.

Chapter 5

Planetary Science



5.1 Intellectual Foundation

Solar system exploration is a grand human enterprise that seeks to discover the nature and origin of the celestial bodies among which we live and to explore whether life exists beyond Earth. The scientific foundation for this enterprise is described in the NRC's Decadal Survey in Planetary Science, *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC, 2003). The quest to understand our origins is universal. How did we get here? Are we alone? What does the future hold? Modern science, and especially space science, provides extraordinary opportunities to pursue these questions. The tools that are available and that will become available in the coming years will enable us to develop an astoundingly vast range of mission opportunities. We are at the leading edge of a journey of exploration that will yield a profound new understanding of our home, the Earth, and of ourselves. Robotic exploration is the key precursor for the expansion of humanity into our solar system.

These grand themes are captured in five fundamental science questions in the planetary science community's *2006 Solar System Exploration Roadmap* that form the basis for NASA's approach to the exploration of the solar system:

- How did the Sun's family of planets and minor bodies originate?
- How did the solar system evolve to its current diverse state?
- What are the characteristics of the solar system that led to the origin of life?
- How did life begin and evolve on Earth and has it evolved elsewhere in the solar system?
- What are the hazards and resources in the solar system environment that will affect the extension of human presence in space?

The theme guiding these questions is habitability—the capacity of an environment (which could cover an entire planet) to support life. This concept includes the existence of liquid water, as well as the availability of energy and organic molecules. There is also a temporal component, since these clement conditions must exist long enough for life to originate, evolve, or migrate to the environment (from, perhaps, another environment). Beyond local conditions, habitability also encompasses issues related to the architecture of planetary systems (e.g., how does planetary architecture influence impact rates on planets close enough to the parent star to support liquid water?) and, to a lesser extent, stellar physics (e.g., is high metallicity a prerequisite for habitable planets to form?) and galactic structure (e.g., can habitable planets exist in environments near gamma-ray bursts or supernovae?).

The fundamental science questions transcend the traditional boundaries of astronomy, physics, chemistry, biology, and geology. To address them requires multidisciplinary approaches, and NASA has pioneered this by providing crucial, early support for planetary science (in the 1960s and 1970s) and astrobiology (in the 1990s). As described in the R&A section below, however, funds available for multidisciplinary research over the next five years are less than expected one year ago.

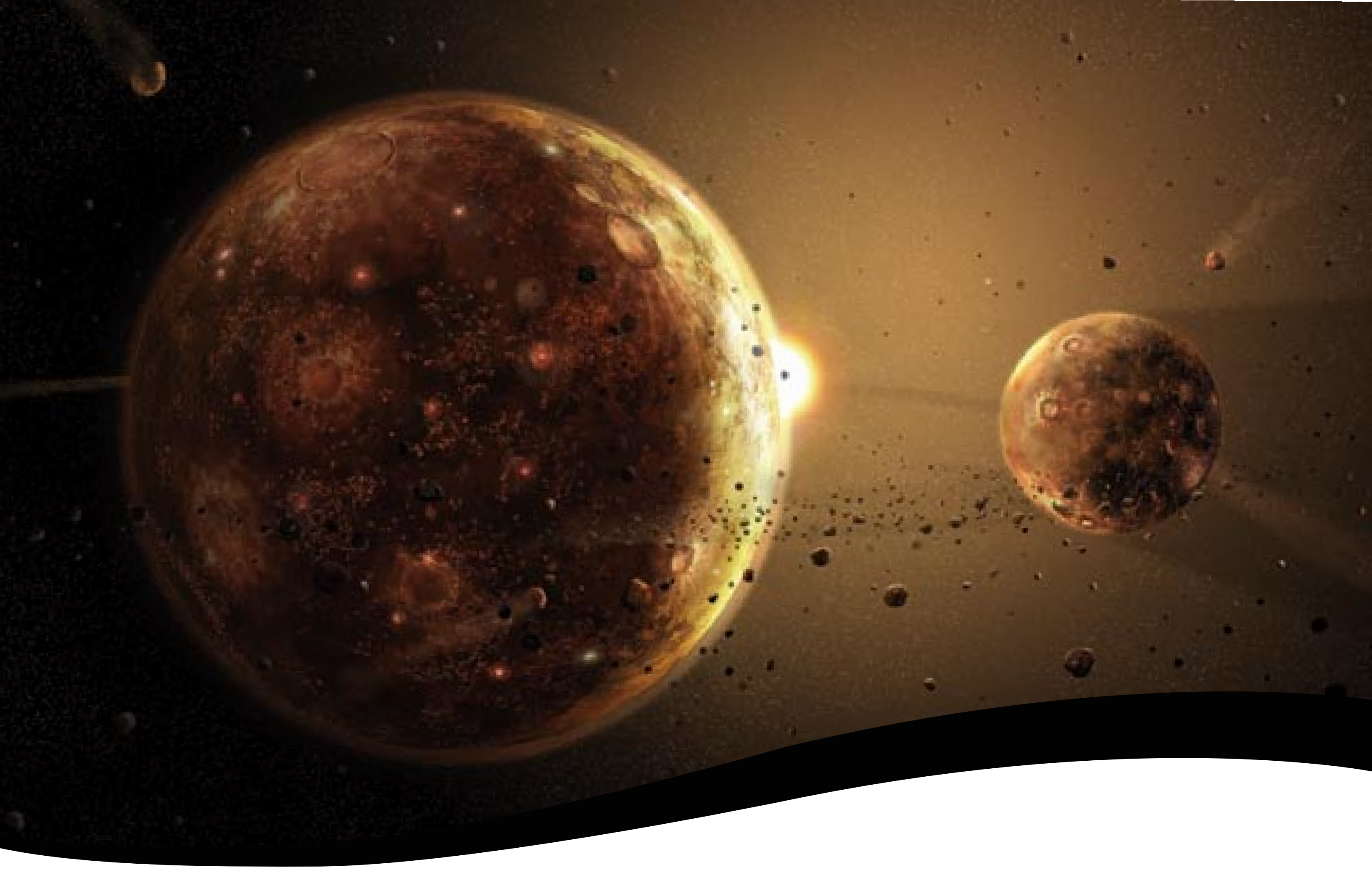
In order to progress in addressing the five fundamental science questions, NASA relies on a balanced program of R&A, technology development, data and sample curation programs, and missions of various sizes. The R&A programs not only leverage NASA's investments by analyzing the data and samples returned by missions, but also serve as the wellspring for new science questions and new mission concepts. These concepts are realized through the development of new technologies. Data and samples returned to Earth by missions are carefully curated and disseminated to researchers, and the results of NASA-funded research are communicated to the public through a vigorous program of public outreach and both formal and informal education.

NASA seeks regular input from the scientific community in developing its approach to addressing these questions. Input is provided through chartered bodies such as the Space Studies Board of the NRC, the Committee on Planetary Exploration (COMPLEX), advisory committees and community-led groups (e.g., Mars Exploration Program Assessment Group, MEPAG). All of their comments and recommendations have been considered in light of budgetary realities, and the resulting plan for the exploration of the solar system is described here. Additionally, the science community has been deeply involved in the creation of *New Frontiers in the Solar System: An Integrated Exploration Strategy* (hereafter called the NRC Decadal Survey), the *2003 Solar System Exploration Roadmap*, the *2006 Solar System Exploration Roadmap* and the *2006 Mars Architecture*. The earlier documents had a profound influence on the Vision for Space Exploration, which state that NASA will: (1) conduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration; and, (2) conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system and to search for resources. Recommendations from all of these documents have been incorporated into this plan.

5.2 Science Objectives and Outcomes: Solar System Destinations and Missions

Planetary science missions are grouped by their respective targets of investigation. Missions to Mercury, Venus, and the Moon are considered to be *Inner Solar System Missions*. Missions to Mars are also considered inner solar system Missions, but are described in a separate section, since the Mars Exploration Program (MEP) is an integrated campaign of exploration, technology development, and public engagement. Missions to the other planets (Jupiter and beyond) and their moons are classified as *Outer Solar System Missions*. Finally, missions to comets and asteroids are described as *Small Bodies Missions*.

In exploring any particular solar system object, NASA has followed a general paradigm of "flyby, orbit, land, rove, and return." This prescription has been followed most completely for investigations of the Moon and Mars. In contrast, the first flyby of Pluto and its large moon Charon will be performed by the New Horizons mission and will not occur until



The image above is an artists rendition of the Great Bombard ment stage of the formation of the moon.

July 2015. A complete campaign may not be performed for each interesting object in the solar system; not all scientific questions can be studied at all objects, and there are high technological and financial hurdles to overcome for some missions and certain destinations. Moreover, a healthy program of solar system exploration requires a balance between detailed investigations of a particular target and broader reconnaissance of a variety of similar targets.

In addition to a description of the missions themselves, each subsection here presents specific goals that are addressed by the various missions that investigate that area.

5.2.1 Exploring the Inner Solar System

Inner solar system bodies are rocky, unlike the gas and water giant planets of the outer solar system. Rocky planets are thought to have formed from the accretion of dust into “planetesimals,” the planetesimals into proto-planets and finally the proto-planets into planets. Many details of this sequence are still unknown, including the composition of the planetesimals. Equally obscure are the histories of the inner solar system worlds: although Venus, the Earth, and Mars are similar to one another, they have evolved in highly distinct ways. We now know that Mars once had water on its surface, and there are tantalizing hints that Venus might have too. Yet only the Earth is currently known to be habitable. Missions currently in operation, development and planning will greatly increase our knowledge of the forces driving planetary habitability and evolution.

Mercury

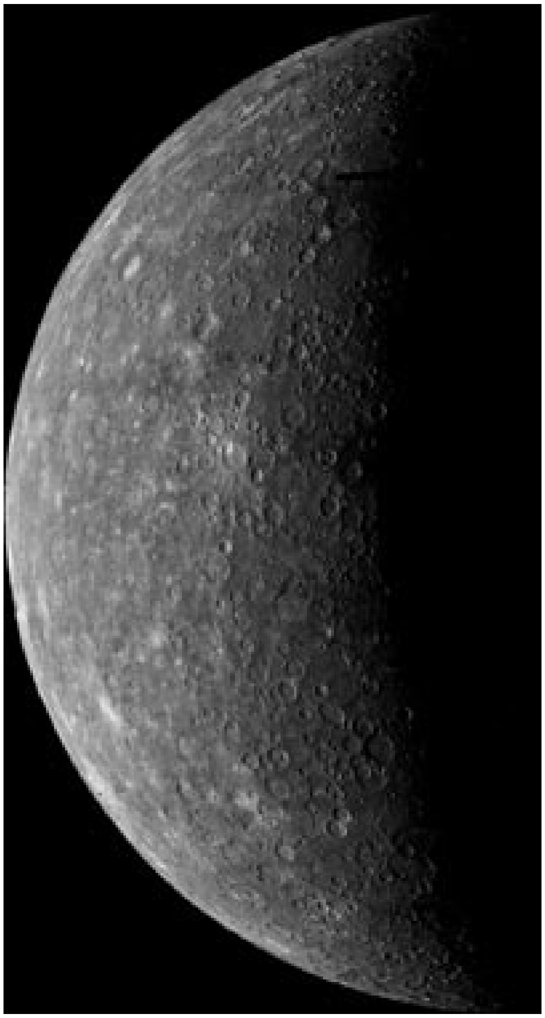
The Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) mission was launched in August 2004 and will use a flyby of the Earth and multiple flybys of Venus and Mercury to arrive in orbit around Mercury in 2011. MESSENGER is the first orbiter sent to Mercury. Previously our only encounters with the innermost planet were the three flybys performed in 1974 and 1975 by the Mariner 10 mission that mapped 45 percent of the planet's surface. With a package of seven science instruments, MESSENGER will determine Mercury's composition, image its surface globally and in color, map its magnetic field and measure the properties of its core, explore the mysterious polar deposits to learn whether ice lurks in permanently shadowed regions, and characterize Mercury's tenuous atmosphere and Earth-like magnetosphere. The MESSENGER mission is a PI-led mission and is part of the Discovery program. Although no NASA strategic missions to Mercury are planned within the decade covered by this plan, the joint ESA-Japanese Space Agency (JAXA) mission to Mercury (named Bepi Columbo), a cornerstone or strategic mission for ESA, is planned for launch in 2013. Future Discovery Program solicitations may receive proposals for the further exploration of Mercury.

Venus

Venus has often been described as Earth's sister planet since the two are very similar in size and bulk composition. Present-day Venus, though, is shrouded by a dense atmosphere thick with sulfur dioxide and sulfuric acid clouds, has an average surface temperature hotter than the melting point of lead, and has an average surface pressure ninety times the average pressure at sea level on Earth. Early Venus, however, may have been a very different planet with surface water and a much more clement, perhaps even habitable, environment. Venus is therefore an excellent laboratory for learning about the forces that drive planetary evolution and may provide a model for the future evolution of Earth's atmosphere and interior.

There are currently no strategic missions targeted at Venus within the timeframe of this plan. One of the New Frontiers Program's target mission concepts as outlined in the NRC Decadal Survey—the Venus *In Situ* Explorer (VISE)—would investigate the surface of Venus and help understand the climate change processes that led to the extreme conditions of Venus today. VISE would land on the surface of Venus, operate for perhaps a few hours using passive thermal control, and lay the scientific and technological groundwork for future, longer-duration missions. A third New Frontiers competition is expected no earlier than 2008. Missions addressing many questions regarding Venus's atmosphere are also targets for the Discovery Program, and the MESSENGER spacecraft will perform investigations of Venus during

Mercury



Mariner 10's first image of Mercury acquired on March 24, 1974. During its flight, Mariner 10's trajectory brought it behind the lighted hemisphere of Mercury, where this image was taken, in order to acquire important measurements with other instruments. This picture was acquired from a distance of 3,340,000 miles (5,380,000 km) from the surface of Mercury. The diameter of Mercury (3,031 miles; 4,878 km) is about 1/3 that of Earth. Images of Mercury were acquired in two steps, an inbound leg (images acquired before passing into Mercury's shadow) and an outbound leg (after exiting from Mercury's shadow). More than 2300 useful images of Mercury were taken, both moderate-resolution (3-20 km/pixel) color and high-resolution (better than 1 km/pixel) black and white coverage.

Figure 5.1

Exploring the Inner Solar System

	Inner Solar System Targets			
Fundamental Science Questions	Mercury	Venus	Moon	Mars
How did the Sun's family of planets and minor bodies originate?	⬡	⬢	⬢	⬢
How did the Solar system evolve to its current diverse state?	⬡	⬢	⬢	⬢
What are the characteristics of the Solar System that led to the origin on life?		⬢	⬢	⬢
How did life begin and evolve on Earth and has it eveloved elsewhere in the Solar System?		⬡		⬢
What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?			⬢	⬢

⬡ Supporting Contribution ⬢ Major Contribution

Venus

This full-resolution radar mosaic from Magellan at 49 degrees south latitude, 273 degrees east longitude of an area with dimensions of 130 by 190 kilometers (81 by 118 miles), shows a 200-kilometer (124-mile) segment of a sinuous channel on Venus. The channel is approximately 2 kilometers (1.2 miles) wide. These channel-like features are common on the plains of Venus. In some places, they appear to have been formed by lava, which may have melted or thermally eroded a path over the plains' surface. Most are 1 to 3 kilometers (0.6 to 2 miles) wide. They resemble terrestrial rivers in some respects, with meanders, cutoff oxbows, and abandoned channel segments. However, Venus channels are not as tightly sinuous as terrestrial rivers. Most are partly buried by younger lava plains, making their sources difficult to identify. A few have vast, radar-dark plains units associated with them, suggesting large flow volumes. These channels appear to be older than other channel types on Venus, as they are crossed by fractures and wrinkle ridges and are often buried by other volcanic materials. In addition, they appear to run both upslope and downslope, suggesting that the plains were warped by regional tectonism after channel formation. Resolution of the Magellan data is about 120 meters (400 feet).

Planetary Science Opportunities Enabled by Human Exploration of the Moon

The return of human explorers to the surface of the Moon by 2020 creates additional opportunities for realizing the science priorities in planetary science. During the period of time covered by this Science Plan, NASA will establish a "Lunar Exploration Architecture"—a baseline plan for the types of missions and the types of facilities that will be developed to support the Nation's exploration goals. This will establish the capabilities that will be available to enable planetary science from the Moon, as well as the timescale in which those capabilities will be available to support planetary science exploration.

At the same time, NASA will conduct studies to identify potential investigations and projects that can realize priority planetary science objectives from the Moon. The interim report on *The Scientific Context for the Exploration of the Moon* (NRC, 2006) identifies a number of priorities for planetary science, including:

- Characterize and date the impact flux (early and recent) of the inner solar system.
- Determine the internal structure and composition of a differentiated planetary body.
- Determine the compositional diversity (lateral and vertical) of the ancient crust formed by a differentiated planetary body.
- Characterize the volatile compounds of polar regions on an airless body and determine their importance for the history of volatiles in the solar system.
- Determine the time scales and compositional and physical diversity of volcanic processes.
- Characterize the cratering process on a scale relevant to planets.
- Constrain processes involved in regolith evolution and decipher ancient environments from regolith samples.
- Understand processes involved with the atmosphere (exosphere) of airless bodies in the inner solar system.

The NRC recommends that NASA explore the South Pole-Aitken basin, determine the composition of the lunar interior, and understand the lunar polar deposits and environment, among other recommendations. Beginning in 2006, NASA is sponsoring workshops, analysis groups, and an NRC study to begin the planning for those planetary science objectives that can be realized from the lunar surface. In 2007, NASA will select several concept studies for science investigations that can be realized on the short sorties that will be the first human exploration missions. Also in 2007, the NASA Advisory Council will sponsor a Lunar Science Workshop aimed at establishing science objectives for the lunar exploration program.

In identifying planetary science investigations that can be realized from the surface of the Moon and in establishing the priorities for those potential missions, SMD will use the same community-based processes that have been used to establish priorities in the current planetary science program. Recognizing that newly enabled opportunities must compete with other missions in this Science Plan for resources, it is necessary to prioritize all planetary science activities with the goal of realizing NASA's planetary science objectives.

one of its two flybys. This will include the first-ever application of lidar to Venus.

The community-led Solar System Exploration Roadmap team has determined that a more capable, strategic mission is needed to conduct more detailed surface exploration of Venus. The Venus Mobile Explorer (VME) was identified to meet this need. The goals of this mission would be to conduct an extended, mobile (possibly aerial), *in situ* investigation of the surface of Venus. The Roadmap identifies 2018 as the earliest opportunity to begin development of VME. A Venus surface sample return (VSSR) mission was also considered a high-priority strategic mission in the NRC Decadal Survey. Both of these strategic missions necessitate the evolution of existing spacecraft and instrument technologies to operate for extended durations under the harsh conditions in the lower atmosphere and on the surface of Venus. Consequently these missions remain long-range goals for Venus exploration.

The Moon

The Moon has a special place among the objects in the solar system, as it is the only place other than Earth where humans have been, and where we will return relatively soon. Studying the Moon and its history will provide critical data on the formation history of the Earth-Moon system, as well as opening a window onto some of the earliest history of the inner solar system.

The NRC Decadal Survey identified a lunar mission as one of the five recommended "Medium Missions" that became the basis for the New Frontiers mission set —the South-Pole Aiken Basin Sample Return mission that would address the impact history of the early inner solar system as well as the nature of the lunar mantle. This mission is one of the small number of target mission concepts for the New Frontiers Program of PI-led missions. The next New Frontiers solicitation is planned to be released no earlier than 2008.

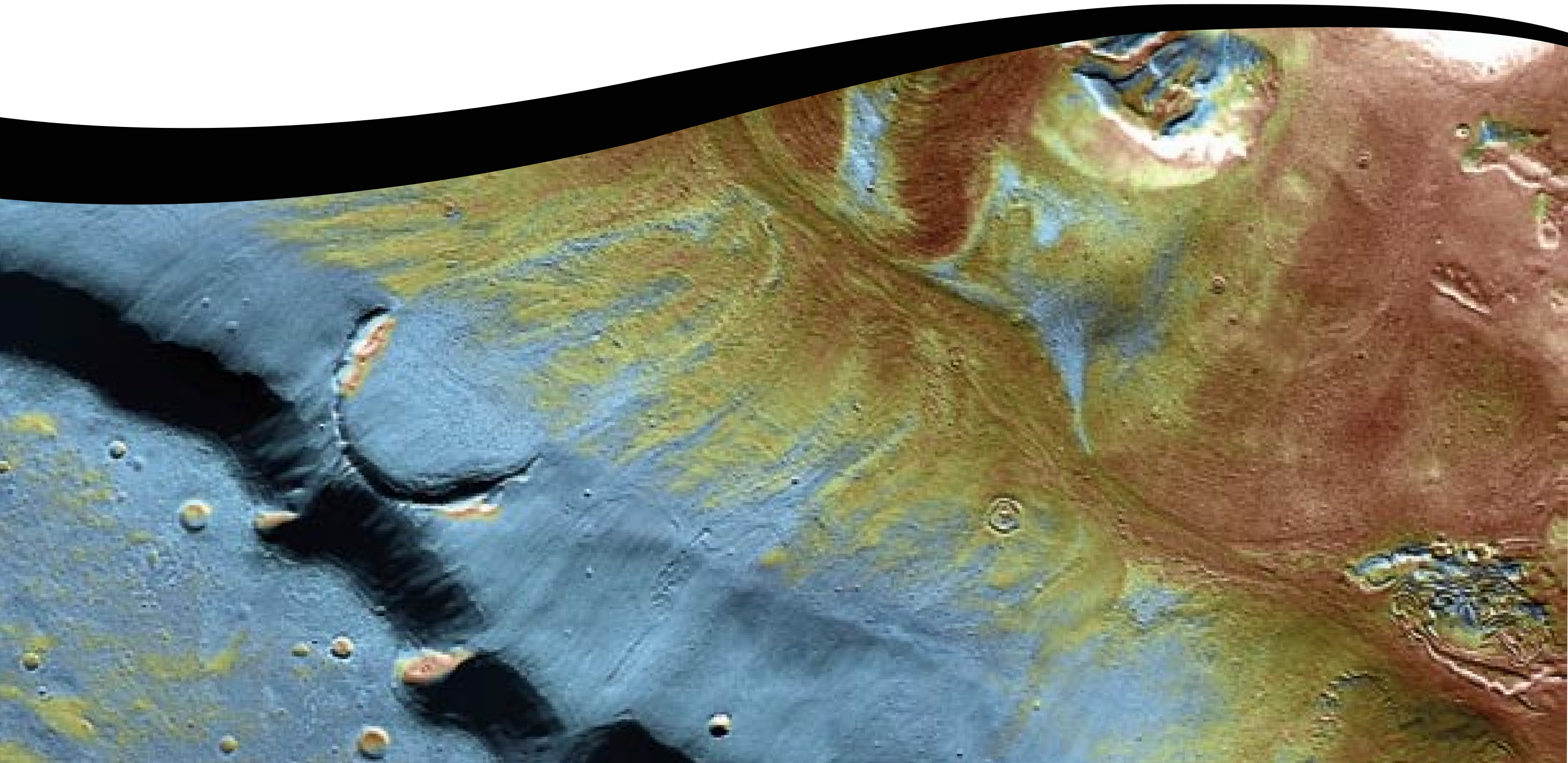
A number of other significant science investigations focused on the Moon can be accomplished, however, within the cost constraints of the Discovery Program. In fact, in 2004 the Discovery Program selected the Moon Mineralogy Mapper (M3) as a "Mission of Opportunity." M3 is scheduled to fly on India's first lunar orbiter, Chandrayaan-1, in 2008.

The Lunar Precursor Robotic Program (LPRP) will also explore the Moon robotically to obtain data to satisfy Exploration Program requirements. The first LPRP mission, Lunar Reconnaissance Orbiter (LRO), will provide high-resolution lunar topography as well as high-resolution stereo imaging of the Moon enabling better definition of geology and surface morphology. A smaller, secondary payload spacecraft will travel with LRO to the Moon on the same rocket. The Lunar CRater Observation and Sensing Satellite (LCROSS) will help determine if there is water hidden in the permanently dark craters of the Moon's south pole using an approach similar to the impactor-flyby spacecraft of the Deep Impact mission. It is likely that future LPRP missions will, as a byproduct of the effort to address exploration needs, provide additional science opportunities. Data from the LRO mission will be archived in the Planetary Data System (PDS) and made available to all researchers. The R&A Program of the Planetary Science Division currently supports a small number of tasks focused on lunar science. As new lunar data become available, this support will likely grow.

Mars

Mars is a highly attractive object of study: not only does it provide an excellent laboratory for studying planetary evolution in the context of the Earth and Venus, but it is the most compelling target in the solar system to search for life's existence beyond Earth. Additionally, Mars is an eventual goal of the *Vision for Space Exploration's* human spaceflight program. Finally, Mars is relatively easily accessed with launch opportunities occurring approximately every 2 years. For these many reasons, the MEP is a fully integrated program, designed to maximize the scientific return, technology infusion, and public engagement of the robotic exploration of the Red Planet. Each strategic mission of the program has both technological and scientific linkages to previous missions and orbiters and landers support each other's operations. E/PO activities of individual missions are coordinated with an overarching public engagement framework.

Results from the missions launched between 1996 and 2003 show that Mars was once wet—something only surmised previously from the Mariner 9 and Viking missions—and that large quantities of water ice remain on and near the surface. Recent data support the theory that surface environments were probably habitable billions of years in the past and that the diversity of environments on Mars through time was far greater than had been appreciated previously. Together, these findings suggest that the search for localized habitats, past or present, and evidence of life on Mars has scientific merit. Therefore, significant progress is being



Glacier Flowlines in Mamers Valles—Mars Odyssey's THEMIS instrument made in determining where and when habitats and, possibly, life may have evolved on the planet.

There are currently five spacecraft exploring Mars: NASA's Mars Odyssey, Mars Reconnaissance Orbiter, the Mars Exploration Rovers (Spirit and Opportunity), and the European orbiter Mars Express. Combined, these spacecraft have begun to reveal Mars as a dynamic planet, with remnants of a magnetic field, recently carved gullies, a history of volcanism, water ice on its poles and a history of major climate change.

Two NASA missions to Mars are currently in development: Phoenix and the Mars Science Laboratory (MSL). The Phoenix mission, scheduled for launch in August 2007, is a PI-led mission and the first mission selected through the Mars Scout Program. Phoenix is a fixed lander designed to measure volatiles (especially water) and complex chemistry (including organic molecules) in the northern polar plains of Mars, where the Mars Odyssey orbiter has discovered evidence of ice-rich soil near the surface. Phoenix is designed to use a robotic arm to dig to the ice layer and analyze samples with a suite of sophisticated on-deck scientific instruments. Competition for the next Mars Scout mission is currently underway with a 2011 targeted launch date.

MSL, the next strategic mission to Mars, will explore the geochemical, mineralogical and geological diversity of Mars in search of potential habitable zones. MSL will be the first roving analytical laboratory on Mars carrying instruments that will precisely identify the mineralogy of rocks and the composition of any organic matter found. The robotic platform will collect rock and soil samples and analyze them to determine mineralogy and the nature of any potential organic compounds. In addition, MSL will measure gases to determine atmospheric composition and evolution. Soon after landing, MSL will be able to verify the presence of methane and its near-surface variability, possibly pointing to a geochemical or biological origin. Another experiment, developed in collaboration with the Exploration Systems Mission Directorate (ESMD), will measure the surface radiation relevant to the surface chemistry of the soil and to future human exploration. MSL will be significantly larger than the Mars Exploration Rovers, with the potential capability to travel longer distances and operate at high latitudes enabled by the use of a radioisotope power system. Additionally, MSL will demonstrate a variety of new technologies including guided entry and a "sky-crane" landing system that will allow for more accurate landing on the surface. MSL is currently the only planetary science strategic mission under development and is scheduled to launch in 2009.

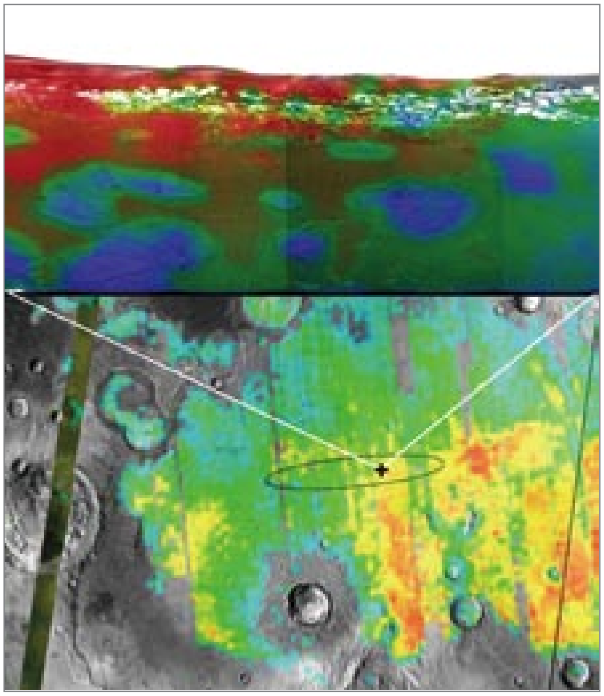
Beyond 2011, there are two strategic missions and one PI-led mission planned. In 2013, the Mars Science Orbiter (MSO) will be launched. It is a strategic mission that will follow up on Decadal Survey priorities that will address planetary evolution and potentially habitability. The exact scientific objectives will be defined in 2007. In addition, MSO will provide missions flown later in this decade with required telecommunications support. In 2016, the Astrobiology Field Laboratory (AFL), a pair of Mid-Rovers, or a set of three to four long-lived landers is planned for launch with the results of MRO's and MSL's investigations determining which mission is developed. "Mid-" refers to size: in between the diminutive Sojourner and the subcompact car-sized MSL. If MSL finds evidence of organic matter or habitable zones in the surface or near subsurface, then AFL will be launched to characterize, in detail, putative biomarkers to determine whether, in fact, there is a connection with prebiotic chemistry or living organisms. AFL is to be a rover, based closely on MSL, but with a payload focused on the detection and characterization of biomarkers with the next-generation sample-processing system. If MSL and MRO discoveries show that the need to understand the spatial diversity (including geology, geochemistry, geophysics, astrobiology) of Mars is more compelling than the need to investigate a single site in detail, then either a pair of Mid-Rovers or a network of landers may be a more logical choice. These Mid-Rovers are anticipated to be MER-like in capability but with an updated instrument suite. Their landing sites will be identified as having high scientific interest from MRO observations.

5.2.2 Exploring the Outer Solar System

The giant planets of the outer solar system—Jupiter, Saturn, Uranus, and Neptune—and their rings and moons and the ice dwarfs (e.g., Pluto, Charon, Sedna) beyond them hold many clues to the origin and evolution of our solar system as well as providing exciting opportunities for the search for habitable environments. Moreover, an understanding of the formation and dynamics of the giant planets will aid greatly in understanding the nature of extra-solar planetary systems. NASA's exploration of the outer solar system began with flybys by Pioneer 10 and 11 and Voyager 1 and 2. The Ulysses and Cassini-Huygens have also studied Jupiter *en route* to their primary missions. The Galilieo mission was the first to orbit Jupiter providing an intensive study of the planet and its moons. The New Horizons mission will also encounter Jupiter in February 2007—studying for the first time Jupiter's long magnetotail—on its nine-year journey to study Pluto and its largest moon, Charon.

Jupiter and its Moon, Europa

The Jovian system was extensively explored by the Galileo mission, which entered into orbit around Jupiter in 1995 and remained active for eight years. It also delivered a probe into



Mars

Composite image of the Meridiani Planum region of Mars. The bottom image shows the hematite abundance in the region as measured by the Thermal Emission Spectrometer (TES) onboard the Mars Global Surveyor orbiter. The landing uncertainty ellipse for the Mars Exploration Rover Opportunity is shown as is the landing location (small cross). Areas estimated to have a high abundance of hematite, an iron mineral usually formed in the presence of water on the Earth, are shown in red while areas with a low abundance are shown in blue. The Opportunity landing site is in a region of medium abundance of hematite. The top image shows an estimate of hematite abundance in the outcrop at Eagle Crater—Opportunity's landing site—as measured by the mini-TES spectrometer superimposed on a pancam mosaic. Again red indicates a high abundance of hematite and blue a low abundance. Note that TES and mini-TES are essentially the same instrument, looking at Mars at different size scales and resolutions.

Jupiter's atmosphere. The Galileo probe collected data for almost an hour as it descended into the Jovian atmosphere collecting the first information on the composition of the upper layers of Jupiter's atmosphere. The Galileo orbiter found evidence of subsurface saltwater on Europa, Ganymede, and Callisto and revealed the intensity of volcanic activity on Io. The Galileo spacecraft was deliberately destroyed, plunging into Jupiter's crushing atmosphere, on September 21, 2003, in order to protect Europa's subsurface ocean from contamination.

Given the great distances in the outer solar system, the extreme temperatures, and the radiation levels, the exploration of the outer solar system requires the funding levels and mission complexity afforded by strategic missions. However, technological innovations have begun to open up the outer solar system to PI-led missions. Juno, the second mission in the New Frontiers Program, is currently scheduled for launch in 2011. Juno will map the gravity and magnetic fields, interrogate the dynamic response of Jupiter's magnetosphere to internal and external influences, and map the atmospheric composition of Jupiter from a unique polar orbit. Juno's 32 orbits will sample Jupiter's full range of latitudes and longitudes and will help to estimate the size of Jupiter's core. Placing limits on the size of the core will constrain models of Jupiter's formation and thereby improve our understanding of how planetary systems form.

Jupiter's moon Europa is an extremely high-priority target for a future mission. Europa's icy surface is believed to hide a global subsurface ocean. Although oceans may exist within many of the solar system's large icy satellites, Europa's is extremely compelling for astrobiological exploration. This is because Europa's geology provides evidence for recent communication between the icy surface and ocean, and the ocean might be supplied by above and/or below with the chemical energy necessary to support microbial life. An orbital mission could explore Europa to determine its potential habitability and accessibility and, if these are confirmed, would lay the groundwork for a future landed mission focusing on the astrobiological potential of Europa.

There have been significant investments in two prior concepts targeting a focused investigation of Europa. These are the Europa Orbiter and the Jupiter Icy Moons Orbiter (JIMO) concepts. Europa Orbiter was in its preliminary design phase when halted in 2001. Development of the JIMO mission was dependent upon the Prometheus Program's successful deployment of a space-based fission reactor. JIMO was indefinitely deferred in the summer of 2005. NASA also initiated a 45-day study of a Europa Geophysical Explorer (EGE) concept in the wake of the deferral of JIMO. All of these studies described the significant technical hurdles to be overcome, and pointed to potential solutions, in the development of an orbital mission to Europa. These past investments have now laid the groundwork for overcoming these hurdles.

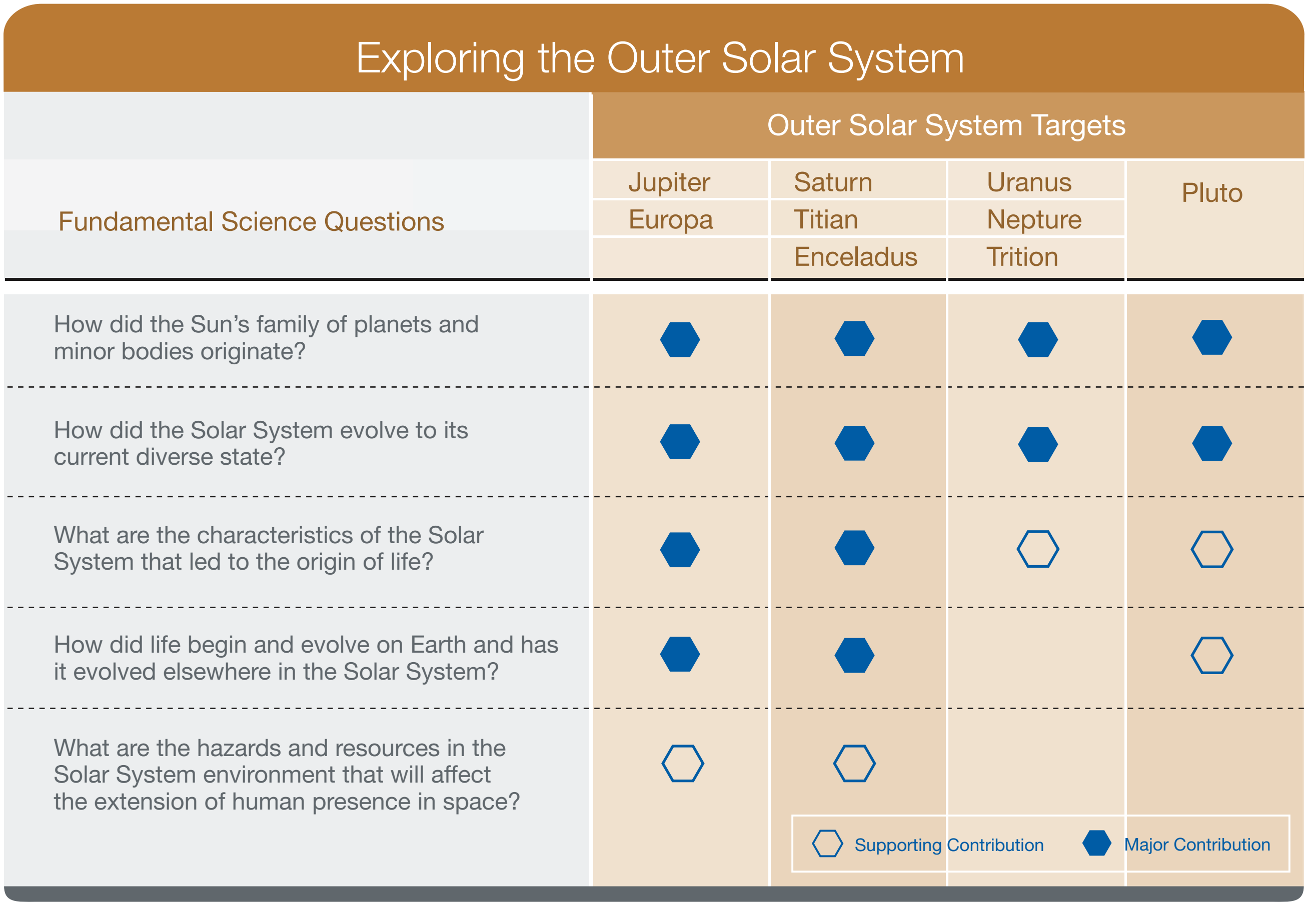
The community-led Solar System Exploration Roadmap team has listed a Europa mission, the Europa Explorer (EE), as the highest-priority target for a strategic mission. As envisioned by the Solar System Exploration Roadmap team, the EE mission would be launched on an indirect trajectory to Jupiter, exploiting gravity-assist flybys of both Venus and Earth. The spacecraft would enter Jupiter orbit and execute a 1- to 2-year tour within the Jovian system. As a result of the Earth and Venus gravity-assist maneuvers, the dry mass of the spacecraft is expected to be three times that of the Europa Orbiter concept from 2001 enabling a much larger scientific payload and a longer lifetime around Europa.

There are several large technology hurdles to be overcome before this mission can proceed to full development, the greatest of which is the harsh radiation environment of Europa's orbit which places severe limits on the use of dense, low-power, solid-state memory chips. A mission concept currently under study at the Jet Propulsion Laboratory may potentially be able to overcome these hurdles. Budget limitations continue to delay the start of this high-priority mission; however, there is strong support in the science community for starting work on the mission as soon as possible.

Saturn and its Moons, Titan and Enceladus

The exploration of Saturn was begun by Pioneer 11 and Voyagers 1 and 2, which executed flybys of Saturn, its rings, and moons. The Cassini-Huygens mission, which entered Saturn orbit in 2004, has continued this exploration. The ESA's Huygens probe entered Titan's atmosphere and landed on its surface. Huygens relayed to Earth stunning

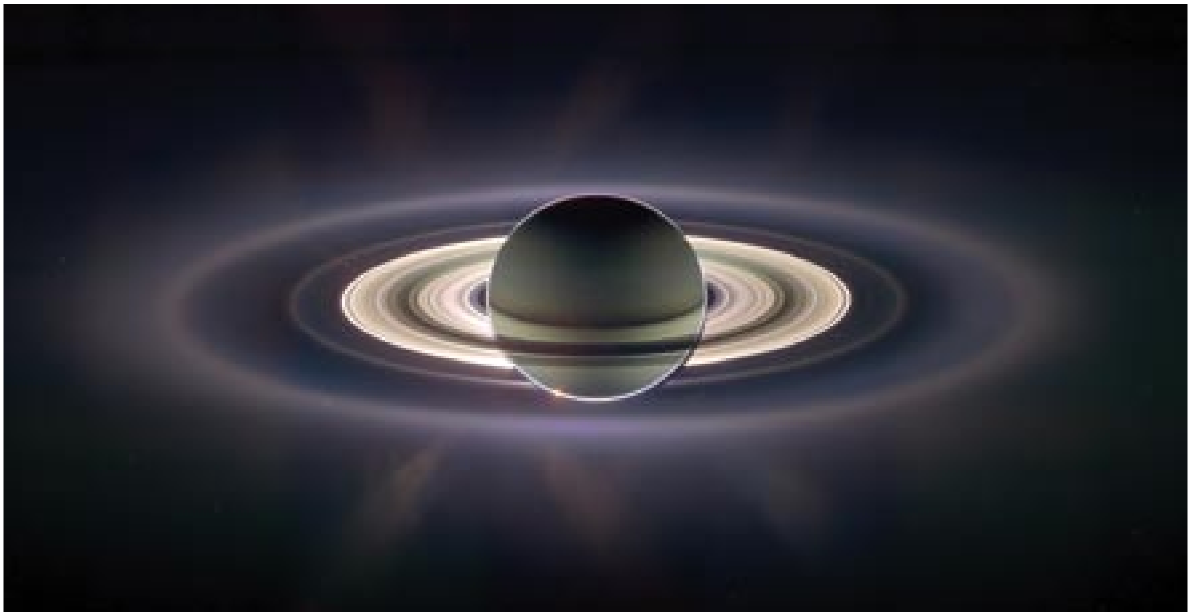
Figure 5.2



Exploring the Outer Solar System

	Outer Solar System Targets			
Fundamental Science Questions	Jupiter Europa	Saturn Titian Enceladus	Uranus Nepture Trition	Pluto
How did the Sun's family of planets and minor bodies originate?	⬢	⬢	⬢	⬢
How did the Solar System evolve to its current diverse state?	⬢	⬢	⬢	⬢
What are the characteristics of the Solar System that led to the origin of life?	⬢	⬢	⬡	⬡
How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?	⬢	⬢		⬡
What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?	⬡	⬡		

⬡ Supporting Contribution ⬢ Major Contribution



Saturn

With giant Saturn hanging in the blackness and sheltering Cassini from the sun's blinding glare, the spacecraft viewed the rings as never before, revealing previously unknown faint rings and even glimpsing its home world, Earth.

This marvelous panoramic view was created by combining a total of 165 images taken by the Cassini wide-angle camera over nearly three hours on Sept. 15, 2006. The full mosaic consists of three rows of nine wide-angle camera footprints; only a portion of the full mosaic is shown here. Color in the view was created by digitally compositing ultraviolet, infrared and clear filter images and adjusting the result to resemble natural color.

The mosaic images were acquired as the spacecraft drifted in the darkness of Saturn's shadow for about 12 hours, allowing a multitude of unique observations of the microscopic particles that compose Saturn's faint rings.

pictures of an alien, yet oddly familiar, world shaped by flowing liquid and blowing winds. Huygens also provided the first analysis of Titan's thick, hydrocarbon atmosphere. Cassini's most unexpected discovery to date was the discovery of water vapor and ice particles streaming from the south polar region of Saturn's moon Enceladus. This geyser-like activity has been interpreted as being indicative of the presence of liquid water as a subsurface ocean, lake, or other unique layer just under the icy surface of Enceladus, although the scientific community has not yet developed a consensus interpretation of this compelling observation.

These new discoveries have reinvigorated scientific interest in the Saturn system. The *Solar System Exploration Roadmap* has given a Titan-Enceladus Explorer (TEE) mission its second-highest priority for strategic missions. The roadmap team envisioned development of this mission starting no earlier than 2013. At Titan, air mobility and long mission duration *in situ* would enable extensive, high-resolution, visual imaging of the surface of Titan below its haze layer well beyond that accomplished by the Huygens Probe. Exploration of lower atmosphere winds, clouds and precipitation, and *in situ* measurements of ices and organic materials at the surface to assess pre-biotic/proto-biotic chemistry would also be performed. Science goals for the Enceladus segment of the mission have not yet been defined. The technology for a Titan Explorer mission is less mature than that needed for the Europa Explorer mission. The challenges include the development of aerocapture for injecting the orbital spacecraft into Titan orbit, aerial mobility under the extremely cold conditions of Titan, and efficient radioisotope power supplies. System trades between orbital relay communications and direct-to-Earth communications remain to be made.

Uranus, Neptune and Neptune's Moon, Triton

The formation of the giant planets had a major effect on the events and processes at work in the early solar system. The gravitational influence of Jupiter in particular governed much of the dynamical behavior that in turn determined many key features of the inner planets. An understanding of the processes and timescale of Jupiter's formation is thus of central importance to understanding the early solar system. Jupiter and Saturn, however, are not the only giant planets in the solar system; Uranus and Neptune are considered "water giants," with a greater proportion of water to hydrogen than Jupiter and Saturn. A comprehensive exploration of a water giant would permit direct comparison with Jupiter and more complete modeling of giant planet formation and its effects on the inner solar system.

Over the 2006–2016 timeframe, there are no strategic missions planned to Uranus. Ultimately, deep-entry probes into Uranus will be necessary in order to understand its composition and compare it to that of the other "water giant," Neptune. However, this has not been defined as a priority for the 2006–2016 timeframe by the Solar System Exploration roadmap team.

A comprehensive study of Neptune, and its moon Triton, on the other hand, is considered a priority for the third decade by the Solar System Exploration roadmap team. Neptune poses a number of important questions regarding how giant planets form and what truncates the formation of multiple giant planets in a planetary system. Residing on the edge of our planetary system, Neptune may hold, deep in its interior, chemical clues concerning the nature of the rocky and icy debris that formed the giant planets. Studies of Neptune will also help us understand if extrasolar planets, just barely detectable with current technology, are water giants like Uranus and Neptune or gas giants or terrestrial planets.

Triton is itself an important science target: like Titan, Triton has a nitrogen-methane atmosphere. Being so far from the Sun, however, Triton's atmosphere is mostly frozen out on the surface and moves seasonally from pole to pole. Triton also shows evidence of a much warmer (perhaps tidally driven) earlier history with geysers, organic materials, and plausible subsurface ocean. Yet the origin of Triton almost certainly lies in the Kuiper Belt, much like Pluto, and so the nitrogen-methane atmospheres of Titan and Triton could have very different origins.

Pluto and Kuiper Belt Objects

Pluto, once the smallest planet in our solar system, was not discovered until 1930. Its moon, Charon, was not discovered until 1978, and two even-smaller moons were discovered as recently as 2005. Pluto and Charon constitute two of the larger members of the Kuiper Belt—a mostly unexplored region beyond the orbit of Neptune thought to contain, unaltered, those building blocks of the planets that never accreted into major bodies. The Kuiper Belt is believed to represent the best available record of the original interstellar materials that formed the solar nebula. This region is also the birthplace of the short-period comets, still smaller bodies that have been gravitationally dislodged from the Kuiper Belt. As the comets enter the inner solar system, they not only become visible from Earth but they also become accessible targets for intensive robotic exploration. Determination of the chemical composition and physical characteristics of Pluto, other Kuiper objects, and short-period comets will give us unique

New Horizons to Pluto

New Horizons is a mission designed to fly by Pluto and its moon Charon and transmit images and data back to Earth. It will then continue on into the Kuiper Belt where it will fly by one or more Kuiper Belt Objects and return further data. The primary objectives are to characterize the global geology and morphology and map the surface composition of Pluto and Charon and characterize the neutral atmosphere of Pluto and its escape rate. Other objectives include studying the time variability of Pluto's surface and atmosphere, imaging Pluto and Charon in stereo, mapping the terminators and composition of selected areas of Pluto and Charon at high resolution, characterizing Pluto's upper atmosphere, ionosphere, energetic particle environment, and solar wind interaction, searching for an atmosphere around Charon and characterizing its energetic particle environment, refining bulk parameters, orbits, and bolometric Bond albedos of Pluto and Charon, searching for additional satellites and rings, and characterizing one or more Kuiper Belt objects.

insight into the materials and processes that dominated the initial stages of planet and satellite formation.

The New Horizons mission, the first mission of the New Frontiers Program, launched in January 2006, will fly by Jupiter in February 2007 and will encounter the Pluto-Charon system in July 2015. New Horizons will make the first reconnaissance of Pluto and one of its moons, Charon. It will map the surface composition, characterize the geology and morphology and map surface temperatures of Pluto and Charon; it will also characterize the tenuous atmosphere of Pluto before it freezes back onto the surface as Pluto recedes from the Sun and search for an atmosphere around Charon. Subsequently, as part of an extended mission, New Horizons could visit one or more objects in the Kuiper Belt.

5.2.3 Exploration of the Small Bodies of the Solar System

The small bodies in the solar system include comets, asteroids, the objects in the Kuiper Belt and the Oort cloud, small planetary satellites, Triton, Pluto, Charon, and interplanetary dust. As some of these objects are believed to be minimally altered from their state in the young solar nebula from which the planets formed, overall they may provide a window into the early history of the solar system through which insights about the process of planet formation may be drawn.

NASA has mounted four PI-led missions in the Discovery Program to investigate small bodies—Near-Earth Asteroid Rendezvous (NEAR), Stardust, Comet Nucleus Tour (CONTOUR), and Deep Impact—and a fifth, Dawn, is in development. NASA is also participating in the ESA Rosetta and JAXA Hayabusa missions. In addition, the New Millennium mission Deep Space-1 studied the nucleus of comet Borelly.

NEAR, closely orbited the asteroid Eros for a year, returning data on its bulk properties, composition, mineralogy, morphology, internal mass distribution and magnetic field. It completed its mission by making a previously unplanned soft touchdown on the asteroid.

Stardust encountered the comet Wild 2, photographed its nucleus, and collected particles from its coma. It also photographed asteroid 5535 Annefrank and collected in-

Figure 5.3

Exploration of the Small Bodies of the Solar System

	Inner Solar System Targets		
Fundamental Science Questions	Asteroids	Comets	KBOs
How did the Sun's family of planets and minor bodies originate?	⬢	⬢	⬢
How did the Solar System evolve to its current diverse state?	⬢	⬢	⬢
What are the characteristics of the Solar System that led to the origin of life?	⬢	⬢	⬡
How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?	⬡	⬡	⬡
What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?	⬢	⬢	⬢

⬡ Supporting Contribution ⬢ Major Contribution

Deep Impact's probe slammed into the nucleus of comet Tempel 1 right on schedule, on July 4, 2005, releasing an immense cloud of fine, powdery material. The team analyzed the data returned by ground-and space-based observa tories, as well as the spacecraft's own instruments.

terstellar dust. The collected materials were returned to Earth on January 15, 2006. Analysis of the returned materials has just begun, but mysteries have already emerged. For example, how did grains of high-temperature minerals such as olivine become incorporated into the cold, icy body of a comet? These precious samples will continue to reveal their secrets, and generate new questions, as analysis proceeds.

The CONTOUR mission was timed to encounter and study two very different comets, Encke and Schwassmann-Wachmann-3 as they made their periodic visits to the inner solar system. Unfortunately, CONTOUR was lost six weeks after launch.

The Deep Impact mission was also directed at understanding the structure and composition of comet nuclei, in this case the comet Tempel 1. Launched on January 12, 2005, Deep Impact traveled 429 million kilometers to encounter Tempel 1 and launched an 814-pound impactor. On July 4, 2006, impact occurred as planned, creating a large crater (as yet unimaged) and an unexpectedly large and long-lived plume of excavated material. The impact was observed by the flyby spacecraft, as well as a wide range of other space- and ground-based observatories. The Deep Impact spectrometer made the first direct measurement of surface water ice on a comet and found it to be much more rare than expected, suggesting that the sources of a comet's water vapor emissions are buried beneath its surface.

The Dawn mission, to be launched in June 2007, will investigate the asteroids Ceres and Vesta—the two largest bodies in the "main belt" of asteroids found between Mars and Jupiter. Ceres and Vesta are thought to be remnant "protplanets," survivors of the latter stages of planet formation. Ceres and Vesta have many contrasting characteristics that are thought to have resulted from them forming in two different regions of the early solar system; Ceres is theorized to have experienced a "cool and wet" formation that may have left it with subsurface water, and Vesta is theorized to have experienced a "hot and dry" formation that resulted in a differentiated interior and surface volcanism.

It is expected that the Discovery Program will continue to support PI-led missions to asteroids and comets. Some missions, however, will require more complex spacecraft than can be developed within the Discovery Program. One of the target missions for the New Frontiers program is the Comet Surface Sample Return (CSSR) mission. Detailed examination of returned samples of comet surface material will help us understand the distribution of volatiles and organics in the solar system and how it has evolved over time. A third New Frontiers competition is expected no earlier than 2008. A more complex mission to capture and return volatile-rich samples (kept at cryogenic temperatures) from below the surface of the comet is considered by the roadmap team as a possible strategic mission in the third decade of this century.

Table 5.1

Targeted Outcomes Through 2016

Origin of Planets and Small Bodies	Evolution of the Solar System	Solar System Characteristics Leading to Life	Origin & Evolution of Life on Earth & Beyond	Hazards and Resources
Understand the early stages of planet and satellite formation	Determine how the processes that shape planetary bodies operate and interact	Determine the nature, history, and distribution of volatile and organic compounds in the Solar system	Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life	Determine the inventory and dynamics of objects that may pose an impact hazards to Earth
• Determine chemical composition and physical characteristics of Pluto and Kuiper Belt objects. • Determine the chemical composition and physical characteristics of short-period comets. • Analyze the chemical compositions of primitive meteorites and their components. • Perform theoretical modeling and experimental investigations of processes involved in the initial stages of planet formation.	• Multidisciplinary comparative studies of atmospheres, surfaces, interiors, and satellites. • Comparative studies of the climate evolution of Earth, Mars, and Venus • Comparative studies of the current state and inferred evolution of Moon and Mercury. • Determine how the impactor flux decayed in the early solar system.	• Analyze the chemical and isotopic composition of comets. • Determine Jupiter's water abundance and deep atmospheric composition. • Determine the chemical and isotopic composition of Venus' surface and atmosphere. • Determine the distribution of organic material on Titan and Enceladus.	• Determine the chemical composition of comets and Kuiper Belt objects. • Study surface organic deposits on Titan and interaction of surface with atmosphere.	• Identify, model, and track near-Earth objects down to 1 km diameter. • Understand the impact process in different planetary settings. • Understand impacts and exogenous delivery/production of organics. • Investigate the relationship between impacts and extinctions.
Study the processes that determined the original characteristics of the bodies in the solar system.	Understand why the terrestrial planets are so different from one another.	Determine the evidence for and age of an ocean on the surface of Venus	Search for evidence for life on Europa, Enceladus, and Titan	Inventory and characterize planetary resources that can sustain and protect human explorers
• Analyze ancient rocks from the Earth, Moon, Mars, and asteroids. • Characterize Jupiter's gravity, magnetic fields, and deep atmospheric chemistry.	• Study Venus' atmospheric chemistry and surface/atmosphere interactions. • Study Mars meteorology and geophysics.	• Search for granitic and sedimentary rocks. • Analyze the mineral composition of hydrated silicates and oxidized iron. • Investigate the interplay of volcanic activity and climate change.	• Identify and study organic deposits from the subsurface ocean on Europa. • Study biomarker signatures in surface organics in active/recently active areas on Titan. • Sample subvent fluids for biological activity.	• Determine water resources in lunar polar regions and near-Earth asteroids. • Determine the inventory of rare metals. • Assess potential long-term resources.
	Learn what our solar system can tell us about extrasolar planetary systems	Identify the habitable zones in the outer solar system	Search for evidence for past life on Venus	
	• Conduct detailed studies of the gas giants and ring systems. • Determine the structure of the Kuiper Belt.	• Characterize the geothermal zones on Enceladus. • Sarch for volcanically generated and impact-generated hydrothermal systems on Titan. • Confirm the presence and study the characteristics of Europa's subsurface ocean. • Conduct comparative studies of the Galilean satellites	• Search Venus samples for chemical and structural signatures of life.	
			Study Earth's geologic and biologic record to determine the historical relationship between Earth and its biosphere.	
			• Investigate biological processes on the early Earth through miltidisciplinary studies. • Examine the records of the response of Earth's biosphere to extraterrestrial events.	

5.3 Mission Summaries

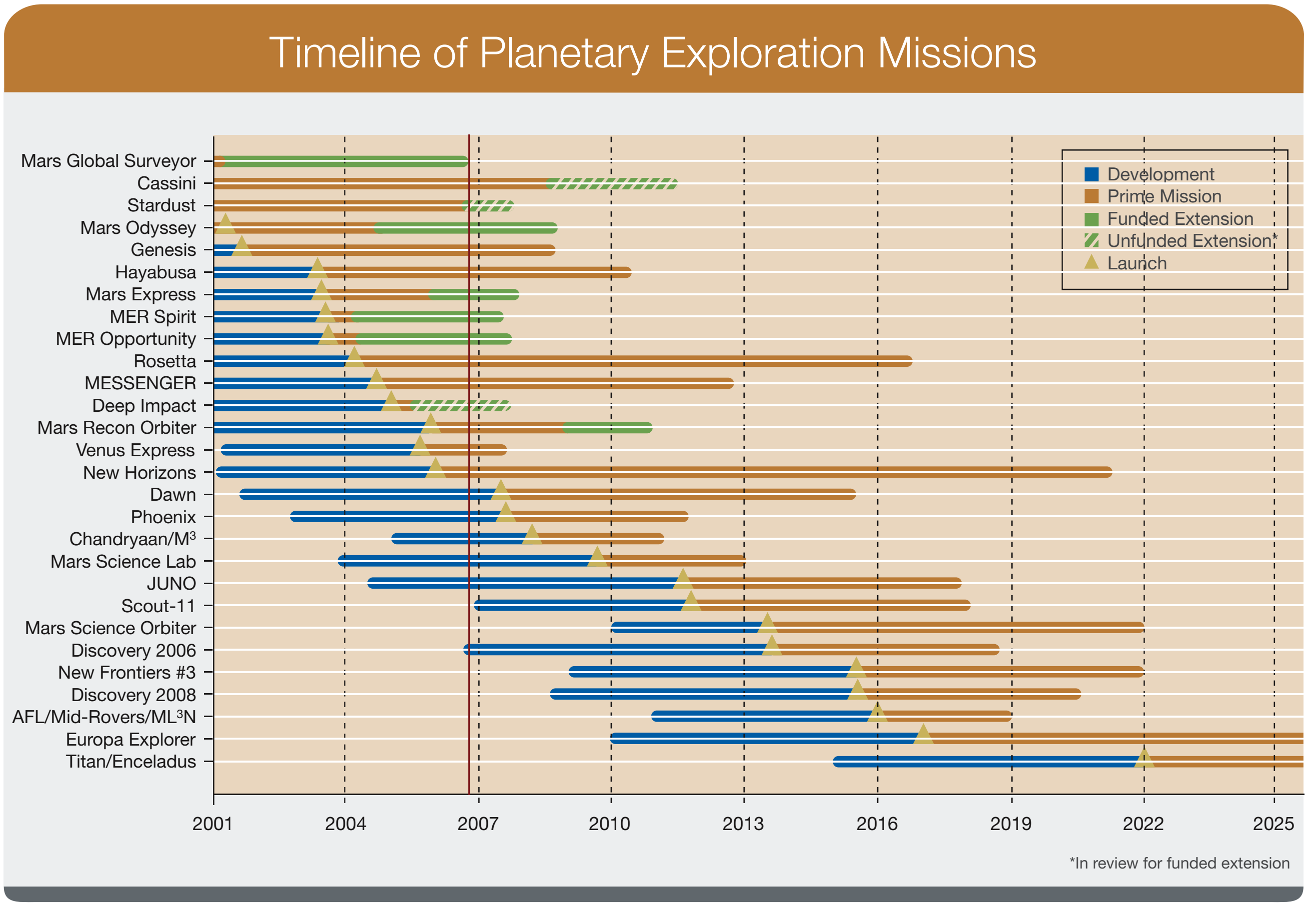
The previous sections presented all the elements required for a vigorous and productive set of missions to explore and to understand the planetary system where we live. This section integrates the previous sections to provide a prioritized list of the missions that will be initiated, developed, launched or operated through at least 2016.

Figure 5.4 - Timeline of Planetary Science Missions to 2024. Shown are the actual, planned, or expected development phases and launch dates and prime and extended mission phases. Blue bars represent development phase, yellow triangles indicate launches, orange bars represent prime missions (which may include long cruises), and green bars represent extended missions. Discovery 2006 and 2008, Mars Scout-11, and New Frontiers #3 are currently notional. The Discovery 2006 and 2008 entries are placeholders and may represent more than one actual mission. The vertical red line is December 2006.

There are currently 11 operational NASA spacecraft exploring the solar system. Some, like Cassini, have been operating for an extended period of time. Others, like the Mars Reconnaissance Orbiter and New Horizons, have just started their prime mission. There are also three missions preparing for launch. By 2008, at least one new Discovery and one Mars Scout mission will have been selected, and preparations for the third New Frontiers competition will be underway. The next strategic mission to Mars, Mars Science Laboratory, is scheduled to launch in 2009. Preparations for the next strategic mission to the outer planets (like Europa Explorer) can begin no earlier than 2010 based on current funding profiles. A summary of future missions is shown in Table 5.2. The launch dates and prime operation phases for these missions are shown in Figure 5.4.

The Mars Scout, Discovery, and New Frontiers Programs solicit for PI-led missions. The Mars Scout Program is open to any proposal for a mission to explore Mars. Likewise, the Discovery Program is open to any proposed mission

Figure 5.4



that explores the solar system (other than Mars) or furthers our understanding of extrasolar planets. In contrast, the New Frontiers Program is restricted to proposals to implement a clearly delineated list of target mission concepts derived from the NRC Decadal Survey. In 2007, the Planetary Science Division will engage the scientific community in a discussion on expanding the list of New Frontiers target mission concepts.

Table 5.2

Planetary Science Future Mission Summary

Program	Mars Mission	Objective (See Table 2.1)					Mission Objectives and Features
		1	2	3	4	5	
ME Core	Mars Science Laboratory (MSL)	●	●	●	●	●	Mineralogy and chemistry of surface samples; atmospheric composition and radiation at the Martian surface. Roving analytical laboratory with robotic arm and sample analysis capability.
Scout	Phoenix			●	●	●	Volatiles and complex chemistry in northern polar plains of Mars. Competitively selected PI-led mission; fixed lander.
ME Core	Mars Science Orbiter (MSO)	●	●				Orbiting, strategic mission; instruments to be selected through open competition once detailed objectives defined.
ME Core	Astrobiology Field Laboratory			●	●	●	Detection and characterization of biomarkers. MSL-like rover with instruments focused on organics and with next generation sample processing system. Strategic mission to be selected from among AFL, Mid-size Rovers, and Network Landers for the 2016 opportunity.
ME Core	Mid-Size Rovers	●	●			●	Spatial diversity of geology, geochemistry, etc. Pair of MER-like rovers with updated instrument suite and sites selected based on MRO results. Strategic mission to be selected from among AFL, Mid-size Rovers, and Network Landers for the 2016 opportunity.
ME Core	Network Landers	●	●			●	Geophysical parameters. Spatially separate small landers linked by existing orbiter(s). Strategic mission to be selected from among AFL, Mid-size Rovers, and Network Landers for the 2016 opportunity.
Scout	Mars Scout-11		●	●			TBD based on competitive selection; PI-led mission

Planetary Science Future Mission Summary—Continued							
Program	Other Planetary Science Mission	Objective (See Table 2.1)					Mission Objectives and Features
		1	2	3	4	5	
NF	Juno	●	●	●			Jovian gravity and magnetic fields and atmospheric composition. PI-led mission; polar orbit around Jupiter.
Discovery	Dawn	●		●		●	Investigations of Ceres and Vesta. Competitively selected PI-led mission.
Flagship	Europa Explorer	●	●	●	●		Probe habitability and accessibility of Europa. Flagship mission; orbiter touring the Jovian system with focus on Europa; perhaps with an impactor or other means to probe the crust.
Discovery	Discovery 2006	o	o	o	o	o	ORISIS asteroid survey and sample return, Vesper Venus atmospheric chemistry and dynamics orbiter, or GRAIL lunar gravity field mapper.
Flagship	Titan/Enceladus Explorer	●	●	●	●		Survey Titan's atmosphere and surface composition and processes. Insertion of an instrumented aerial vehicle into Titan's atmosphere; Enceladus portion is TBD.
NF	New Frontiers-3	o	o	o	o	o	TBD; large competitively selected, PI-led mission; will reassess field of candidates prior to next Announcement of Opportunity.
Discovery	Discovery 2008	o	o	o	o	o	TBD; competitively selected, PI-led mission.

● Applies to the objective o Could apply to any objective

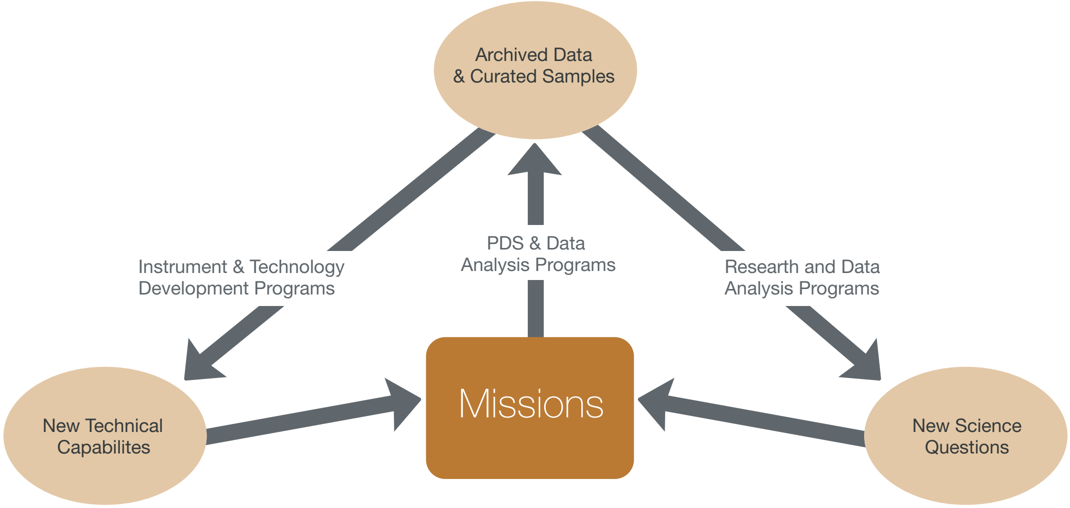
5.4 Program Elements

A strong scientific and technical community is required to envision, develop, and implement solar system exploration missions and to interpret and apply results from these missions for the benefit of society. The data and samples returned from missions must be archived and curated and the results widely disseminated. In this section, the elements of the Planetary Science Program that nurture and support missions are described.

5.4.1 Research and Analysis

Discoveries and concepts developed in the R&A Program are the genesis of scientific priorities, missions, instrumentation, and investigations. The R&A Program is the primary interface with NASA for university faculty and graduate students; it allows training of the next generation of mission team members, principal investigators, and project scientists. Although not always tied to specific missions, the tasks funded by the R&A Program add value to missions in the form of post-mission data analysis, observations required for mission design, mission observation support, and joint scientific campaigns. Increasingly this support has expanded to include international,

Figure 5.5



multidisciplinary campaigns in conjunction with spacecraft observations, greatly increasing the value of data from all platforms through combining current observations and comparing different data types. A recent example is the massive campaign organized to support observations and characterization of the Deep Impact encounter with comet Tempel 1. Computational and theoretical resources were devoted to the problem, and a large fraction of the available Earth- and space-based observational assets of the world's scientific community supported the campaign, including networks of amateur astronomers. Funded at less than 10 percent of the total funds expended annually on the robotic exploration of the solar system, the R&A Program greatly leverages NASA's significant investment in missions.

Due to the broad nature of the fundamental science questions addressed by the exploration of our solar system, the various elements of the Planetary Science R&A Program cover an extraordinarily broad range of scientific investigations. In particular, the R&A program supports two necessary multidisciplinary sciences: planetary science and astrobiology. Planetary science grew from the discoveries of the space missions of the 1970s and forms the foundation for the scientific exploration of the solar system. NASA remains the primary funding source for planetary science research. Astrobiology is a new field, started by NASA a decade ago, that brings together scientists from diverse disciplines including Earth and planetary science, astrophysics, heliophysics, microbiology, evolutionary biology, and cosmochemistry to develop the scientific foundation needed to pursue the search for evidence of life and habitability in the solar system and beyond. Astrobiology and the missions it supports bring modern science to bear on questions that, in one form or another, are as old as humanity itself: How does life begin and evolve? Does life exist elsewhere in the universe? What is the future of life on Earth and beyond?

In addition to planetary science and astrobiology, the R&A Program also studies the origins of the solar system and the interrogation of those materials left over from the birth of planets: asteroids, meteorites, comets and interplanetary dust particles. An additional component is the analysis of data returned and archived by missions.

Recent changes to NASA's budget, including cuts to the R&A Program, however, have adversely affected NASA's ability to analyze data and materials returned from missions and to lay the foundations for future missions. These cuts have also reduced NASA's financial support for astrobiology research by about half. As part of the budget-formulation process, NASA will annually reassess the balance of investment among R&A, missions, and technology development.

5.4.2 Data Curation, Dissemination and Analysis

The outcomes of planetary exploration missions are of two sorts: data recorded and transmitted to Earth by spacecraft and samples that are returned to Earth by various means. The curation, dissemination, and analysis of these require rather different approaches.

The PDS is the active data archive for NASA's Planetary Science Division. It is a distributed archive, with datasets archived at a number of Science Discipline Nodes (Atmospheres, Geosciences, Imaging, Planetary Plasma Interactions, and Small Bodies). The Science Discipline Node Principal Investigators maintain a strict set of PDS compliance standards to ensure the integrity and long-term usability of the datasets and to determine the appropriate formats for data product deliveries from NASA and international flight projects.

Support nodes (Engineering, Navigation Ancillary Information Facility) and a support function (Radio Science) assist the Discipline Nodes through infrastructure development and flight project support. In addition, a number of Science Subnodes and Data Nodes interface with the Discipline Nodes to provide access to specific sets of data, often for short periods of time. Geographically dispersed mirrors of data are maintained within the PDS to ensure continuity of operations, and a "deep archive" is held at NASA's National Space Science Data Center (NSSDC).

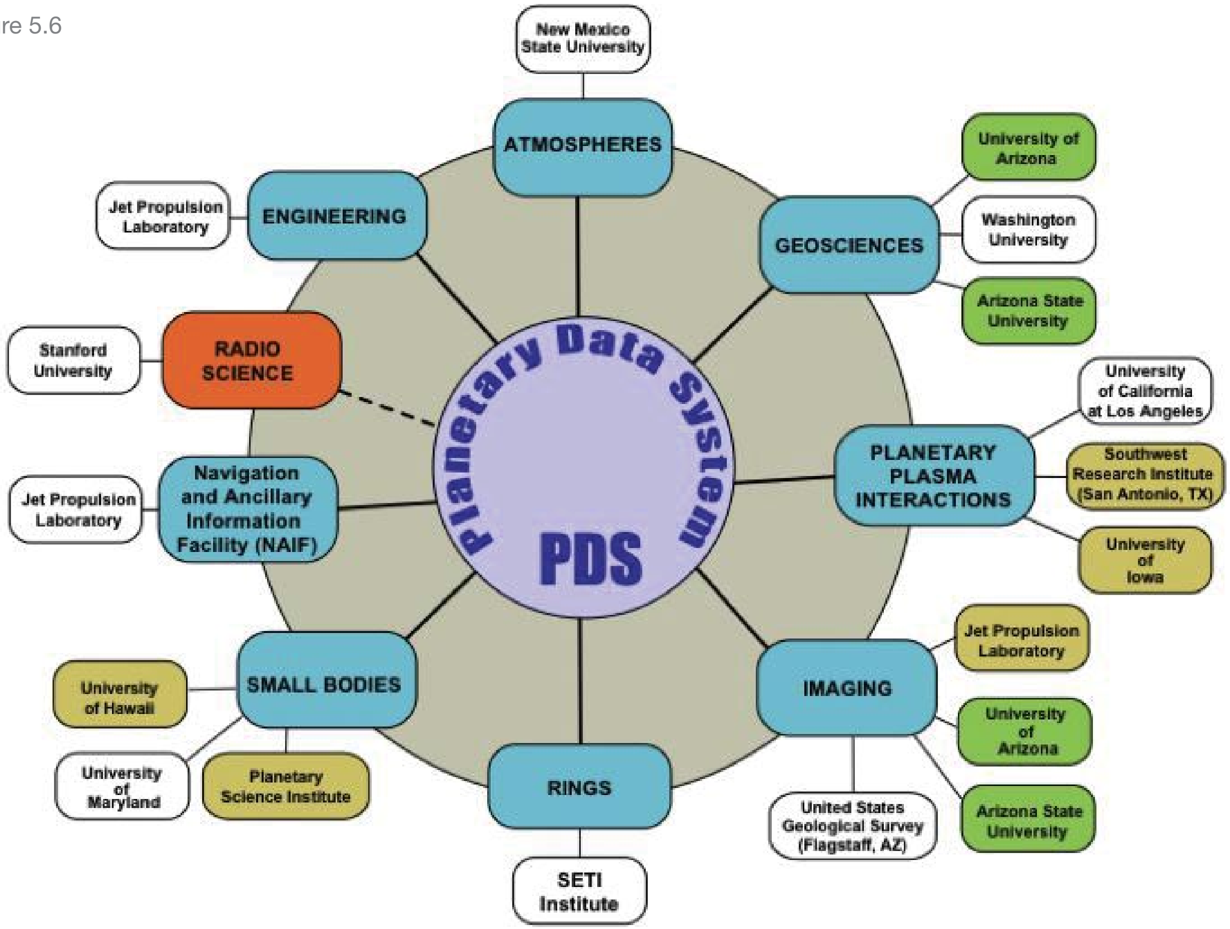
Data from particular ESMD missions, such as LRO, will also be archived by the PDS by agreement between SMD and ESMD.

The Johnson Space Center (JSC) Astromaterials Curation Facility provides services for all returned planetary materials that do not require planetary protection laboratories. This facility has been in operation since the Apollo lunar samples were returned. Later, meteorites collected by U.S. teams in Antarctica and interplanetary dust collected in the stratosphere were added to the collections. In 2004 and 2006, the Genesis and Stardust missions returned the first solar system materials from outside Earth's atmosphere since Apollo. Special new cleanroom laboratories were constructed for both the Genesis solar wind samples and Stardust comet samples. These samples are currently being studied in laboratories worldwide.

In the next decades we anticipate missions to collect samples from the Moon, Mars, comets, and asteroids. Each of these new sample collections will require new curation laboratories, while the facilities for the older collections will require routine maintenance and upgrades. Samples to be returned from Mars

Figure 5.6 - Structure of the Planetary Data System. Discipline nodes are shown in turquoise balloons with their host institutions in white balloons. Subnodes are shown in mustard balloons, and data nodes are shown in green balloons. A function is shown as an orange balloon. Although distributed over many physical locations, the PDS has a seamless presence on the World Wide Web.

Figure 5.6



pose even greater challenges due to special planetary-protection requirements. It is imperative that attention be paid to curation facilities to assure that new samples will be available for analysis in laboratories around the world and that the remaining samples are available for further investigations with new advanced instruments for many years to come.

5.4.3 Planetary Protection

Planetary protection refers to the practice of protecting solar system bodies from biological contamination from Earth and protecting Earth from possible life forms that could be returned from elsewhere. Planetary protection practices preserve our ability to study other worlds as they exist in their natural state—avoiding contamination that would obscure our ability to find extraterrestrial life, if it exists, while ensuring prudent precautions to protect Earth's biosphere. NASA's planetary protection policy is a component in the U.S. adherence to the 1967 United Nations Outer Space Treaty, which requires that states who are parties to the treaty "shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination," and also shall avoid "adverse changes in the environment of Earth resulting from the introduction of extraterrestrial matter."

For NASA, planetary protection requirements for each mission and target body are based on the advice of the National Research Council's Space Studies Board for strategic issues and with the NAC Science Committee's Planetary Protection Subcommittee for implementation issues under NASA and international guidelines. Each mission is categorized according to the type of encounter it will have (e.g., flyby, orbiter, or lander) and the nature of its destination (e.g., a planet, moon, comet, or asteroid). If the target body has the potential to provide clues about life or prebiotic chemical evolution, a spacecraft going there must meet a higher level of cleanliness and some operating restrictions will be imposed. Spacecraft going to target bodies with the potential to support Earth life must undergo stringent cleaning and sterilization processes and greater operating restrictions. Missions returning samples to Earth may be either "unrestricted" in their return phase or may be subject to stringent precautions to protect the Earth's biosphere if it is thought that life could exist on the target body.

The NRC Decadal Survey offered several recommendations on the need for ongoing improvements in the ability to respond to planetary protection requirements to solar system exploration missions. Missions to outer satellites were considered a challenge due to the presence of subsurface oceans potentially containing life, as well as organic compounds and potential prebiotic chemistry. In preparation for future Mars sample-return missions, it was recommended that a sample-analysis program be established with a suitable investment well in advance of the mission. Clearly, the challenges of implementing planetary protection constraints for solar system exploration missions are only beginning.

The NRC has recently (2005) provided recommendations about planetary protection requirements to prevent Mars forward contamination, taking into account new results from the Mars Global Surveyor, Mars Odyssey, and Mars Exploration Rover missions. This report emphasized the importance of a strong research program for planetary protection in understanding microbial diversity, spacecraft sterilization, and Martian environmental conditions conducive to life—while emphasizing the need for additional resources to be invested in adopting molecular microbiological methods to account for potential biological contamination. The report also endorsed the concept of "special regions" on Mars that may support Earth life (as put forth by NASA and COSPAR), and recommended that NASA explicitly define conditions and datasets that describe these regions, while maintaining strict spacecraft cleanliness standards to avoid their contamination during future Mars missions.

Titan and Enceladus

Cassini image of Titan and Enceladus (foreground), two of Saturn's fascinating moons. Both bodies are, to varying degrees, geologically active. For Enceladus, its southern polar vents emit a spray of icy particles that coats the small moon, giving it a clean, white veneer. On Titan, yet undefined processes are supplying the atmosphere with methane and other chemicals that are broken down by sunlight. These chemicals are creating the thick yellow-orange haze that is spread through the atmosphere and, over geologic time, falls and coats the surface. The thin bluish haze on its limb is caused by the scattering of sunlight by particles in the atmosphere.

5.4.4 Technology

The plan for the robotic exploration of the solar system outlined in previous sections is highly ambitious. Missions to the outer solar system and to Venus will require a range of new technologies to be successfully implemented. A host of these technologies are broadly applicable to a range of missions. These high-priority "systems" technologies are:

- Advanced inspace propulsion systems, especially the development of a robust, practical, and affordable solar-electric propulsion system for use by Discovery, New Frontiers and strategic missions;
- Aerocapture, advanced mobility, and entry, descent and landing systems to enable missions to targets with atmospheres, especially Titan, Triton, Neptune and Mars;
- Advanced power generation and storage, notably low-intensity, low-temperature, solar arrays and high-efficiency radioisotope power systems for use in the outer solar system;
- Technologies for operation in extreme environments, including high-temperature and pressure, low-temperature, and high-radiation environments. This technology includes passive and active cooling for components and instruments and radiation-hardened computers and computer memory;
- New systems-level methods for benignly sterilizing spacecraft and ensuring their organic contamination cleanliness,
- Advanced radio-frequency and optical communications for higher-bandwidth data return;
- Robust vehicle and science autonomy for decreased operations complexity, increased tolerance to long communication latencies, and increased science return, especially for the observation of unpredictable events;
- Novel sample acquisition, handling, and processing tools that can access subsurface materials, function under extreme conditions, and replicate modern geology and molecular-biology laboratory procedures; and
- New scientific instruments, components, lasers, and detectors that are smaller, lighter, and use less power than current technology.

Specific missions will also require new technologies. Missions to study Venus's atmosphere and Titan's surface will require the development of new concepts of aerial mobility (e.g., balloons, dirigibles, gliders) while advanced missions to asteroids will require new techniques for operating near, and landing on, low-gravity, airless bodies. Missions to the surfaces of Mars, Venus, Europa and Enceladus will also benefit from precision-landing capability.

The Mars Program has the advantage, as an integrated program, of developing technologies to enable and enhance missions with a common target and its unique characteristics—Mars. Technologies being developed focus on entry, descent and landing robustness, increased mass for greater mission capability on the surface, and improved landing precision; rover mobility and power advancements, operations, navigation and autonomy; mid-TRL instrument development for implementation; and surface-to-orbit communications. The Program's technologies currently focus on the 2013-2016 mission options, but no finances or plans exist for investing in sample-return technologies.

Additional technology investments for the future are being developed in the In-Space Propulsion and Radioisotope Power Systems Programs and instrument development programs (e.g., Astrobiology Science and Technology for Instrument Development (ASTID), Mars Instrument Development Program (MIDP), Astrobiology Science and Technology to Explore Planets (ASTEP), Planetary Instrument-Development and Definition Program (PIDDP)). Efforts are underway to integrate the Planetary Science Division's technology-development efforts to optimize the critical technology development funds to address the needs of the highest priority future missions.

5.4.5 Nationally Unique Facilities

There are several nationally unique facilities that are used by the Planetary Science Division to achieve its goals. The Infra Red Telescope Facility (IRTF), located on the summit of Mauna Kea, Hawaii, is operated by SMD to provide timely observation of solar system objects and collection of planetary research data in support of spacecraft missions. It may also be used as a platform to develop and demonstrate new technologies for planetary observations and future spacecraft missions. The IRTF consists of a telescope designed for maximum performance in the infrared portion of the spectrum with mounts for the simultaneous use of multiple instruments. Facility instruments are provided for data acquisition and are developed and maintained by personnel assigned under the management and operations agreement. Compatible guest instrumentation may also be used when properly coordinated with the IRTF management and operations. The facility includes the observatory building at the summit, which houses the telescope, all operations, support, and maintenance work space, and all computer equipment to control the telescope and support the collection of data (including a remote telescope control system for remote observers world-wide).

The Goldstone Solar System Radar (GSSR) is the only fully steerable radar in the world for high-resolution ranging and imaging of planetary and small-body targets. These observations provide information on orbits, rotations, and surface characteristics for a wide assortment of solar system objects. The resulting data are used for both basic research on planetary objects and frequent support of NASA planetary missions. Specific mission support examples include landing site evaluation for surface missions to both the Moon and Mars (LPRP, MER and MSL), high-precision measurements of the rotation of Mercury (MESSENGER), and the search for polar water ice on Mercury, the Moon, and Mars. GSSR Doppler ranging is also used for high-precision orbit determination of Near Earth Objects and to determine their shape (including whether or not they are binary objects) and surface features to determine their potential as future spacecraft mission targets and hazards for potential collision with Earth. GSSR is one of only two planetary radar instruments in the world, the other being NSF's Arecibo Observatory. However, the GSSR has several advantages for NASA, including the ability to study smaller-scale structure, observation of targets over a wider declination range and longer duration (i.e., accessibility), the use of multiple receiving antennas within the Goldstone complex for radar interferometric studies, and the ability to control the use of the facility to meet NASA's needs.

There are also two unique facilities at Ames Research Center: the Mars Surface Wind Tunnel and the Vertical Gun Range. The Mars Surface Wind Tunnel is capable of simulating Martian surface atmospheric pressures and has been used to study the transport of dust and the behavior of dust devils.

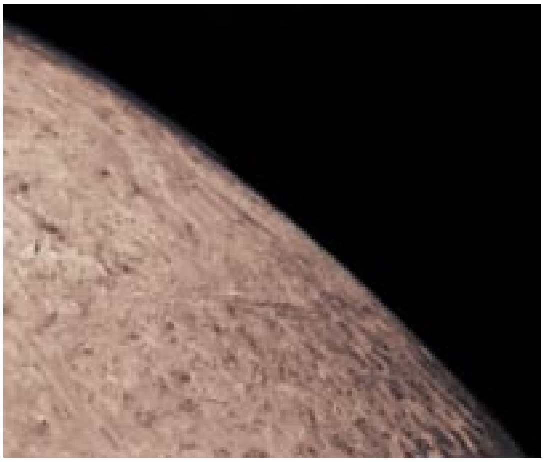
The Ames Vertical Gun Range (AVGR) was designed to conduct scientific studies of lunar impact processes in support of the Apollo missions and, since 1979, has been heavily used to study the physics of impacts. The AVGR can launch projectiles to velocities ranging from 0.5 to nearly 7 km/sec. By varying the gun's angle of elevation with respect to the target vacuum chamber, impact angles from 0° to 90° relative to vertical are possible. This unique feature is extremely important in the study of crater-formation processes. Most recently the AVGR has been used to support the analysis of samples returned by the Stardust mission.

5.5 Planetary Science Beyond 2016

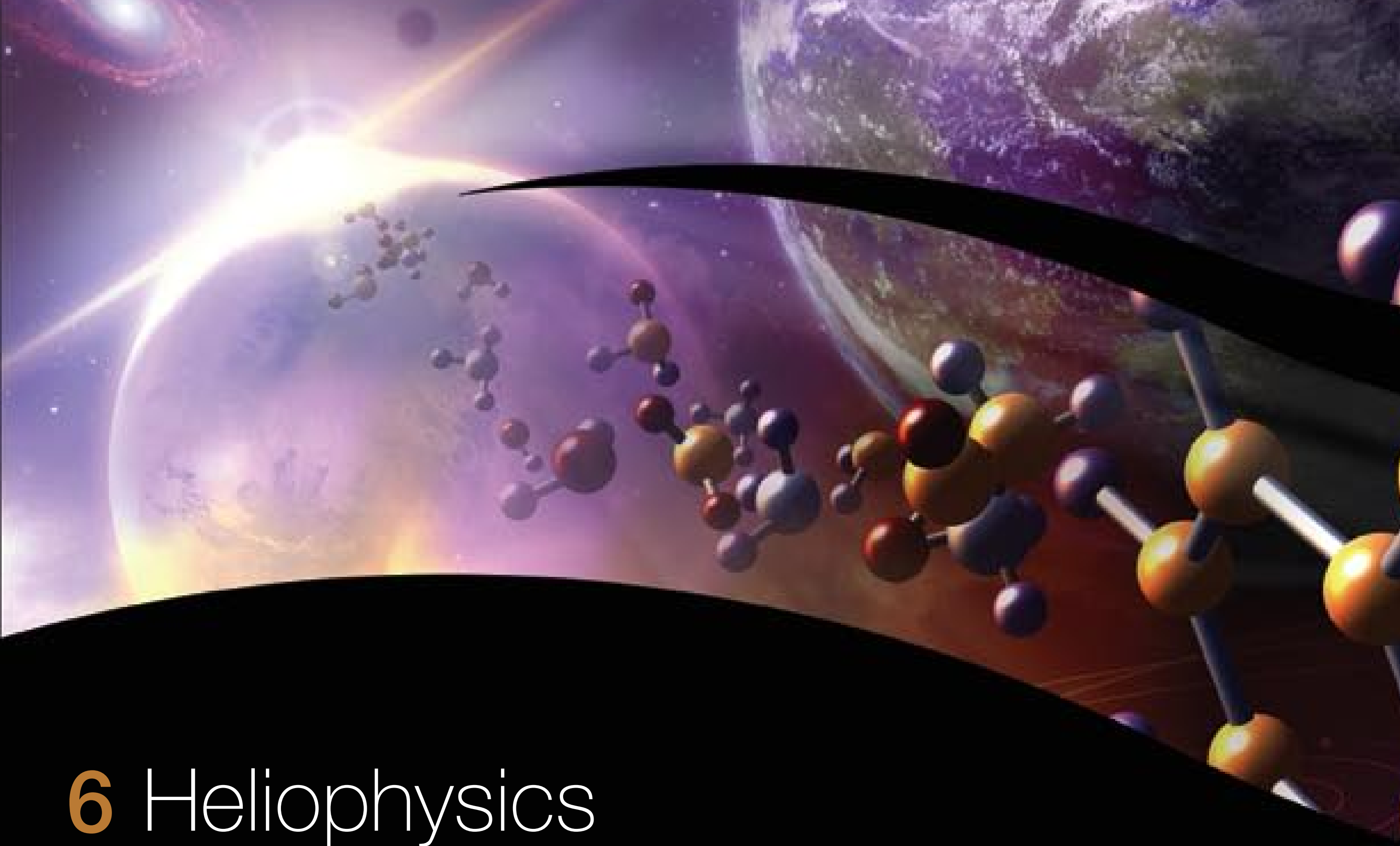
In the time period beyond 2016, the Solar System Exploration Roadmap lays out a series of four strategic missions. They are the Titan Explorer, the Venus Mobile Explorer, the Europa Astrobiology Lander, and the Neptune Orbiter/Triton Explorer. The notional launch dates are 2020, 2025, 2030, and 2030, respectively, with the choice between the latter two determined by the results from the Europa Explorer. There are currently substantial technical hurdles to be overcome before development can start on either the Titan Explorer or the Venus Mobile Explorer. In the coming decade, technology development programs will be focused on overcoming them. The final two strategic missions are linked by the results of the Europa Explorer mission. Should the Europa Explorer mission determine that water or material from the subsurface ocean are accessible, then the Europa Astrobiology Lander would focus on the investigation of chemical and biological properties of surface/subsurface materials associated with habitability. If the Europa Explorer does not find evidence that the subsurface ocean or materials produced there are accessible, then the Roadmap recommends the initiation of the Neptune Orbiter/Triton Explorer, an "all-in-one" exploration package that would study the Neptune system in a way similar to the way Cassini-Huygens mission studied the Saturn system. Farther out in time, the Roadmap suggests possible strategic missions to return samples from Venus' surface and cryogenically preserved samples from a comet nucleus. A vigorous program of PI-led missions is also envisioned starting with another Discovery Program solicitation occurring no earlier than 2008.

In the post-2016 time frame, there are currently three Mars missions anticipated: a PI-led Mars Scout, the Mars Long-Lived Lander Network (ML^{3}N) (which is actually an option for 2016 as discussed previously), and a Mars sample return mission. The ML^{3}N is conceived of as a network of landers equipped to perform meteorological and geophysical measurements. This mission concept has been highly rated by the NRC Decadal Survey. With international collaboration, an earlier launch of a network mission could be accomplished. Mars sample return is an important mission, also highly rated by the NRC decadal survey. This mission is anticipated as an early third decade mission due to its complexity and cost, and will undoubtedly require significant international collaboration. This is also an important mission in support of the Vision as a preparatory and safety assessment mission for the first human landing.

Triton



This image of Triton shows a thin cloud layer along the limb of the moon. The image was obtained as Voyager 2 swept past Triton at a speed of 27 kilometers per second and passed within 39,800 kilometers. Voyager discovered that Triton possessed a thin atmosphere of 15 microbars or 0.000015 times the surface pressure on Earth at sea level. The limb of Triton also showed a thin haze about 13 kilometers from the surface of the planet and thin patches of clouds as shown by this image.



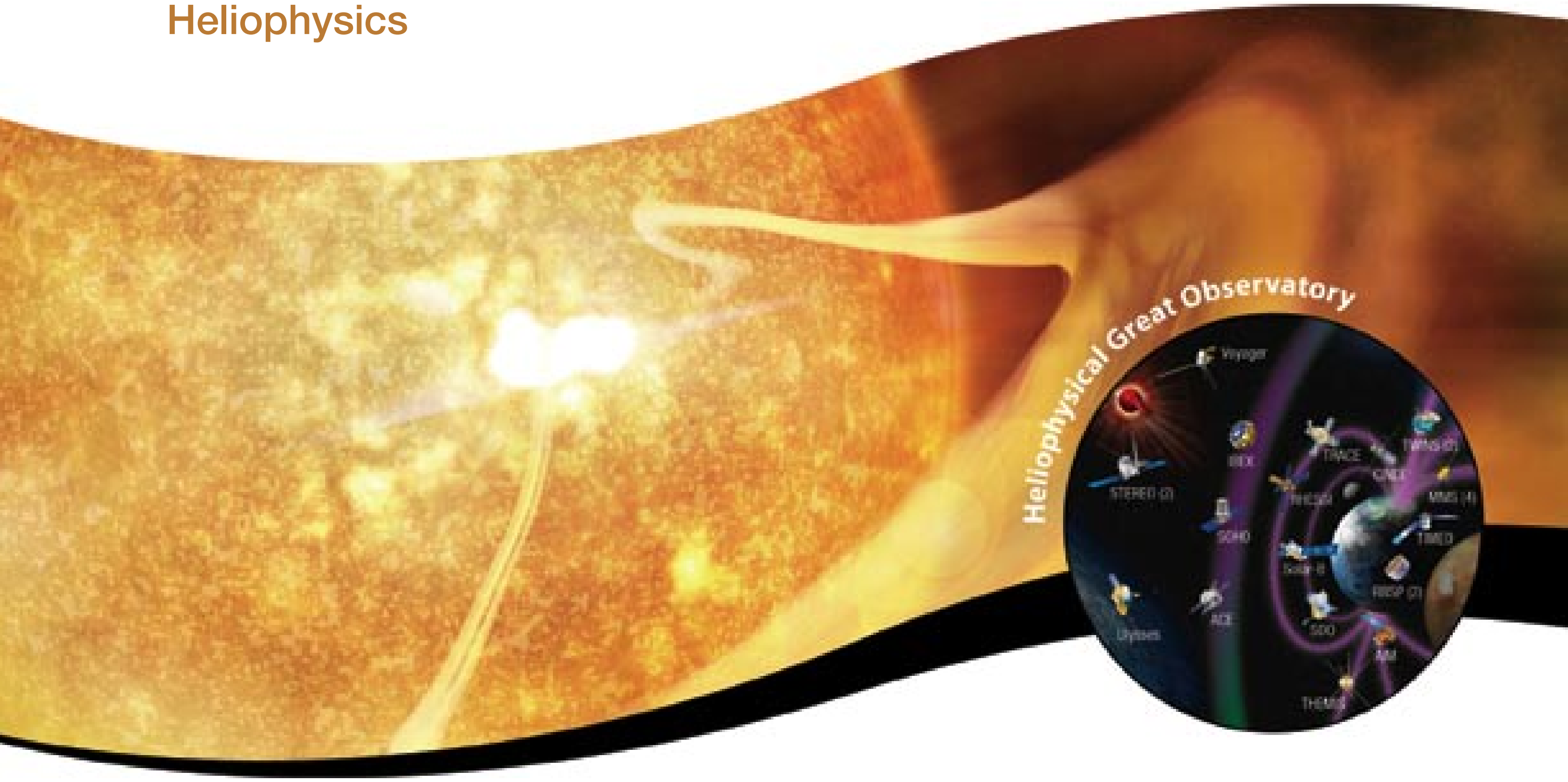
6 Heliophysics

Strategic Goal:

Understand the Sun and its effects on the Earth and the solar system

Chapter 6

Heliophysics



Heliophysics derives from the Greek *helios* for the Sun and its environs and *physika*, the science of the natural world. Heliophysics is the exploration of the Sun, its effects on Earth and the planets of the solar system, and space environmental conditions and their evolution.

Heliophysics encompasses cosmic rays, particle acceleration, aurorae, space weather, radiation, dust, magnetic reconnection, magnetohydrodynamics, solar activity and stellar cycles, aeronomy and space plasmas, magnetic fields and global change, and the interactions of the solar system with our galaxy.

Heliophysics embraces science that safeguards the Exploration journey by developing the capability to forecast both hazardous and safe working conditions in space for human and robotic exploration.

Heliophysics uses remote sensing and *in situ* measurements from a fleet of targeted missions that are integrated into a synergistic Great Observatory, suborbital rockets, balloons, ground-based instruments, theory, and modeling to acquire insight into the complex interactions of this interconnected system.

6.1 Intellectual Foundation

NASA launched the Mariner 2 spacecraft to Venus in August 1962. Completely successful in its planetary mission, it also resolved a long-burning controversy: interplanetary space is completely filled with streams and clouds of material ejected by the Sun. Not everyone had accepted Eugene Parker's theory of the solar wind when it was first published in 1958. It was fiercely debated until these and other *in situ* observations confirmed the vigorous and dynamically complex outflow.

Thus, a new view of our solar system was born. At the center is a magnetically variable star that affects the planets of the solar system and sculpts the heliosphere out of the local interstellar medium. The variability of this star has significant impacts on life and technology that are felt here on Earth and throughout the solar system.

A new field of science—the determination of the mechanisms and processes of the solar system as driven by the Sun—has emerged. NASA is working to understand the complex behavior of the Sun to develop the capability to predict changes to Earth and its space environment. A collection of spacecraft, the Heliophysical Great Observatory, patrols the expanse from the Sun to the frontiers of the solar system and beyond. This observatory reveals not a placid star and isolated planets, but an immense, dynamic, interconnected system of which our home planet is part and through which space explorers must journey.

In the future, the power of this constellation of satellites will evolve to provide newfound understanding to predict hazardous events wherever explorers may travel. New measurement databases will be integrated into physics-based numerical models. Resolved images of other stars will provide insights into the varying activity of our own Sun. We will understand the effects of our modulating star across the reaches of the solar system and at the planets, including the effects upon Earth and its systems. We will gain insights into how the star that supplies energy for life on Earth may have shaped Earth's early existence and development.

This Heliophysics chapter of SMD's Science Plan is designed using the recommendations of the 2003 NRC decadal survey, *From the Earth to the Sun: A Decadal Survey for Solar and Space Physics*, and the 2006 community roadmap *Heliophysics: The New Science of the Sun-Solar System Connection*.

6.2 Science Objectives and Outcomes

Earth moves through the heliosphere, the exotic outer atmosphere of a star. The space beyond Earth's protective atmospheric cocoon is highly variable and far from benign. The Sun, our solar system, and the region of the galaxy just outside present us with a complex, interacting set of physical processes. It is the one part of the cosmos accessible to *in situ* scientific investigation, our only hands-on astrophysical laboratory.

Building on NASA's rich history of exploration of Earth's neighborhood and distant planetary systems, we are poised to provide a predictive understanding of our place in the solar system. We do not live in isolation; we are intimately coupled with the Sun and the space environment through Earth's climate system, our technological systems, the habitability of planets and solar system bodies we plan to explore, and ultimately the fate of Earth itself. Variability in this environment affects the daily activities that constitute the underpinning of modern society, including communication, navigation, and weather monitoring and prediction. Because the space environment matters to humans and their technological systems both on Earth and in space, it is essential as a space-faring Nation that we develop an understanding of these space plasma processes.

The science objectives listed in Table 2.1 and below represent a science community consensus on priorities. They guide the selection of investigations and other programmatic decisions. We have unfolded NASA's strategic goal 3.2, *Understand the Sun and its effects on Earth and the solar system*, into three science and exploration objectives:

- *Open the Frontier to Space Environment Prediction:* Understand the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium;
- *Understand the Nature of Our Home in Space:* Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields; and,
- *Safeguard the Journey of Exploration:* Develop the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers.

These will be accomplished by studying the Sun, the heliosphere, and planetary environments as elements of a single interconnected system, one that contains dynamic space weather and evolves in response to solar, planetary, and interstellar conditions. Such an understanding represents not just a grand intellectual accomplishment for our times —it also provides knowledge and predictive capabilities

Table 6.1

Heliophysics Research Objectives and Focus Areas	
Research Objectives	Specific Research Focus Areas
Open the Frontier to Space Environment Prediction: Understand the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium	• Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms • Understand the plasma processes that accelerate and transport particles • Understand the coupling between planetary ionospheres and their upper atmospheres mediated by strong ion-neutral interactions • Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments
Understand the Nature of Our Home in Space: Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields	• Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment • Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects • Understand the role of the Sun as an energy source to Earth's atmosphere and, in particular, the role of solar variability in driving change • Apply our understanding of space plasma physics to the roles of stellar activity and magnetic shielding in planetary system evolution and habitability
Safeguard the Journey of Exploration: Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space	• Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers • Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events • Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers • Understand and characterize space weather effects on and within planetary environments to minimize risk in exploration activities

essential to future utilization and exploration of space. Herein, we describe current plans for NASA's research programs in this area and the guiding principles we will follow in pursuit of the forthcoming exploration challenges.

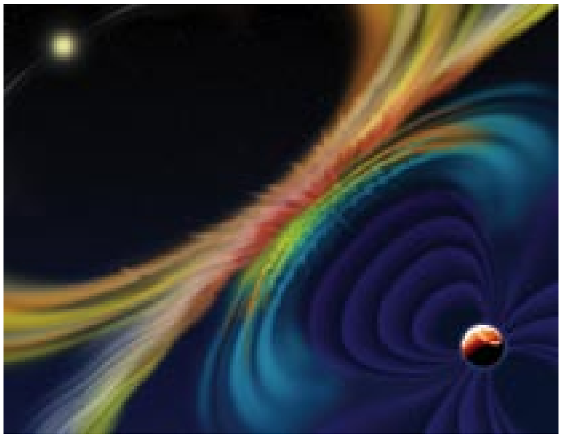
6.2.1 Open the Frontier to Space Environment Prediction

Magnetic Reconnection

Understand magnetic reconnection as revealed in solar flares, coronal mass ejections (CME), and geospace storms. Magnetic reconnection occurs in localized regions when interacting magnetic fields "snap" to a new, lower energy configuration, as if a pair of twisted rubber bands broke and relinked to form two new relaxed bands. Reconnections can release vast amounts of stored energy and are responsible for solar flares, CMEs, and geospace storms. The explosive release of energy can be devastating to space assets and human travelers and can seriously affect worldwide communications. Although we have developed an initial picture of where reconnection may occur and the observable results, the detailed physical mechanisms, in particular the microphysical processes and the role of large-scale topology, are not understood. Heliophysics will deliver a fundamental understanding of this universal process in the different regimes where it occurs.

Plasma Processes

Understand the plasma processes that accelerate and transport particles. In contrast to the neutral states of matter near planets, plasmas produce prodigious amounts of radiation. Because radiation has the most direct impact on human and robotic space explorers, detailed understanding of the particle acceleration processes that produce radiation, the regions in which these processes operate, and the conditions that control them is crucial to the exploration of space. We will investigate the mechanisms that accelerate particles, including small-scale waves, shocks, and quasi-static electric fields. Radiation can be produced almost instantaneously through explosive processes, but also built up stepwise by processes acting under more benign conditions. Providing essential predictions of the radiation



Magnetic Reconnection

Immense jets of electrically charged particles are regularly created in space via the process of "magnetic reconnection". The jets, which are powered by clashing magnetic fields, are the result of natural particle accelerators dwarfing anything built on Earth. Scientists build miles-long particle accelerators on Earth to smash atoms together in an effort to understand the fundamental laws of physics. Similar reconnection-powered jets occur in Earth's magnetic shield and within the solar wind, producing effects that disable orbiting spacecraft and cause severe magnetic storms.

environment along the end-to-end path of space explorers will involve accounting for particle acceleration in all its forms and locations, from Earth's aurora to the radiation belts to the solar corona and the edges of the heliosphere.

Plasma and Neutral Interactions

Understand the coupling between planetary ionospheres and their upper atmospheres mediated by strong ion-neutral interactions. Complex behavior occurs where charged plasmas and neutral gases interact. Plasma-neutral coupling occurs throughout the solar system: in turbulence and charge exchange in the solar wind and planetary magnetospheres, in electrodynamic rearrangements of ionospheres and thermospheres, and in gravity waves and chemical/collisional interactions in atmospheres. The lower-level boundary layers in planetary upper atmospheres are affected from above by electric fields, waves, particle precipitation, currents, and solar photons. They are affected internally by electric fields, chemistry, turbulence, currents, and winds, and from below by a wide spectrum of waves in the neutral atmosphere. The interactions and coupling mechanisms remain obscure due to a lack of information on all the parameters that describe the fully coupled system. This work has specific applicability to the operation of satellites in Earth's and Mars' atmospheres, the mitigation of the effects of global change, as well as understanding how habitable planets retain their atmospheres. It is within extended atmospheres where almost all processes that impact human technologies originate.

Magnetic Dynamos

Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary, and stellar environments. Understanding the variations of the magnetic fields of the Sun and planets on both long and short time scales is a key element for a fully predictive understanding of the Heliophysical system. The creation of these fields—the magnetic dynamo problem—remains one of the outstanding problems in physics. How dynamos operate in such widely disparate systems—from stellar interiors to planetary cores—is poorly understood. Dynamos determine the characteristics of the solar activity cycle. The Sun's magnetic field controls the structure of the heliosphere and, thus, regulates the entry of galactic cosmic rays into the solar system. Therefore, we need to understand the origin and variability of solar magnetism. Earth's interior dynamo sustains the geomagnetic field and provides the shield that enables life to flourish in the harsh radiation environment of space. Understanding how dynamos are created and sustained, how they affect the nearby space environment, and how to predict their variations and ultimately their demise lies at the heart of understanding our own planet.

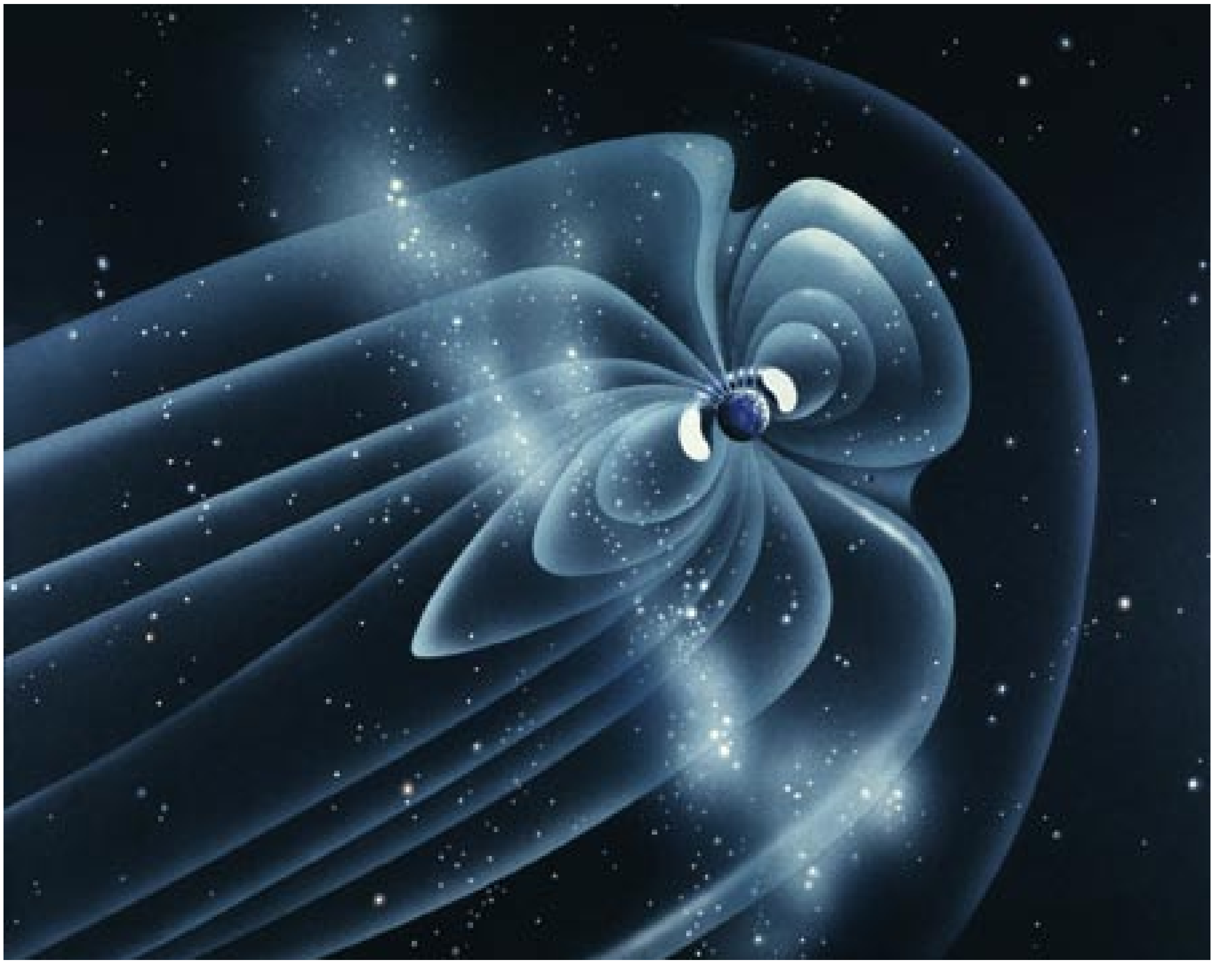
6.2.2 Understand the Nature of Our Home in Space

Cause and Evolution of Solar Activity

Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment. The climate and space environment of Earth are significantly determined by the impact of plasma, particle, and radiative outputs from the Sun. Therefore, it is essential to understand the Sun, determine how predictable solar activity truly is, and develop the capability to forecast solar activity and the evolution of disturbances as they propagate to Earth. Our star's output varies on many time scales: from explosive reconnection and convective turnover, to the 27-day solar rotation, to the 22-year solar magnetic cycle, and to even longer, irregular fluctuations, such as the 17th-century Maunder minimum. The variability is linked to the emergence of magnetic field from below the photosphere, its transport and destruction on the solar surface, and the eruption into the heliosphere of energy stored in the solar atmosphere as flares, shocks, and coronal mass ejections. Longer-term changes that can affect Earth's climate include solar total and spectral irradiance. Like terrestrial weather, it is not yet clear how long in advance solar activity is predictable. Continuous observations of the solar vector magnetic field and high-resolution observations of the atmosphere will be as critical for resolving this question as helioseismology will be for revealing the subsurface conditions.

Earth's Magnetosphere, Ionosphere, and Upper Atmosphere

Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere in order to enable specification, prediction, and mitigation of their effects. Heliophysics seeks to develop an understanding of the response of the near-Earth plasma regions to space weather. This complex, highly coupled system protects Earth from the worst solar



Earth's Magnetosphere

A magnetosphere is that area of space, around a planet, that is controlled by the planet's magnetic field. The shape of the Earth's magnetosphere is the direct result of being blasted by solar wind. It prevents most of the particles from the sun, carried in the solar wind, from hitting the Earth. The Sun and other planets have magnetospheres, but the Earth has the strongest one of all the rocky planets. The Earth's magnetosphere is a highly dynamic structure that responds dramatically to solar variations. Life on Earth developed and is sustained under the protection of this variable magnetosphere.

disturbances while redistributing energy and mass throughout. A key element involves distinguishing between the responses to external and internal drivers, as well as the impact of ordinary reconfigurations of environmental conditions, such as might be encountered when Earth crosses a magnetic sector boundary in the solar wind. This near-Earth region harbors spacecraft for communication, navigation, and remote sensing needs; conditions there can adversely affect their operation. Ground based systems, such as the power distribution grid, can also be affected by ionospheric and upper atmospheric changes. Key near-term investigations emphasize understanding the nature of the electrodynamic coupling, how geospace responds to external and internal drivers, and how the coupled middle and upper atmosphere respond to external forcings and how they interact with each other.

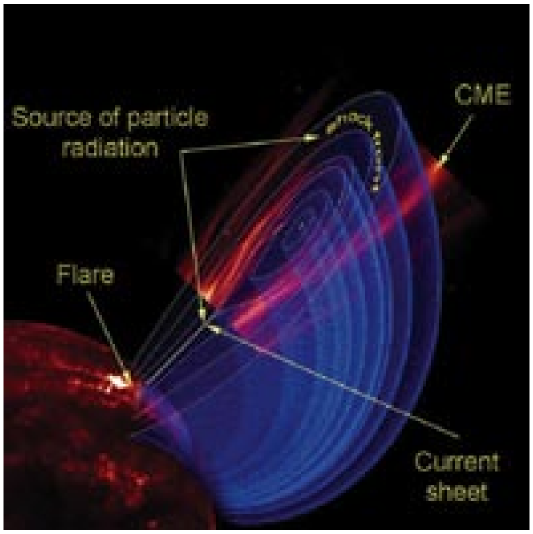
The Sun: An Energy Source to Earth's Atmosphere

Understand the role of the Sun as an energy source to Earth's atmosphere and, in particular, the role of solar variability in driving change. The long-term input of solar energy in the form of photons and particles drives the chemical and physical structure of our atmosphere, which in turn plays an important role in protecting life. We seek to understand the atmospheric response to solar variability, both spectral changes in electromagnetic radiation and changing levels of energetic particles. Foremost is to determine the processes that redistribute solar energy and then to determine how this is accomplished. Also, energetic particles from aurorae, the radiation belts, and solar flares affect ozone chemistry, and galactic cosmic rays contribute to cloud nucleation, but the details of these impacts remain uncertain. Addressing these issues requires high-resolution spectral observations of the atmospheric response to solar energy deposition as well as modeling of the processes that distribute the effects of solar energy. Analysis of the lunar regolith has the potential to provide an extremely long historical record of solar activity.

Broader Applications of Space Plasma Physics

Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability. Stellar plasmas and their embedded magnetic fields affect the formation, evolution, and destiny of all planets and planetary systems. As we begin to understand the role that plasmas and their embedded fields play in planetary formation and in the evolution of planetary atmospheres, we also begin to understand the ultimate habitability of planets. For example, our heliosphere shields our inner solar system from galactic cosmic radiation and the Earth's magnetic field protects it from solar and cosmic particle radiation and from erosion of the atmosphere by the solar wind. How have long-term changes in the local interstellar medium affected the history of life on Earth, and how do they affect the sustainability of life within our solar system? What are the implications of past and future magnetic field reversals at Earth? A series of investigations will target the structure of the heliosphere and its inner and outer boundaries, the role of magnetic fields in the formation of planetary systems, the long-term impact of planetary interactions with stellar winds, and the study of activity on stars other than our own. An applied goal is to understand the importance of planetary magnetic fields for the development and sustenance of life. Observing activity on other stars will tell us how conditions can change with time. Such investigations represent the most important linkages with the other SMD fields of study.

Solar Flare



One of the most difficult problems in space weather is the prediction of solar energetic particles. These relatively rare events travel from the Sun to Earth in about an hour, giving astronauts and spacecraft operators little time to prepare. New theoretical models are providing information about the precise source region of the energetic particles. Instead of blasting outward from the flare itself, many of these particles may arise in a thin electrified sheet of gas that stretches from the flare site to the base of the coronal mass ejection. This current sheet acts much as a particle accelerator, pushing atomic particles to almost the speed of light.

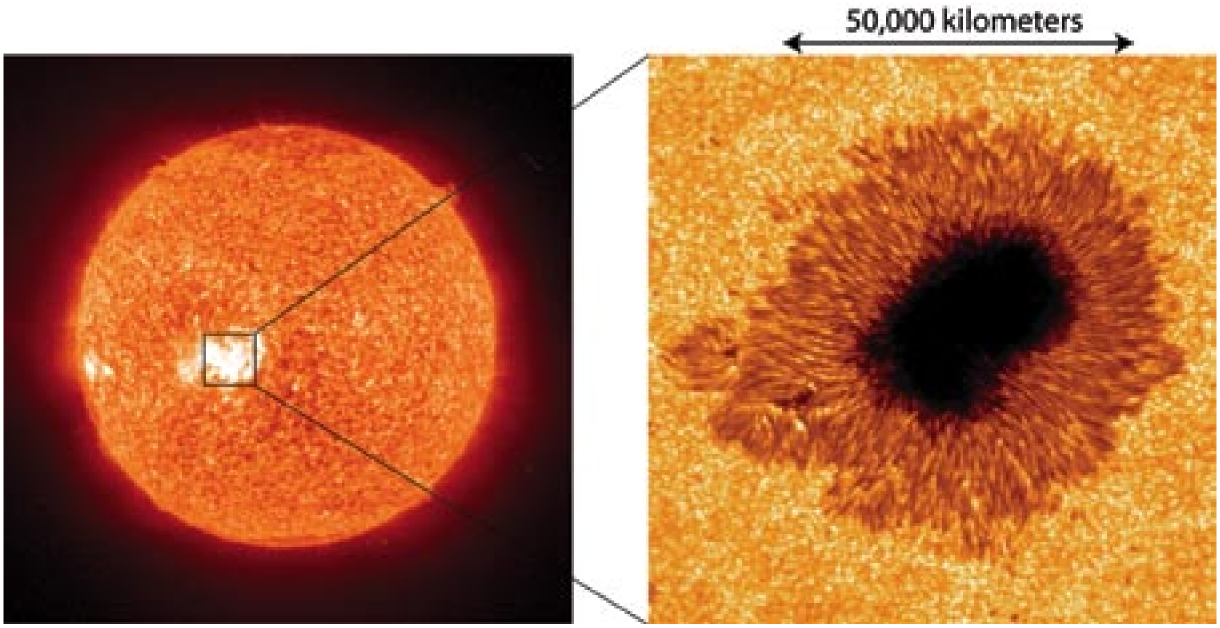
6.2.3 Safeguard the Journey of Exploration

Human and Robotic Explorers' Space Environment

Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers. The SMD is committed to determining the full range of extreme conditions that may occur in the inhospitable environments that human and robotic explorers will encounter. Learning about these limits takes more than just observational surveys; it requires basic understanding of the dynamics controlling each space environment. This entails developing an understanding of the internal mechanisms, the critical boundary conditions, and the external drivers that constitute the sources of external variability at the Sun and the interplanetary medium that modulates its extremes. This knowledge can then be fed into the design of exploration activities and equipment. We also need to be able to nowcast the space environment, so astronaut explorers can react to current conditions. Measurements from a wide range of heliospheric longitudes including the far side of Sun will be required to accurately characterize, and ultimately predict the conditions throughout this region of the inner solar system. Progress in understanding the modulation of the continuous galactic cosmic-ray background radiation requires measurements far from the ecliptic plane and from the inner and outer reaches of the heliosphere. Carefully selected lunar samples have the potential to show historical conditions. In addition, because the near-Earth region is a staging point and the site of much of our space-based communications and logistical infrastructure, characterizing the variability and extremes of the hazardous radiation environment within the Earth's magnetosphere is equally important for safeguarding exploration activities.

Solar Disturbance Prediction

Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events. Successful prediction begins with a reliable characterization of impulsive solar disturbances and their global effects on the corona and solar



The Solar Optical Telescope on the recently launched Solar-B mission is the largest solar telescope flown in space and provides new "microscopic" views of fine structures within sunspots. Shown is a large November 2006 sunspot as seen on the
ri
Observatory (SOHO) mission (EIT He II line at 30.4 nm). As is demonstrated by this solar minimum event, the Sun can have considerable activity and large sunspots even during solar quiet periods.

Solar Atmosphere

Colorized extreme-ultraviolet images from the SOHO and TRACE missions have been melded to show that the magnetic field in the Sun's upper atmosphere confines gas at widely differing temperatures virtually side by side. The Solar Dynamics Observatory (SDO), to be launched in 2008, will image the entire Sun every few seconds in several temperatures and measure surface velocity and magnetic field. SDO data will dramatically advance our ability to determine the origins of these structures and understand how they change.

wind through which they propagate. Presently solar flares and coronal mass ejections are little more predictable than earthquakes or volcanic eruptions. Complex active regions and other features with high potential for eruption can be identified on the visible solar disk and, absent such regions, it is quite feasible to enable the prediction of "all clear" periods, when sensitive activities can be safely accomplished. However, during most of the 11-year solar activity cycle, when active regions are almost continuously present or could emerge at any time, even short-term forecasting is unreliable with our current level of knowledge. On longer time scales, we need to enable the ability to predict when and where active regions will arise, when the magnetic field will become unstable, and what the heliospheric consequences will be. This requires spacecraft observations of the entire solar surface both to follow the evolution of active regions over the full solar disk and to observe complex active regions that may be magnetically connected to human or robotic explorers far from Earth.

Prediction of Solar Disturbance Evolution

Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers. Predicting the heliospheric radiation environment requires an understanding of how solar energetic particles are produced, how solar wind disturbances evolve as they propagate outward, and how solar magnetic clouds modulate galactic cosmic rays. We need to understand the production and evolution of harmful solar energetic particle events that present risks to explorers because they extend tens of degrees in latitude and longitude and can last for days as a storm propagates through the interplanetary medium. *In situ* measurements within 0.1 to 0.3 astronomical units (AU) are needed in order to characterize the radiation before it is scattered into the interplanetary medium. Knowledge of the bulk properties of the solar wind is important for determining the strengths of shocks involved in energetic particle acceleration. Understanding the physics of these critical regions is necessary to be able to predict the radiation environment throughout the solar system because the evolution of solar disturbances and galactic cosmic rays depends on the pre-existing state of the solar wind.

Space Weather Prediction

Understand and characterize the space-weather effects on and within planetary environments to minimize risk in exploration activities. Hazards in certain planetary environments must also be understood, characterized, and mitigated. Space weather impacts planetary environments in ways that affect spacecraft staging, and entry, descent, and landing at Earth and Mars. Reliable communication and navigation for spacecraft and surface crews will require predictive understanding of the ionospheres at Earth and Mars. Asset staging and operations, as well as astronaut health and safety, are impacted by planetary radiation environments including the Earth's during launch of lunar and planetary missions. The radiation environment at the Moon varies as it traverses in and out of Earth's magnetosphere. While the Sun and its variability drive these environments, the planetary processes responding to the solar variability have not been adequately studied for the purposes of making operational predictions for these activities. In addition the lunar surface to be encountered by human and robotic explorers contains charged dust grains. Due to the lack of any appreciable atmosphere, the grains are exposed to a plasma and solar ultraviolet radiation environment. This creates a known problem of dust grain adhesion on space suits and instrumentation. This plasma physics problem is not yet understood.

6.2.4 Anticipated Science Outcomes

The Heliophysics science objectives put forth in this plan describe realms of scientific inquiry that will take decades to complete. The road to near-term progress can be chart-

Table 6.2

Targeted Outcomes Through 2016

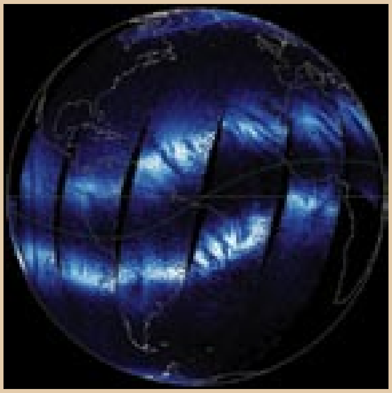
Open the Frontier to Space Environment Prediction	Understand the Nature of Our Home in Space	Safeguard the Journey of Exploration
		
• Measure magnetic reconnection at the Sun and Earth • Determine the dominant processes and sites of particle acceleration • Identify key processes that couple the Sun to Earth's atmosphere to the heliosphere and beyond	• Understand how solar shocks and disturbances propagate to Earth • Identify how space weather effects are produced in near-Earth space • Discover how space plasmas and planetary atmospheres interact • Identify modifications of Earth's atmosphere by solar variability	• Determine extremes of the variable radiation and space environments at Earth, Moon, and Mars • Nowcast solar and space weather, forecast "All-Clear" periods for explorers near Earth

Table 6.2 - Further illustrates anticipated applications of this scientific program to the mitigation of space weather effects for the benefit of our Nation and for NASA's human and robotic exploration program. The program will progress from observational projects that confirm theoretical understandings of the end-to-end system and then, when successful, will be able to provide situational awareness products for a variety of end users, through high-fidelity system modeling, attaining eventually a true predictive capability that enables routine forecasting of all forms of space weather.

ed, however, by identifying a series of near-term outcomes that are identifiable as significant progress toward accomplishing the desired objectives. The targeted outcomes in Table 6.2 have been established after careful consideration of the Research Focus Areas, consolidation of investigation requirements, anticipation of the mission, theory and modeling capabilities likely to be available and required at different times, as well as an estimation of available resources.

Figure 6.1

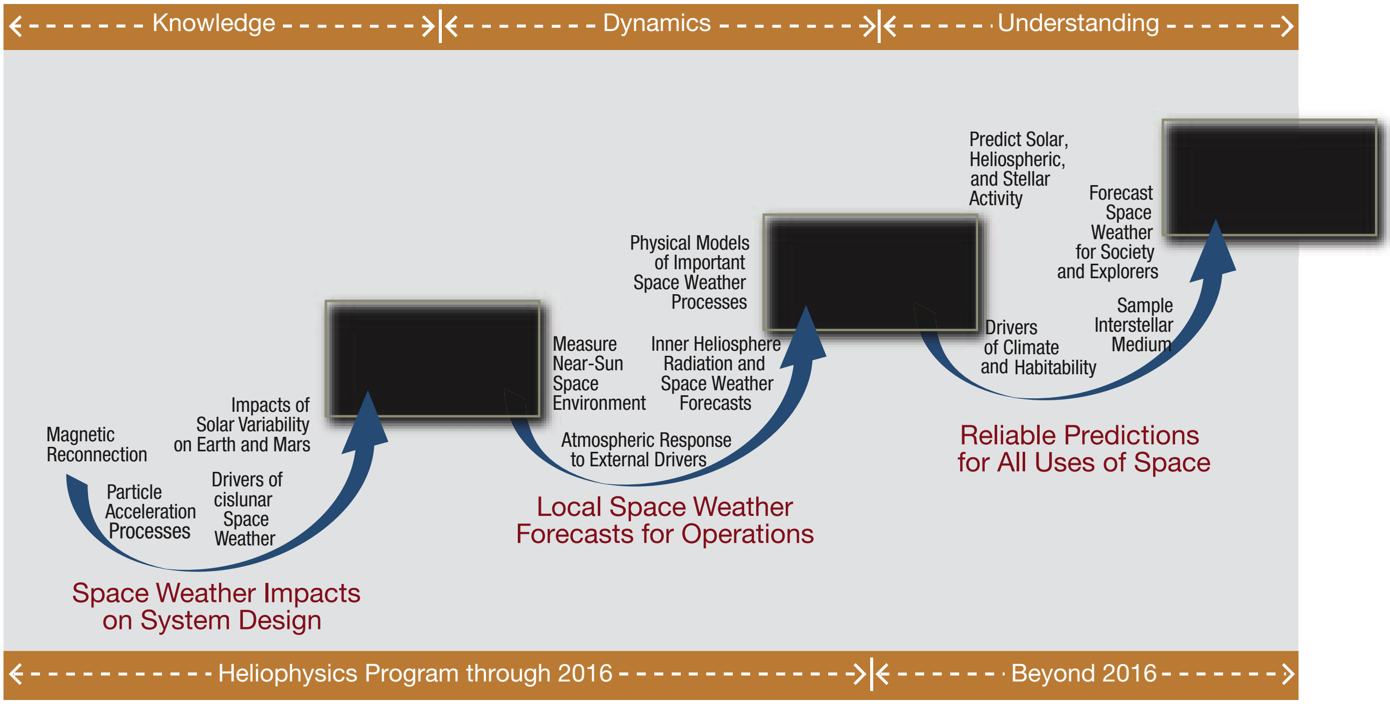


Figure 6.1- From Observation to Prediction for Space Weather. The Heliophysics program will contribute practical knowledge for issues that affect our technological society. The first development phase is already underway, utilizing current program assets and near-term launches. Subsequent phases will develop the new knowledge base, understanding, and capability to provide reliable space-weather predictions.

Heliophysics Opportunities Enabled by Human Exploration of the Moon

Th heliophysics. During the period of time covered by this Science Plan, NASA will establish a “Lunar Exploration Architecture”— a go in which those capabilities will be available to support heliophysics exploration.

At the same time, NASA will conduct studies to identify potential investigations and projects that can realize priority heliophysics objectives from the Moon. The interim report on *The Scientific Context for the Exploration of the Moon* (NRC, 2006) identifies “constraining processes involved in regolith evolution and deciphering ancient environments from regolith samples” as one priority and suggests that obtaining paleoregolith samples may help determine early solar activity. The report also identifies “determining the utility of the Moon as a platform for observations of solar-terrestrial processes” as a priority and recommends that NASA evaluate the Moon’s potential as an observation platform for scientific observations of Sun-Earth connections. Beginning in 2006, NASA has sponsored an NRC study to identify those heliophysics science objectives that can be realized from the lunar surface and to determine the additional studies necessary to establish their cost and benefit. In 2 the first human exploration missions. Also in 2007, the NASA Advisory Council will sponsor a lunar science workshop aimed at establishing science objectives for the lunar exploration program.

In identifying heliophysics mission concepts that can be realized from the surface of the Moon and in establishing the priorities for those potential missions, SMD will use the same community-based processes that have been used to establish priorities in the current heliophysics program. Recognizing that newly enabled candidate missions must compete with other miss science objectives in heliophysics.

6.3 Mission Summaries

The Heliophysics Program is constructed to address the most important fundamental Sun-solar system connection science problems. Science investigations are prioritized to produce the greatest impact toward understanding the end-to-end system—from the solar sources to their ultimate consequences.

The flight strategy is to deploy modest-sized missions, frequently, to form a small fleet of solar, heliospheric, and geospace spacecraft that function in tandem to understand the coupled Sun-Earth system. By operating this group of spacecraft as a single observatory (the Heliophysics Great Observatory), measurements across distributed spatial scales can be linked with a variety of models to fill observational gaps and provide predictions of tomorrow’s space weather.

Careful management of the resources available to address the most important science pointed to a three-prong implementation strategy. First, focused science missions must be deployed to solve the fundamental physical problems identified as key impediments in understanding how heliophysical processes operate. Second, these targeted science missions should be strategically ordered to ensure that complementary measurements are taken at a sufficient number of locations through the vast system of interest. Finally, data from multiple sources must be synthesized through analysis, modeling, and theory so as to develop the scientific understanding and practical knowledge of system-wide behavior as solar storms evolve. The science of heliophysics is most efficiently addressed with platforms deliberately and strategically distributed throughout the important interaction regions.

As shown in Figure 6.2, the interplay of discovery and understanding and the need to inform exploration activities provided the context for prioritizing program elements with the intent of providing an executable program that best advances the vital, compelling and urgent space weather needs.

Numerous mission options were considered based on advice from the National Academy of Science, community input throughout the Heliophysics Roadmap process, detailed strategic mission definition studies, and 12 new mission studies commissioned by the roadmap team. The Heliophysics Division solicited input from the many stakeholders of the program, both internal and external, in formulating the plan.

The proposed Heliophysics Program implements the best science and exploration effort that can be accomplished within program budget constraints. The missions described in the following sections are those specifically recommended after consideration of the roadmap process.

The program relies on several elements: strategically planned missions in the Solar Terrestrial Probes (STP) and Living With a Star (LWS) lines to address widely recognized critical problems; competitively selected Explorers to optimize responsiveness to strategic needs; coordinated operation of existing space assets as part of the Heliophysics Great Observatory; support for the Low Cost Access to Space program for unique science, workforce investment, and instrument development needs; technology development; supporting research, modeling, theory, and analysis programs; and a strong effort in education and public outreach. Partnerships with other areas of NASA and other agencies, both U.S. and international, are essential. This listing does not include specific exciting Explorer mission candidates, nor does it include the strategically planned missions that cannot be accomplished in the time period we considered, even with optimistic resource scenarios. In the past, Explorers have sometimes accomplished, at much lower cost, an appreciable portion of the scientific goals of comparable strategic missions.

Each of these program elements is described in more detail in the sections that follow. Strategic mission lines afford the space physics community the opportunity to plan specific

Figure 6.2

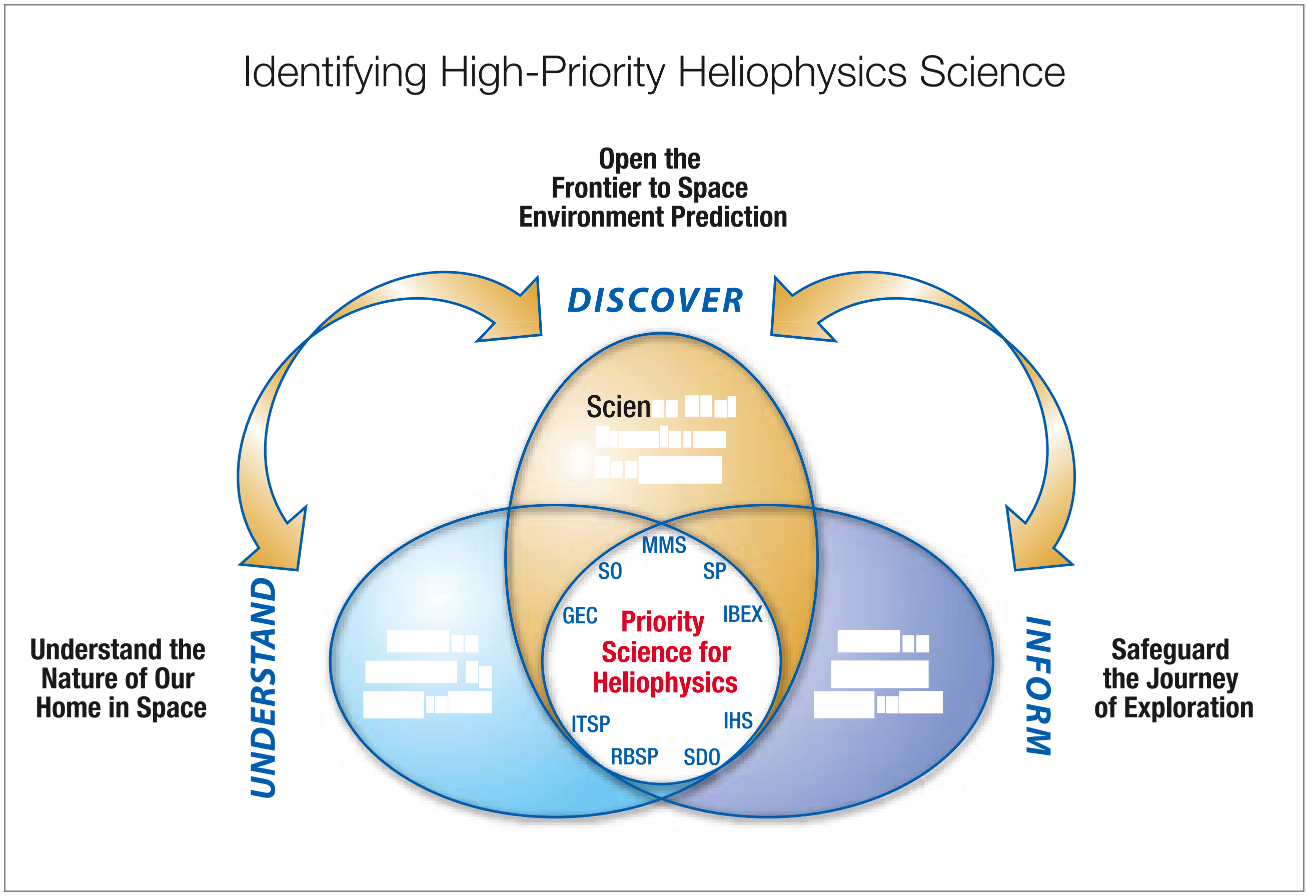


Figure 6.2 - The intersecting ovals illustrate the intersection of three categories of science: scientific understanding that is enabled by exploration, science that transforms our knowledge, and science that informs and so enables exploration. At the intersection is the 'sweet spot' where the highest priority Heliophysics missions, represented by their acronyms, lie.

missions to address one or more of the Research Focus Areas and, thus, make significant progress in elucidating the fundamental processes of the coupled Sun-Earth system. In addition, such capable spacecraft missions often result in unexpected new discoveries.

6.3.1 Efficient Use of Current Assets

The currently operating missions supporting heliophysics research constitute a great observatory that is used to address larger-scale "system" science problems. The Heliophysics Great Observatory provides simultaneous measurements at widely spaced locations to resolve temporal and spatial changes throughout the complex system of solar system regimes. This capability will evolve over time with the addition of new missions and reconfigurations into "smart" constellations—sets of strategically located satellites whose value-added datasets will be made available through the virtual observatories in near real-time. It will support a comprehensive understanding of the solar system as a whole and, together with modeling of these regimes, will extend the range of predictive capabilities.

The current version of the Heliophysics Great Observatory has capabilities for studying the solar structure and phenomena (the SOHO, TRACE, and RHESSI missions), the resulting solar energetic particles and solar wind at 1 AU (Wind, ACE, and SOHO missions) and in other regions of the heliosphere (Cluster, Geotail, Ulysses, and Voyager), the terrestrial magnetospheric which responds to solar drivers (Cluster, Geotail, FAST, Polar, geosynchronous measurements), and the upper terrestrial atmosphere (TIMED, and ground-based optical and magnetometer networks). It is the evolution of this collective asset that will ultimately provide the knowledge that enables timely, on-demand space weather predictions and analysis for the benefit of national policymaking, economic growth, and hazard mitigation.

6.3.2 Implementation

The following mission lines comprise the Heliophysics Space Flight Program:

Solar Terrestrial Probes (STP)

STP missions focus on specific scientific areas required to advance our fundamental understanding of the Sun—solar system connection. Successive missions target the "weakest links" in the chain of understanding how plasma processes operation from the Sun to the Earth's space environment. STP missions are strategically defined and investigations are competitively selected. STP is one of two funded strategic lines for the Heliophysics program.

Living With a Star (LWS)

The LWS program emphasizes the science necessary to understand those aspects of the Sun and space environment that affect life and society. The ultimate goal is to provide a predictive capability understanding of the system, almost to the point of predictability, of the space weather conditions at Earth as well as the interplanetary medium. LWS missions have been formulated to answer specific science questions needed to understand the linkages among the interconnected systems that impact us. LWS investigations build on the fundamental knowledge gained by the STP and Explorer missions and very directly address the needs of Nation as well as the Vision for Space Exploration.

Supporting LWS Program Elements:

- **Targeted Research and Technology (TR&T)** The LWS TR&T program integrates the science efforts across LWS missions into a cohesive approach toward solving the most pressing space-weather problems of the interconnected heliosystem. It supports science areas that cross discipline boundaries and the development of comprehensive models that provide both science understanding and utility. The TR&T program also supports postdoctoral fellowships and summer schools to build the cross-disciplinary science community necessary for addressing compelling science issues.

- **Space Environment Testbeds** LWS SET performs flight and ground investigations to characterize the space environment and its impact on hardware performance in space. SET projects will improve the engineering approach to mitigate the effects of solar variability on spacecraft design and operations. The first SET payload is scheduled to launch on the Air Force satellite in 2008.

Explorer Program

The Explorer Program provides a vital and effective means of achieving urgent strategic goals in a timely way. Explorers are highly responsive to new knowledge, new technology, and updated scientific priorities by launching smaller missions that can be conceived and executed in a relatively short development cycle. Priorities are based on an open competition of concepts solicited from the scientific community. The program also enables participation in missions of opportunity provided by other U.S. or international agencies. Explorers demonstrate the ability of the science community to respond rapidly to decision points, an important element in the strategy put forth in the Vision for Space Exploration initiative. Explorers have been responsible for major scientific achievements that have profoundly transformed our understanding of the Sun-Earth system and of astrophysics. Some heliophysics highlights include:

- visualization of the global dynamics of the Earth's magnetospheric system by IMAGE;
- the first solar gamma-ray imaging by RHESSI, discovery of coronal magnetic complexity by TRACE;
- discovery of trapped anomalous cosmic rays in Earth's magnetosphere by SAMPEX; and the
- discovery of parallel electric fields in the auroral acceleration region by FAST.

Future missions are determined in response to Explorer Announcements of Opportunity. They fill critical gaps in the planned strategic program based on the most current scientific knowledge. Maintaining frequent flight opportunities is important.

Flagship and Partnership Missions

The need for progress across a range of topic areas and regions means that all Heliophysics funding resources cannot be applied to a single problem for an extended interval. Yet, some major roadblocks to progress cannot be overcome within the mission lines available. The Heliophysics Program has one flagship mission and several international partnerships planned to provide a path toward that increased scientific return. At this time, a flagship mission cannot be supported within the available funding resources.

Figure 6.3 gives the mission timelines the currently operating missions through those for which formulation begins by 2016. The blue bar begins at the beginning of formulation; the triangle marks the launch date; the orange bar ends with cessation of prime mission operations. The timeline extends to 2025 to show the runout of listed missions. Note that missions whose formulation begins after 2016 are **not** shown here, even though there will be missions inaugurated between 2016 and 2025.

Figure 6.3

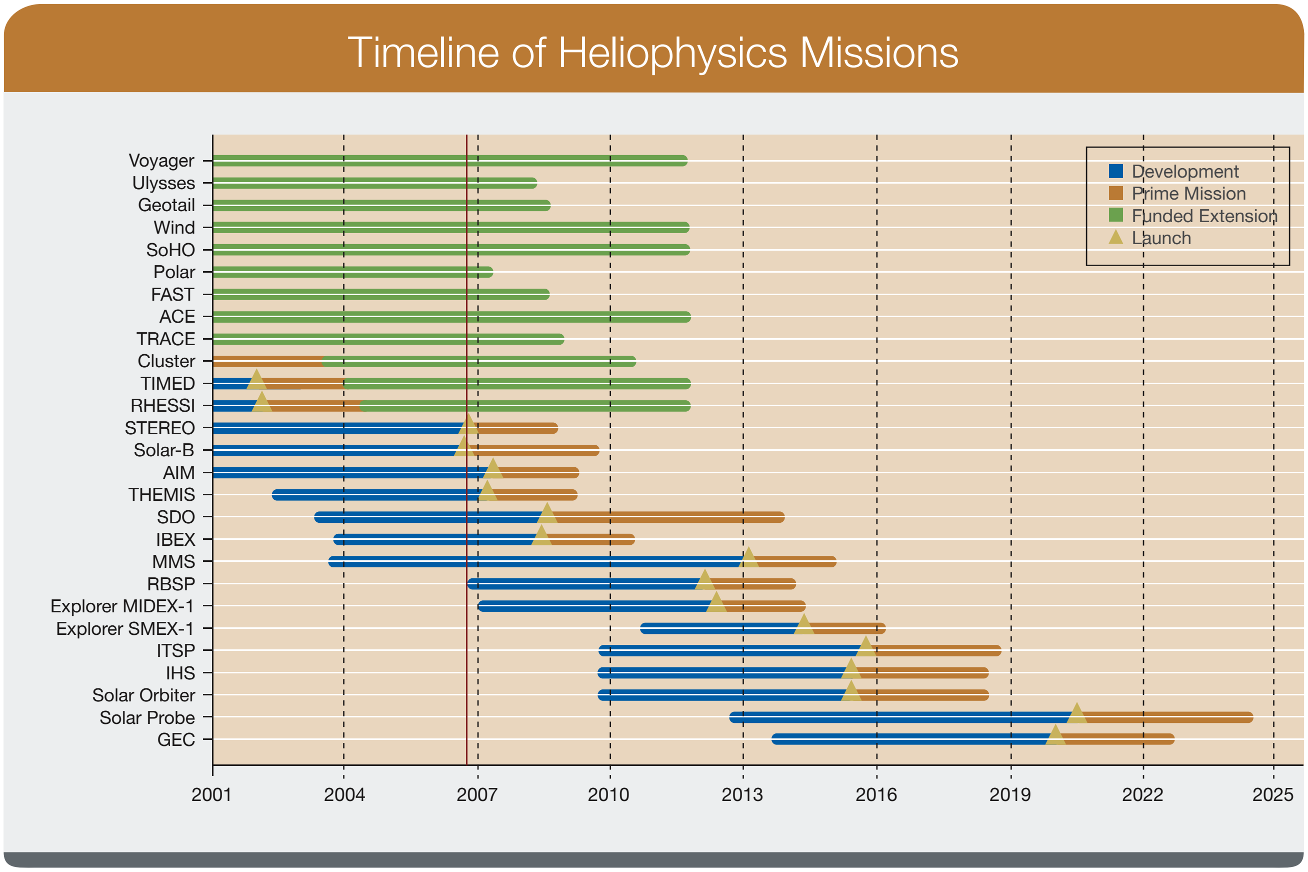


Table 6.3

Heliophysics Future Mission Summary

Program	Mission	Objective (See Table 2.1)			Mission Objectives and Features
		1	2	3	
STP	Solar TErrestrial RElations Observatory (STEREO)	●	●	●	A two-observatory mission to provide 3-D measurements of the Sun and inner heliosphere to study the nature of coronal mass ejections. These powerful eruptions are a major source of the magnetic disruptions on Earth and a key component of space weather. Launched in 2006.
Explorer	Time History of Events and Macroscale Interactions during Substorms (THEMIS)	●	●	o	THEMIS is a five-spacecraft constellation mission that will resolve a long-standing controversy concerning the spatial and temporal development of magnetospheric substorms—a fundamental feature of the magnetosphere. THEMIS is scheduled for launch in 2007.
Explorer	Aeronomy of Ice in the Mesosphere (AIM)	o	●	o	AIM will explain polar mesospheric cloud formation and variability, as well as their relationship to global change in the upper atmosphere and the response of the mesosphere to solar energy deposition. AIM is scheduled for launch in 2007.
LWS	Solar Dynamics Observatory (SDO)	●	●	o	A single geosynchronous spacecraft to observe how the Sun's magnetic field is generated and structured in its interior and how stored magnetic energy in the corona is released into the heliosphere. Launch is in 2008.
Explorer	Interstellar Boundary Explorer (IBEX)	●	o	o	IBEX will image the 3D boundary region of our heliosphere, the vast (~100 AU thick) region where the solar wind decelerates because of the pressure of the local interstellar plasma. IBEX will launch in 2008.
STP	Magnetospheric Multiscale (MMS)	●	●	o	A four-spacecraft mission designed to study magnetic reconnection, charged particle acceleration, and turbulence in key boundary regions of Earth's magnetosphere. These results will enable a predictive science of space weather. MMS is in transition to Phase B; STP funding will allow MMS to launch in 2013.
LWS	Geospace/Radiation Belt Storm Probes (RBSP)	●	●	●	Twin spacecraft in elliptical Earth orbit to answer how, in response to the variable inputs of energy from the sun, charged particles in space are accelerated to hazardous radiation energies producing satellite anomalies and affecting the safety of astronauts and of flight crews in high-altitude aircraft. RBSP is conducting Phase A studies; launch is planned for 2012.
LWS	Geospace/ Ionosphere - Thermosphere Storm Probes (ITSP)	●	●	o	Twin-spacecraft in LEO to understand ionospheric variability and the irregularities that adversely affect communications, navigation and radar systems. Concept studies are complete.

Heliophysics Future Mission Summary—Contiunued

Program	Mission	Objective (See Table 2.1)			Mission Objectives and Features
		1	2	3	
LWS	Solar Sentinels/ Inner Heliospheric Sentinels (IHS)	●	●	●	Four spacecraft in inner heliospheric orbits to understand the acceleration and transport of solar energetic particles harmful to astronauts and technology in interplanetary space. These in situ observations will also address the initiation and evolution of geoeffective solar wind transients like shocks and coronal mass ejections. Concept studies are underway.
LWS	Solar Orbiter	●	○	○	Solar Orbiter is a partnership with the European Space Agency (ESA) that will characterize the properties and dynamics of the inner solar wind, understand polar magnetic fields, identify links between activity on the Sun's surface and coronal disturbances, and characterize coronal regions from high inclination orbits. Discussions with the ESA are ongoing.
Flagship	Solar Probe	●	○	●	Solar Probe will transform our understanding of the physical processes controlling the heating of the solar corona, the acceleration of the solar wind, and the magnetic release of eruptive activity. This mission could be implemented as early as 2016 if funding were made available.
STP	Geospace Electrodynamic Connections (GEC)	●	●	○	A multispacecraft mission to determine the fundamental processes coupling the ionosphere and thermosphere. Using formation flying into the depths of the atmosphere GEC will unravel the spatial and temporal coupling of neutral-plasma transition region phenomena. GEC pre-phase A studies are on hold until STP funding becomes available for further mission development activities. Launch is beyond 2016.

● Major Contribution ○ Supporting Contribution

6.4 Program Elements

6.4.1 Scientific Theory, Modeling, Research and Analysis

Heliophysics science objectives are achieved through the efforts of a distributed scientific and technical workforce that envisions and develops the missions and then applies the results from those missions for the benefit of society. Over the past decade and more, physics-based modeling has played an increasingly important role both in defining the missions and in interpreting the observations. It is anticipated that, within three years, vast arrays of datasets will be available for real-time assimilation into predictive models. Working with universities, other government facilities, and industrial labs, individual and group theory, modeling, and research and analysis efforts are identified through three competitive programs:

- The Supporting Research and Technology (SR&T) program comprises an ever-evolving suite of individual PI-proposed investigations that cover the complete range of science disciplines and techniques essential to achieve the Heliophysics science objectives;

- The Theory Program supports larger PI-proposed team efforts that require a critical mass of expertise in order to make significant progress in understanding

Figure 6.4

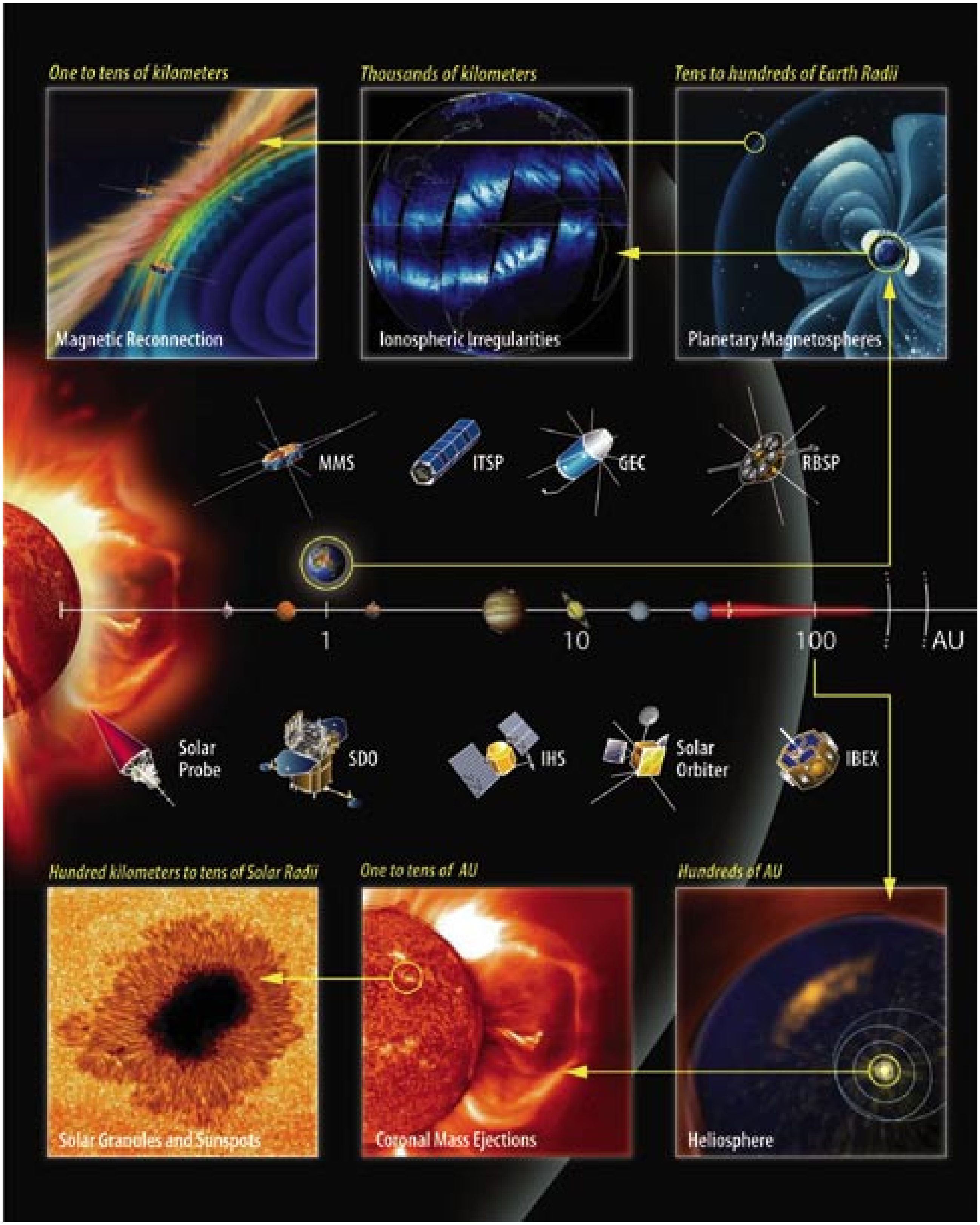

One to tens of kilometers
Thousands of kilometers
Tens to hundreds of Earth Radii
Magnetic Reconnection
Ionospheric Irregularities
Planetary Magnetospheres
MMS
ITSP
GEC
RBSP
1
10
100
AU
Solar Probe
SDO
IHS
Solar Orbiter
IBEX
Hundred kilometers to tens of Solar Radii
One to tens of AU
Hundreds of AU
Solar Granules and Sunspots
Coronal Mass Ejections
Heliosphere

Figure 6.4 - Our work over the past few years has taught us enough about our local space environment to know that our task to produce reliable space weather predictions is a formidable challenge. Observations are needed on scale sizes ranging from the size of our solar system down to microphysical plasma processes. This requires a range of observational techniques: *in situ*, imaging, spacecraft clusters, and, for the largest-scale sizes, the Heliophysics Great Observatory.

The scale lengths and boundaries of the processes studied with the Heliophysics missions are shown in this figure on a logarithmic scale. The exact locations change dramatically as the Sun and the local interstellar medium vary.

complex physical processes with broad importance, such as magnetic reconnection or particle acceleration; and

- The Guest Investigator (GI) program is a synergistic component of the Heliophysics Great Observatory. The GI program enables the broadest community of researchers in universities and institutions across the country to use Great Observatory data in innovative scientific research.

6.4.2 Low Cost Access to Space (LCAS)

The LCAS suborbital program, whose key elements are the sounding rocket and balloon programs, is an essential component of NASA's Heliophysics Research Program. LCAS investigations make cutting-edge science discoveries using state-of-the-art instruments developed in a rapid turnaround environment. They fill important gaps in the prescribed program, augmenting strategic-line missions and training the next generation of space explorers. The LCAS program provides essential support for the development of new instrumentation and important hands-on training for future engineers and scientists. It also offers the high-context learning environment necessary for NASA's future explorers to gain the management skills necessary for more complex missions.

Sounding Rockets

Sounding rockets present unique, low-cost platforms that provide direct access to the Earth's mesosphere and lower thermosphere (40–120 km), to precipitation regions of the Earth's magnetosphere, and allows researchers to reach above the Earth's atmosphere to observe the Sun. Rockets offer the ability to gather *in situ* data in specific geophysical targets (e.g., the aurora and noctilucent clouds), calibration underflights of orbiting missions, and the ability to recover and re-fly instrumentation.

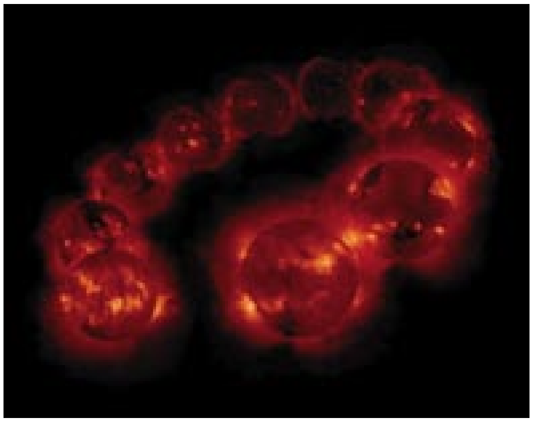
Balloons

Balloon missions flown in the continental U.S. and Antarctica serve as "proof of concept" for new technology and future spaceborne instruments (recent examples include the RHESSI hard X-ray and gamma-ray imaging spectrometer and the SoHO/LASCO). Science capabilities include the mapping of when and where the radiation belts drain into the Earth's atmosphere and how the Earth's global electric field can be short-circuited by solar flares.

6.4.3 Technology Investment

Innovation is the engine that drives scientific progress. Breakthroughs in heliophysics science will come through two primary innovations: (1) the ability to simultaneously

The Solar Cycle



Annual soft X-ray images of the Sun show dramatic changes over an 11-year cycle. Less regular, but equally large, changes can occur on shorter (27- day) and much longer (millennial) time scales.

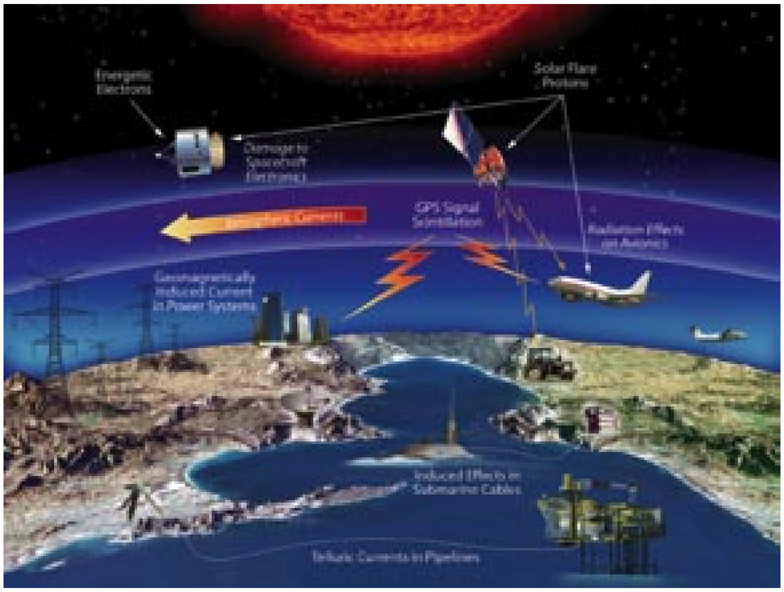
sample the system at multiple coordinated locations; and (2) observing the system at vantage points previously considered inaccessible. NASA is on the verge of realizing the benefits of this vision via an infusion of new technology development activities:

Simultaneous and cost-effective sampling of space plasmas at multiple points. Because of the complexity and large scale of solar system plasmas, progress requires clusters or constellations of spacecraft making simultaneous multi-point measurements. To be cost effective and efficient, these missions require low-mass, low-power, and low-volume instrumentation, as well as low-mass, economical spacecraft. The New Millennium Program mission, ST5, recently validated several new technologies for microsatellite constellations. Considered to be a precursor mission to the Magnetospheric Constellation mission, ST5 demonstrated methods for operating a constellation of three microsatellites as a single system. The next important step is the development of low-power electronics for the instruments and spacecraft bus. Other high-priority developments are "assembly-line" test and integration methods for the spacecraft builds as well as autonomous operation methods to minimize ground operations.

Achieving unique vantage points such as upstream of the Earth-Sun L1 point, polar orbit around the Sun, or traveling beyond the heliosphere. Several promising scientific breakthroughs are tied to achieving unique observing vantage points or non-Keplerian orbits. One example is imaging of the Sun's polar regions from a high-inclination, heliocentric orbit. This and other examples require highly efficient propulsion alternatives, solar sails being one of the most promising. A solar sail precursor mission is under study for the New Millennium Program ST9 opportunity.

Developing the next generation of capable, affordable instrumentation. To continue leading the world in space science research, the Heliophysics Division must continue to support the design and validation of the highest quality scientific instrumentation and components along with the appropriate instrument development and test facilities. For some applications, NASA's low-cost access to space (LCAS) program provides an ideal avenue for low-cost testing and validation of innovation ideas. A prime example of this is the development of electrostatic plasma analyzers, which were first used for sounding rocket studies of Earth's aurora. The rocket successes led to the advanced plasma instruments on the current, highly successful magnetospheric missions.

Enabling the return and synthesis of vast datasets from anywhere in the solar system. New mission concepts have placed increasing demands on NASA's communication resources. The future points to the deployment of optical communication technologies and arrays of small antennas to increase the available bandwidth and enhance operational agility as we increase the number of spacecraft clusters



Space Weather Effects

Our past, present, and future are intimately coupled to the relationship between the Earth and Sun. Increasingly, we are sensitive to changing conditions on the Sun and in the space environment because of our technology. We have a practical interest in the habitability of the planets and solar system bodies we plan to explore, and we recognize how astrophysical phenomena influence life and climate on our home planet. Variability in this environment affects the daily activities that constitute the underpinning of our society, including communication, navigation, and weather monitoring and prediction.

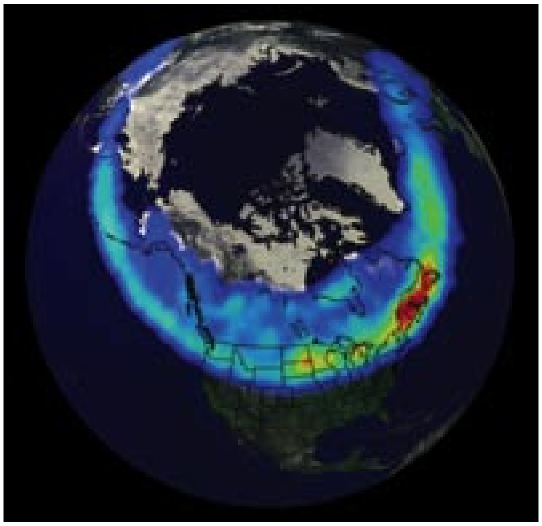
to be supported. Information from these multi-spacecraft distributed observatories will be absorbed via real-time data ingestion and assimilation techniques appropriate to a sparsely sampled system. Methods successfully developed for Earth science analysis are being adapted for use.

6.4.4 Computation, Information Management, and Communications

Harnessing the full benefit of heliophysics science over the coming decade requires a move from single observatory, single topic analysis techniques to the implementation of well-managed archives, virtual observatory systems, data assimilation, and the application of knowledge support tools appropriate to modeling a sparsely sampled system. Some groundwork for these activities has begun. A confluence of new technologies (internet, XML and web services, broadband networking, high-speed computation, distributed grid computing, ontologies and semantic representation) is changing the data landscape. Examples currently under development include the virtual observatory tools, which are providing integrated access to the distributed databases built from the observations made by multiple platforms, and the Columbia supercomputer, which provides an order-of-magnitude increase in NASA's computing capability.

Organizations that produce integrated space weather modeling, transition research tools into operational infrastructures, and build software frameworks that link models are of increasing importance. These efforts are by definition cross-disciplinary and interagency, requiring expertise in numerical analysis, high-performance computational science, and solar, interplanetary, magnetospheric, ionospheric, and atmospheric physics. NASA works closely with NOAA's Space Environment Center, one of NOAA's National Centers for Environmental Prediction, to enable accurate forecasting and prediction of space weather.

Future progress will require an enveloping systems architecture to provide the necessary coupling among high-data-rate sensors, robust datasets, data-mining capabilities, state-of-the-art models and simulations, and high-performance computing. The Earth sciences have long been engaged in the process of understanding and simulating our atmosphere and oceans in sufficient scope and detail to support the prediction of weather. A similar advance is underway in the case of space weather prediction. NOAA, DOE, and DoD, along with NASA, are working actively toward the characterization, "nowcasting," and, increasingly, forecasting of near-Earth space weather. NASA will now expand this purview to the Moon and Mars. What will ultimately emerge is a research-supported operational capability directed toward Inner Solar System Environment Services, one that is highly analogous to the National Weather Service for tropospheric weather.



Aurora

Image of the Earth's auroral oval during a powerful geomagnetic storm. Auroras are the footprints of plasma dynamics acting in more distant regions of a planetary magnetosphere. They delineate the nature of solar wind-magnetic field interactions, they reveal magnetosphere-ionosphere coupling mechanisms, and are a prime tool for the identification and timing of magnetic substorm processes. Such observations will be unavailable in the future at the end of the IMAGE and Polar missions.

6.4.5 Linkages and External Partnerships

Heliophysics and Other NASA Activities

Like seafaring voyagers, space explorers must be constantly aware of their environment and be prepared to handle the most severe conditions that might be encountered. Most critical will be a sudden influx of energetic particles and radiation and encounters with plasmas that cause spacecraft charging and discharging. Space weather affects the state of atmospheres, where knowledge of density and wind distributions are critical for aerocapture, ascent, and descent scenarios. Space weather also alters the state of planetary ionospheres that influence navigation and high-bandwidth communications. *Therefore, we recognize strategic linkages between Heliophysics and the plans for Lunar Science, Mars Science, and the Crew Exploration Vehicle.*

The effects of space weather on Earth's atmosphere are of practical interest. Enhanced ozone depletion is a documented consequence of energetic particle precipitation. We are aware of space processes that erode Earth's atmosphere, removing approximately 1000 kg of hydrogen and oxygen daily during quiet times and vastly greater quantities during space storms. Computer simulations imply an even greater loss of atmospheric constituents at Mars, which lacks the shielding provided by an intrinsic magnetic field. *For these reasons, we also recognize strategic linkages between heliophysics and Earth science.*

The same processes and phenomena that drive space weather in our solar system also shape environments throughout the universe. We have a typical, variable, main-sequence star in our cosmic back yard, the Sun. We live on a habitable planet that is largely protected from hazardous elements of our local space environment by a magnetic shield (Earth's magnetosphere), a feature not shared by all planetary bodies. As we try to understand the remote universe and its potential to sustain life, it is imperative that we take as full account as possible of the lessons we learn from the specimens we can virtually touch with our hands. *Therefore, we recognize important linkages between Heliophysics and both Astrophysics and Planetary Physics and, in particular, the search for other habitable worlds.*

U.S. External Partnerships and Relationships

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities become more obvious. The Nation's efforts to mitigate space weather effects have placed more urgency on the need to understand the Sun, heliosphere, geospace, and other planetary environments as a single connected system. The NSF and NOAA's Space Environment Center sponsor many of the efforts that use NASA's space weather data and enabling technologies to provide worldwide space weather predictions. External constituencies requesting and making use of new knowledge and data from NASA's efforts in this area include the Federal Aviation Administration, the DoD, the power industry, and the industry of satellite manufacturers and operators. Cooperative efforts between agencies are coordinated through the National Space Weather Program (NSWP).

International Cooperation

The International Heliophysical Year (*http://ihy2007.org*)*:* In 1957 a program of international research, inspired by the International Polar Years of 1882 and 1932, was organized as the International Geophysical Year (IGY) to study global phenomena of the Earth and geospace. The IGY involved over 60,000 scientists from 66 nations, working at thousands of stations from pole to pole to obtain simultaneous, global observations on Earth and in space. There had never been anything like it before. Fifty years after the IGY, the world's science community will again come together for an international program of scientific collaboration: the International Heliophysical Year (IHY) 2007. Heliophysics at NASA is one of many leading organizations identified for this event, which will involve all 191 United Nations member states.

International LWS (ILWS): In January 2002, the Inter-Agency Consultative Group (IACG) established the ILWS program. The charter for ILWS is to "stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity." More than 20 international organizations are active contributors and ensure that international collaborations for heliophysical science leverage the physical, financial, and intellectual resources of all involved parties, providing a yield that is greater than the sum of the parts.

6.4.6 Education and Public Outreach

Heliophysical science provides unique opportunities to engage students and the general public because its achievements are potentially directly relevant to the public. The Sun and its effect on the Earth have been important throughout history and extremely popular outreach events such as *Sun-Earth Day 2005: Ancient Observatories, Timeless Knowledge,* exemplify the type of activities that can be exciting and relevant.

In the future, the Heliophysics E/PO efforts will continue to focus on the important themes of understanding the Sun and space weather and how this understanding helps safeguard our society and the exploration of the solar system, both manned and unmanned. Our outreach will continue to stress that hands-on high-context learning is very important in generating long-lasting results. This extends from K-12 education (e.g., the IMAGE spacecraft's Soda Bottle Magnetometer which is part of the Student Observing Network) to using the suborbital programs (rockets and balloons) to train the next generation of scientists and engineers within a high-context, cost-effective experience.

6.5 Heliophysics Beyond 2016

Beyond 2016, Heliophysics plans to continue its strategy of deploying frequent smaller missions for the purpose of establishing a full solar system observing capability. This next phase will overlap with NASA's Lunar exploration activities and so, for this period, Heliophysics aims at enabling an operational Space Weather forecasting infrastructure and capabilities for the Earth-Moon-system.

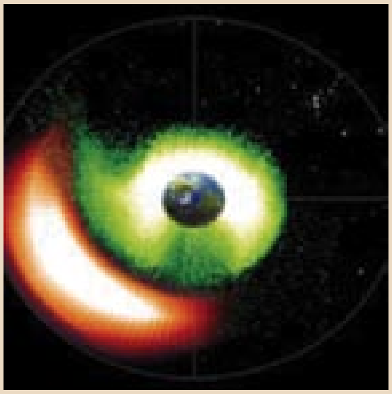
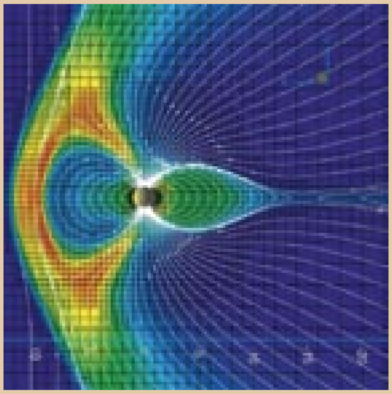
Mission concepts to address Heliophysics science goals have been defined and cost studies performed. Plans for enabling global, physics-based predictive models are being scoped, and the steps toward development mapped. Priority science targets identified for future fundamental research are understanding the initiation and the coronal evolution of flares, current sheets, and CME shocks that produce solar energetic particles; quantifying the extent to which electric fields accelerate particles by probing the auroral region at Earth; exploration of the outer boundary of the heliosphere by measuring the components of the interstellar medium that survive into the inner solar system; and discovery of the wave processes that couple distinct altitude regions of Earth's atmosphere.

Future STP Program missions will measure reconnection near the Sun and observe lower-latitude disturbances in the ionosphere-thermosphere-mesosphere; a stellar imager (likely a flagship mission) will spatially resolve activity on other stars to enable us to complete our objectives. Magnetosphere Constellation (MagCon) will be the first Heliophysics sensor web (~36 spacecraft) to resolve the temporal and spatial structure of complex turbulent plasma processes occurring throughout the vast regions of the Earth's magnetosphere.

Future LWS Program missions include additional elements of the Solar Sentinels mission to understand energetic-particle production near the Sun. A Near-Earth Sentinel will make ultraviolet and white-light observations of the solar corona and a Farside Sentinel will measure magnetic fields within the Sun's photosphere at longitudes not observable from the Earth. These mission candidates can be smaller in cost than typical strategic missions. Solar sails can be used to hover twice as far upstream of the L1 point in the solar wind for advance warning of geospace disturbances.

Table 6.3

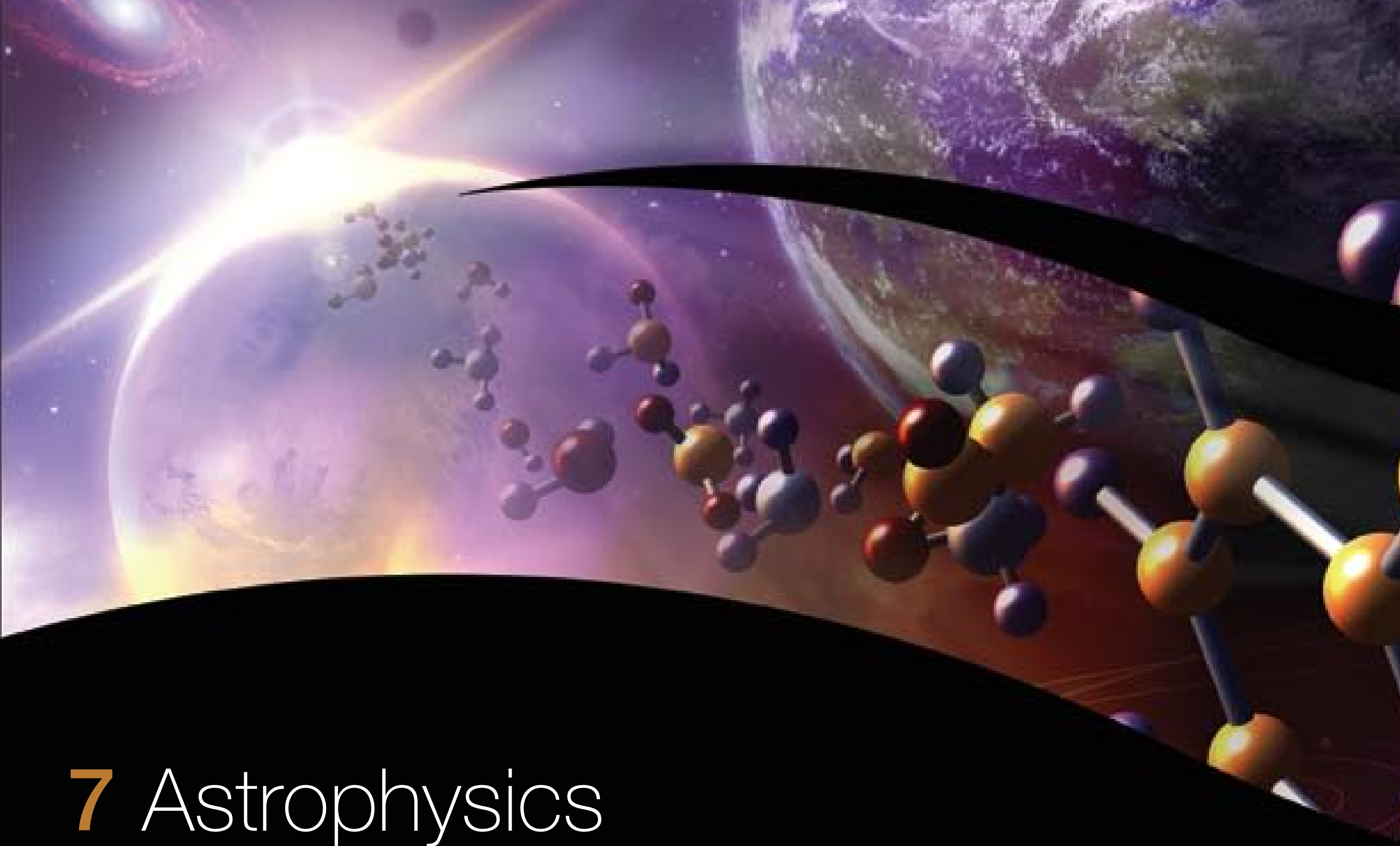
Heliophysics Science Future Outcomes

Open the Frontier to Space Environment Prediction	Understand the Nature of Our Home in Space	Safeguard the Journey of Exploration
		
2016–2025		
• Model the magnetic processes that drive space weather • Quantify particle acceleration for the key regions of exploration • Understand nonlinear processes and couplings to predict atmospheric and space environments	• Identify precursors of important solar disturbances • Quantify mechanisms and processes required for geospace forecasting • Determine how magnetic fields, solar wind and irradiance affect habitability of solar system bodies • Integrate solar variability effects into Earth climate models	• Characterize the near-Sun source region of the space environment • Reliably forecast space weather for the Earth-Moon system and begin nowcasts at Mars • Determine Mars atmospheric variability relevant to exploration activities
Beyond 2025		
• Predict solar magnetic activity and energy release • Predict high-energy particle flux throughout the solar system • Predict the transfer of mass and energy through planetary systems • Understand the interactions of disparate astrophysical systems	• Enable continuous scientific forecasting of conditions throughout the solar system • Determine how stellar variability governs the formation and volution of habitable planets • Analyze the first direct samples of the interstellar medium • Forecast atmospheric and climate change (joint with Earth Science)	• Provide situational awareness of the space environment throughout the inner solar system • Reliably predict atmospheric and radiation environment at Mars to ensure safe surface operations

Later activities for understanding the Sun's influence on our solar system's environment will push the limits of our technological capabilities. Mission selections will depend on the scientific progress achieved to that point in time. Priorities will shift based on progress of the exploration initiative and what we learn from spacecraft launched in the next 10 years. Mission concepts include space-weather buoys to fully understand how the solar wind and hazardous disturbances propagate outward from the Sun; a mission to explore the destruction of ozone by solar energetic particles; and a mission to make the first 3-D observations of global geospace dynamics in response to external solar drivers and internal coupling. Further selections might include high-latitude solar observations to understand the solar cycle and interior, two or three solar imagers stationed far from Earth to provide global coverage, a constellation of spacecraft to understand the inner magnetosphere, and exploration of the dayside boundary layer where energy from the solar wind crosses the magnetopause. Prioritization of these depends on results from earlier investigations.

Noctilucent Clouds

Noctilucent clouds, also known as polar mesospheric clouds, are rare, bright cloud-like atmospheric phenomena visible in a deep twilight. Most commonly observed in the summer months, they are the highest clouds in the Earth's atmosphere. The AIM Explorer satellite, scheduled for launch in 2007, is dedicated to research into noctilucent clouds.



7 Astrophysics

Strategic Goal:

Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets.

Chapter 7

Astrophysics

7.1 Intellectual Foundation

In the Astrophysics plan that follows, we tell our science story in a roughly chronological fashion, starting with the beginning of time and ending with the search for life on extrasolar planets. The science goals described are breathtaking: we are starting to investigate the very moment of creation of the universe, and are close to learning the full history of stars and galaxies. We are discovering how planetary systems form and how environments hospitable for life develop. And we will search for the signatures of life on other worlds, perhaps to learn that we are not alone.

The priorities reflected in this Astrophysics section of the Plan have their source in the NRC's 2001 decadal survey *Astronomy and Astrophysics in the New Millennium* and its predecessors. In addition, the 2003 NRC report Connecting Quarks with the Cosmos provided the intellectual foundation for key aspects of the Beyond Einstein program described herein. The National Science and Technology Council report, *Physics and Astronomy in the 21st Century*, contains the U.S. government's interagency plan for responding to this second NRC report. This Astrophysics section is derived from the 2006 community roadmap for Astrophysics, which drew on all of these reports.

We restrict our discussion to only those missions that have yet to be launched and that will begin formulation by 2016. There are missions in earlier roadmaps that extend well beyond this date, and which are still considered as part of our longer-range vision, but these are not covered here. Although occasionally referred to, it is not the purpose of this document to describe our ongoing missions or their successes.

Figure 7.1

Spiral Galaxy M81

Spitzer Space Telescope image of the nearby spiral galaxy M81 shows how infrared images neatly separate the major components of a galaxy. The stars in the dense stellar bulge are shown in blue; the interstellar dust which permeates the spiral arms in green; and dense regions of current star formation in red. James Webb Space Telescope (JWST) will produce comparable images of thousands of nearby galaxies, greatly extending Spitzer's studies of the structure and evolution of objects like our own Milky Way galaxy. Image courtesy of the Spitzer Science Center.

7.2 Science Objectives and Outcomes: The Story of the Universe

7.2.1 The Birth of the Universe; the Extremes of Spacetime

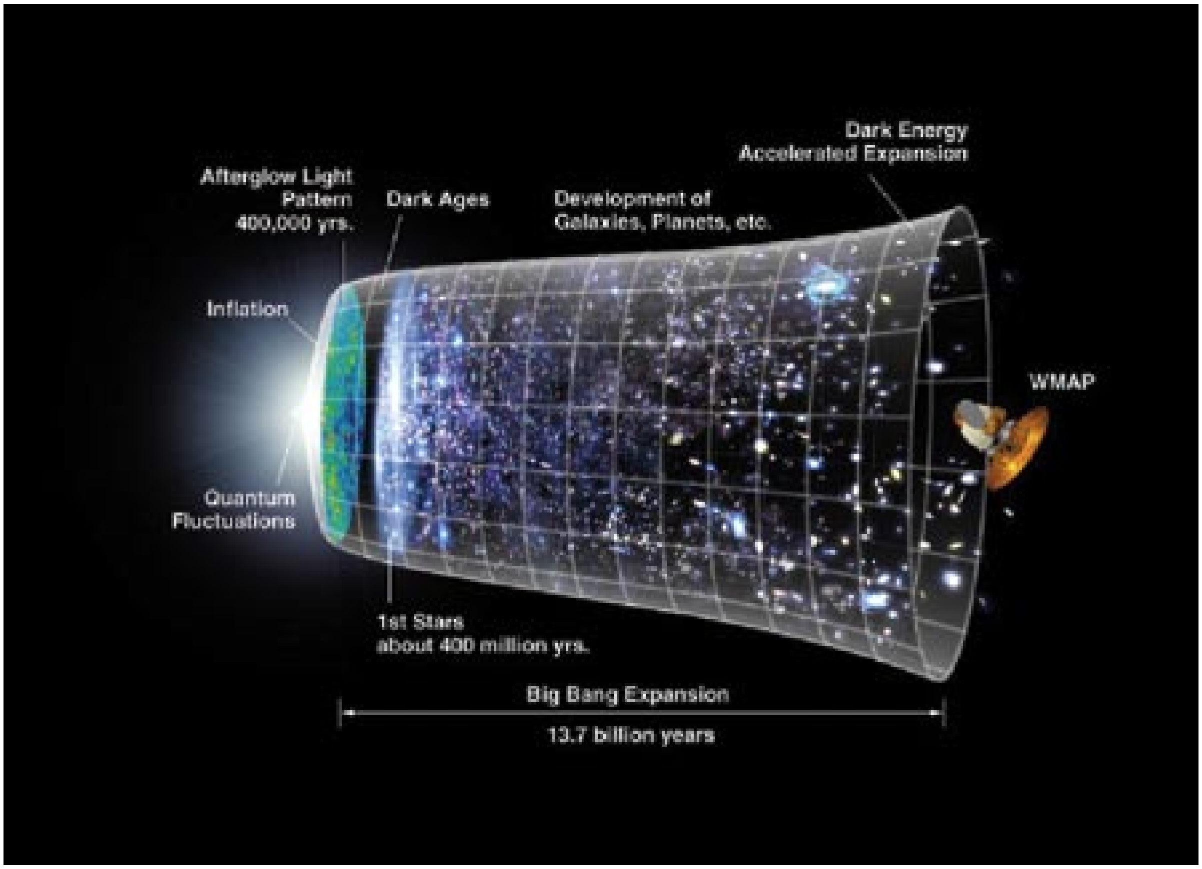
A century ago, Albert Einstein began creating his theory of relativity—the ideas we use to understand space, time, and gravity—and took some of the first steps towards the theory of quantum mechanics—the ideas we use to understand matter and energy. The spacetime and quantum views of reality have not yet come together into a unified story about how nature works, and yet this is what we need to achieve if we are to understand the evolution of the universe immediately after its birth. How is the universe growing? How did the dense, hot, uniform plasma of fundamental particles cool and form into structures, which we now see as galaxies and stars? The science story of the Astrophysics Division begins at the beginning of time.

The Beginning of Time

The universe is expanding. Abundant evidence shows how it began in a hot, dense state, the Big Bang. Einstein's general relativity explains how the universe expands, but does not explain what made the Big Bang—the explosive growth of the universe—happen in the first place. Clues to the Big Bang origin are found in its relic heat, the cosmic microwave background (CMB). The CMB is light that has been traveling to us since the universe was 380,000 years old, allowing us to "see" what the universe looked like at that time. Observations of the CMB show its brightness, or temperature, to be nearly uniform across the sky, with only the slightest of variations. But these temperature variations were the tiny imperfections that later grew into the stars that illuminate our night sky.

Inflationary cosmology theory posits that a mysterious energy, present during the first tiny fraction of a second of the universe's existence, generated a repulsive force which caused the early universe to rapidly expand and become smooth. Small quantum fluctuations in this energy field led to imperfections in the cosmic expansion, imperfections seen in the maps of the CMB. We do not know that the inflationary scenario is correct, however; the details of the plot remain a mystery. One striking prediction of inflation theory

Figure 7.2



Timeline of the Universe

The expansion of the universe over most of its history has been relatively gradual. The notion that a rapid period of "inflation" preceded the gradual expansion has been reinforced by recent Wilkinson Microwave Anisotropy Probe (WMAP) observations.

is that in addition to its tiny temperature fluctuations across the sky, inflation would have also generated gravitational waves. Observing these inflationary waves—faint ripples in the structure of spacetime itself—would not only confirm our model of how the universe began, but also would allow us to see as close to the beginning of time as we can ever, in principle, observe.

Dark Energy and the Destiny of the Universe

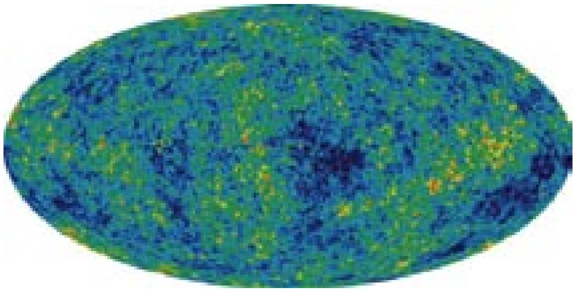
As deep as Einstein's general theory of relativity may be, it remains silent on a profound question: Is empty space really empty? Inflation models predict that it was not so in the past, and suggest that it may not be so today. Einstein introduced a cosmological constant into his equations to represent the possibility that even empty space has energy and couples to gravity.

Although Einstein later claimed that his introduction of the cosmological constant into his general theory of relativity was the "greatest blunder of my life," the recent discovery that the growth of the universe is accelerating, not decelerating, suggests that Einstein might have been right the first time. The existence of a cosmological constant, or "dark energy," that is driving space apart was revealed by observations of Type Ia supernovae and was confirmed in detail by the Wilkinson Microwave Anisotropy Probe (WMAP, an Explorer mission). Other than its existence, we know noth-

Figure 7.3

The Cosmic Microwave Background

The detailed, all-sky picture of the infant Universe from three years of WMAP data. The image reveals 13.7 billion-year old temperature fluctuations, shown as color differences, that acted as seeds that grew to become the galaxies. Future studies of the CMB will be able to search for signatures of gravitational radiation predicted by inflation, perhaps allowing us to see back to the very beginning of time.



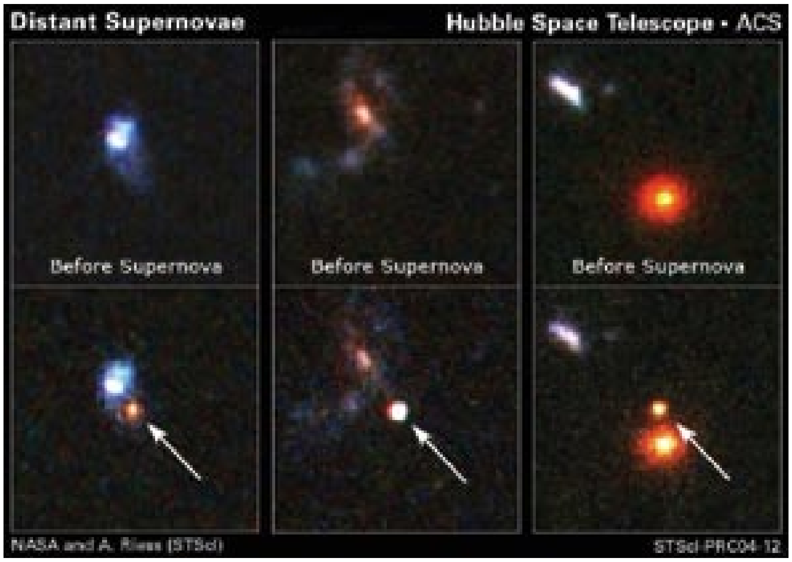
ing about dark energy. Is it truly a cosmological "constant," or does it evolve with time? Since there is no theory of dark energy, anything we learn is an unexpected discovery. Many scientists believe that the reality of dark energy portends an imminent revolution in our understanding of the fundamental laws of nature, comparable to the introduction of quantum theory nearly a century ago.

Exploring Edges of Spacetime with Black Holes

Understanding gravity is fundamental to understanding how our universe evolved. Since Einstein's general theory of relativity is currently our best theory of gravity, it must be strenuously tested to learn if anything is "missing" from it. Most of what we know directly about gravity comes from experiments within the solar system, where gravity is generated by the Sun and its planets and is very weak. The more extreme predictions of Einstein's general theory of relativity include the fact that gravity should appear in its *pure* form in two ways: in vibrations of spacetime called gravitational waves and in knots of curved spacetime called black holes. So far, we have largely indirect, but nevertheless compelling, evidence that these two astonishing predictions are true. We can therefore plan future missions that study these phenomena to test in detail the theoretical underpinnings on which they rest.

Einstein's theory tells us that a black hole is made of pure gravitational energy. Though we infer that the universe contains many black holes, we have yet to see one in detail.

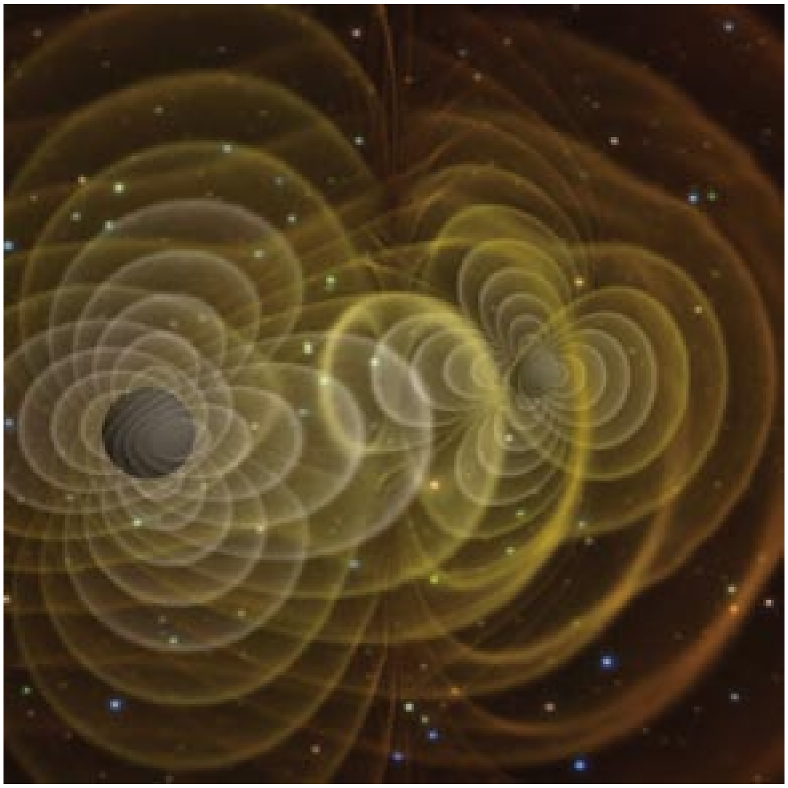
Figure 7.4a



Dark Energy

Distant supernovae can be used to trace the expansion rate of the universe, which allows us to determine how the universe is affected by the repulsive force of the dark energy that pervades all of space. The nature of dark energy is considered to be the most important current question in physics and cosmology.

Figure 7.4b



Gravitational Waves

Researchers crunched Einstein's theory of general relativity on the Columbia supercomputer at the NASA Ames Research Center to create a 3-D simulation of merging black holes. This was the largest astrophysical calculation ever performed on a NASA supercomputer. The simulation provides the foundation to explore the universe in an entirely new way, through the detection of gravitational waves by the Laser Interferometer Space Antenna (LISA) mission.

The general theory of relativity provides a mathematical picture of what one should be like. At a black hole's heart is a singularity, where space and time are infinitely curved and energy is infinitely concentrated. Surrounding the singularity is a region from which nothing can escape (hence the name "black hole"). The edge of this region is called the event horizon. There, time is so warped that it seems, from outside, to have stopped. We can test Einstein by observing supermassive black holes, which are believed to exist at the center of most galaxies. X-ray observations can show us the time-warping experienced by matter falling into supermassive black holes, while gravitational radiation emitted during collisions of black holes could be measured by space-based gravitational wave detectors.

A New Astronomy: Gravitational Radiation

We are on the verge of a new astronomy, one involving not electromagnetic radiation, but *gravitational* radiation. Instead of looking at light (electromagnetic radiation), we listen for the sounds of gravitational radiation, carried to us as ripples in spacetime traveling at the same speed as light. Currently we can only "see" the universe, but we cannot "hear" it. With a new sense of hearing, enabled by future space-based gravitational wave detectors, we will have a completely new vision of the universe. Because gravitational waves couple very weakly with matter, they come to us essentially unchanged from their point of origin. We may therefore be able to hear back to the origin of time itself, when the structure of spacetime was being established.

Gravitational radiation, predicted by Einstein in 1915, has never been directly observed, although it is thought to radiate from binary star systems, massive colliding neutron stars and black holes, and from the Big Bang itself. Detecting gravitational waves will give Einstein's theory a workout it has never had before. We know that Einstein's theory works very well in ordinary circumstances. Without "spacetime curvature technology" in their software, airplanes using GPS navigation would miss their runways by miles. But gravitational waves offer a much more profound test of Einstein's theory. And the sounds of the universe will allow us to penetrate to times and places impossible to see with light, such as the birth of our universe, perhaps revealing startlingly violent events, such as the formation of our three-dimensional space from an original space with ten dimensions.

The Beyond Einstein Program

Einstein's general theory of relativity provides the framework for understanding the evolution of our universe. With the incorporation of inflation theory, essentially all of the observed characteristics of the universe can be explained with a handful of cosmological parameters. And yet so much is still not understood: Is inflation correct, and if so, what is its fundamental nature? What is the dark energy that is causing the universe to accelerate? Do space and time behave as he predicted at the edges of black holes? We know that at some level Einstein's theory must fail, since this is required to achieve a synthesis of gravity (general relativity) and quantum theory. But where does it fail, and how does that failure affect what we see in the sky today?

These questions are addressed by a suite of future missions called the *Beyond Einstein Program*. These include two Beyond Einstein Observatories: Constellation-X, which will observe X-ray radiation from matter as it falls into supermassive black holes; and the Laser Interferometer Space Antenna (LISA), which will measure gravitational radiation for the first time from space, inaugurating the era of gravitational astronomy. In addition there will be three Beyond Einstein Probes: one to determine the nature of the mysterious dark energy pervading the universe (the Joint Dark Energy Mission, JDEM); another to both test the theory of inflation and to reveal what the inflationary field is (Inflation Probe); and a third to provide details to both the demography and workings of the many types of black holes populating the universe (the Black Hole Finder Probe).

7.2.2 The Origin and Evolution of Cosmic Structure

The Beyond Einstein program addresses how the universe began. But how did the rich and complex universe, filled with stars, galaxies, and planets, come to be? The images of the infant cosmos obtained initially from the Cosmic Background Explorer (COBE), and dramatically augmented by the WMAP, show that half a million years after the Big Bang, the universe was extraordinarily smooth, with a nearly uniform temperature across the sky, varying by only a few parts in 100,000. WMAP and other data also reveal that the universe is 13.7 billion years old and is composed of a mysterious force dubbed dark energy (70 percent), an abundance of mysterious dark matter (26 percent), with only a small part (4 percent) being ordinary matter, the stuff that stars, planets, and life are made from.

We seek to understand how these early tiny temperature differences, the seeds of structure, grew into a cosmic web of dark matter and ordinary matter, punctuated by galaxies and clusters and enriched with heavy elements. Our key questions on cosmic structure are: How did the first stars, galaxies and quasars form, and how did they influence their surroundings? How do ordinary matter and dark matter interact to form galaxies and systems of galaxies? Is it true that the dark matter formed structures first, that nucleated the cosmic web? How do supermassive black holes form and grow, and how do they interact with their galactic hosts? What is the formation history of elements necessary for planets and ultimately life, and the history of evolution of our Milky Way galaxy and its neighbors?

The First Stars

The very first stars, although extremely massive and luminous, are nevertheless too faint to detect at cosmological distances. Most of these first stars will explode as supernovae, allowing us to see them briefly. The first stars will also influence their immediate environment, heating and ionizing the surrounding material, and later ejecting and mixing the elements produced in the stars' interiors and during their supernova explosions. Subsequently, the first globular clusters will form, containing hundreds of thousands of hot stars and star explosions called supernovae. These globular clusters and their supernovae are detectable. So too are quasars, galaxies made exceedingly bright by the presence of a central supermassive black hole heating infalling gas to high temperatures, and their fainter cousins called active galactic nuclei (AGN). These are the distant sources we are after on our journey to the frontier of cosmic structure, to the so-called "dark ages" just before the first stars turned on. Polarization measurements by WMAP suggest—in agreement with direct observations of very distant galaxies by the Hubble and Spitzer Space Telescopes—that stars turned on between 300 to 400 million years after the Big Bang; our next generation telescopes therefore need to view the universe back to these early times.

The Hubble Space Telescope (HST) sees hints of the earliest structure, but we need to probe deeper. A new infrared instrument to be installed during Hubble's Servicing Mission 4 will help in this regard. The James Webb Space Telescope (JWST), with its extraordinary sensitivity at infrared wavelengths, will be the premier instrument of the next decade for investigating the dark ages. Deep-imaging surveys with JWST can detect star-forming regions as far back as 200 million years after the Big Bang, if they exist that early. These surveys could also uncover hundreds of active black holes at redshifts of 6 and beyond. A complementary all-sky survey with the Wide-field Infrared Survey Explorer (WISE) may find hundreds of the brightest quasars in the sky at these redshifts. Spectroscopic studies of bright quasars at redshifts of 6 to 10 will probe the late phases of cosmic reionization from the first stars, tracing the evolution of hydrogen and mapping regions of ionization.

The Formation and Evolution of Galaxies

HST has so far been the premier instrument for understanding mechanisms of galaxy formation and evolution, including the history of star formation and the processes that determine the characteristics of present-day galaxies. Vigorous star formation often occurs in dense clouds thick with interstellar dust. The ability to penetrate dust with near-infrared observations and to observe the dust emission at mid-infrared and far-infrared wavelengths is crucial to unraveling the story of galaxy evolution. The combination of Spitzer and HST observations is rapidly advancing our understanding of the relative contributions of quiescent star formation and violent starbursts to the growth of galaxies' stellar masses. Future observatories, such as JWST, are required to go back further in time to see how galaxies originally formed and evolved.

The most vexing challenges in galaxy formation theory involve feedback from supernovae, stellar winds and accreting black holes, which likely play an essential role in regulating star formation and enriching the intergalactic medium (IGM). Such mechanisms may control galaxy mass by ejecting gas before it can form into stars, or by preventing gas from cooling and accreting onto galaxies in the first place. Developing an empirically grounded picture of feedback requires sensitive observations of all galaxy types over a range of wavelengths. Especially important diagnostics of the large-scale outflows observed in rapidly star-forming galaxies come from ultraviolet and X-ray spectra, which detect the main transition lines from highly ionized atoms.

Figure 7.5

JWST Deep Field

A simulation of the JWST deep field showing the very distant galaxies in the early Universe.

The Chandra X-ray Observatory (Chandra) and the Far Ultraviolet Spectroscopic Explorer (FUSE) are valuable tools for this purpose, but Constellation-X (Con-X) and the HST (after new instruments are installed during its next servicing mission) will be much more powerful probes of the gas dynamics within nearby galaxies. JWST, the Wide-field Infrared Survey Explorer (WISE), the Stratospheric Observatory for Infrared Astronomy (SOFIA), and the ESA-partnered Herschel Observatory, all operating in the infrared, will provide detailed physical diagnostics of galaxies over time using high angular resolution and spectroscopy to characterize structure, temperature and chemical composition.

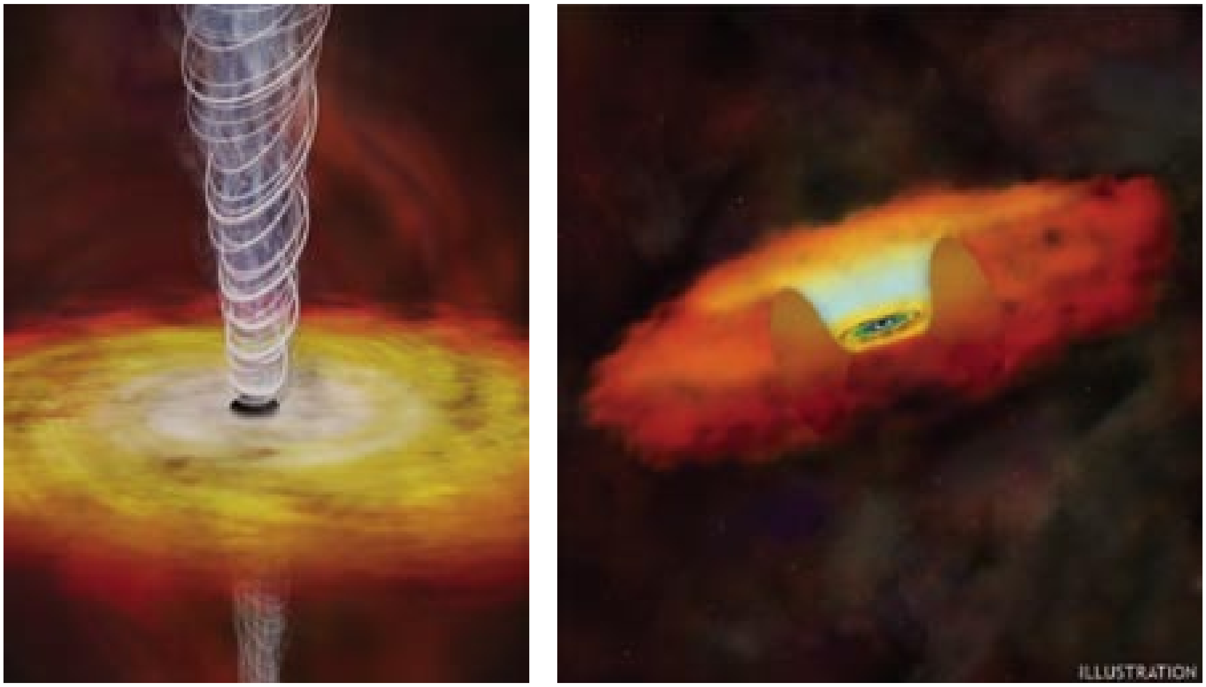
The Galaxy–Black Hole Connection

While galactic-scale outflows driven by supernovae and stellar winds have been studied for many years, it has only recently become apparent that black holes may play a key role in galaxy formation. Essentially all nearby galaxies with substantial stellar bulges harbor central supermassive black holes (SMBHs). The ubiquitous presence of these central objects shows that most massive galaxies must once have hosted quasars or lower-luminosity AGN, even if they are quiescent today. Understanding the growth and history of galaxies requires an understanding of the growth of their interior SMBHs.

Our own Milky Way has an interior SMBH with a mass of approximately three-million solar masses. Larger galaxies have SMBHs with masses in the billions of solar masses. How do these grow? Some growth must be by the accretion of matter (gas, stars) falling into the black holes, which produces copious X-ray emission. The collisions of early galaxies, which result in the merger of their separate SMBHs into a single SMBH, produce the most powerful pulses of energy in the universe; these pulses are emitted not in the electromagnetic spectrum, but as gravitational waves, powerful ripples of spacetime created as the black holes merge into one.

The mass, spin, and growth rates of SMBHs, as well as the exotic processes which convert the gravitational energy of infalling matter into galactic jets, presumed to be the sources of the universe's most powerful cosmic rays and gamma rays, require observations in a wide range of wavelengths in the electromagnetic spectrum, along with the gravitational spectrum as well. Infrared measurements can give us the velocities of stars rapidly orbiting a SMBH, as well measuring

Figure 7.6



Black Holes

Artist's impression of gas flows into black holes. Future X-ray observations with Constellation-X will allow us to study these, thereby probing the extreme gravitational field close to the black hole. Gamma-ray observations with GLAST will elucidate the ubiquitous "jets" observed in these systems, and X-ray observations by the Black Hole Finder Probe will provide a census of black holes in our local universe.

the warm dust around obscured AGN. X-ray spectra tell us of the physics of accretion flows of matter onto SMBHs. Gamma-ray measurements will give us a close view of galactic jets, allowing us to finally understand how these ubiquitous yet exotic structures are formed from spinning SMBHs. And gravitational waves will allow us to "hear" the black hole mergers that accompany the collisions of galaxies.

Higher angular resolution at near-infrared and optical wavelengths are needed for studying the galaxies that host AGN and bright quasars. JWST will offer significant advances over HST and Spitzer. The Black Hole Finder Probe will conduct an all-sky black hole survey, achieving a complete census of bright AGN. High-resolution X-ray spectra from Chandra and the ESA's X-ray Multi-Mirror (XMM)-Newton mission are yielding extraordinary insights into the physics of accretion flows around supermassive black holes, but these detailed physical measurements are possible only for the nearest AGN, not the luminous systems of the "quasar era," 2 to 6 billion years after the Big Bang, when large black holes experienced most of their growth. This will be done by Con-X, with its one-to-two orders of magnitude increase in effective telescope area over the existing instruments. LISA will detect mergers via their gravitational radiations. The Gamma-ray Large Area Space Telescope (GLAST) will detect gamma rays emitted from the jets formed by spinning SMBHs. WISE will perform an all-sky survey that will find dusty AGN and SMBHs. Finally, SOFIA will examine the black hole in the center of our own Milky Way galaxy with mid-infrared observations that are crucial for understanding its luminosity.

The Intergalactic Medium and Dark Matter

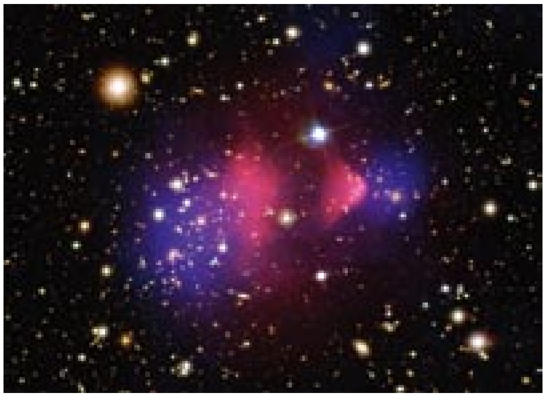
Galaxies, however numerous, account for only ten percent of the known baryon density. Most of the remaining protons and neutrons likely reside between galaxies in a diffuse intergalactic medium. Mapping this gas is crucial because it serves as a tracer of the cosmic web of dark matter to which it is gravitationally attracted. Quasars reveal this invisible gas—the so-called missing baryons, neutral hydrogen atoms in a filamentary dark matter web—when their light passes through and creates telltale absorption lines. The absorption lines in quasar spectra are nicknamed the Lyman-alpha forest.

The more distant the quasar, the greater the number of absorption lines, indicating that missing baryonic matter (the forest) is thicker in the early universe. Hubble and FUSE have detected absorption lines from cool oxygen gas; Chandra has detected X-ray lines from hotter oxygen gas. Yet these are analogous to seeing the edge of the forest. To get into the thick of the woods and to indirectly trace the more complex cosmic web of dark matter, we need deeper observations with higher resolution. Key targets in this search are galaxy clusters, which lie at the nodes of the cosmic web, where dark matter filaments intersect. Most of the baryons in clusters reside in the intergalactic gas, readily detectable in X-ray emission.

Chandra and XMM-Newton enable high-resolution X-ray spectroscopy, the indispensable capability for intergalactic gas measurements. The high sensitivity of Constellation-X will provide a further revolutionary advance. If the standard account of the missing baryons is correct, Con-X will reveal an "X-ray forest" of oxygen, carbon, neon, silicon and iron lines, which trace the dominant, hotter phases of the shocked IGM. Completing the picture will require comparable capabilities at ultraviolet wavelengths to map the cooler gas. Studies with Con-X and future ultraviolet/X-ray missions will measure the enrichment of the IGM, showing how and when heavy elements spread from galaxies to their surroundings.

Figure 7.7

Dark Matter



This image shows the "Bullet Cluster," formed after the collision of two large clusters of galaxies. Shown in pink is the hot X-ray emitting gas (as seen by the Chandra X-ray Observatory), while the blue areas show where most of the mass of the clusters is concentrated (as seen by HST and the ESO ground observatory). The separation of pink from blue gives direct evidence that nearly all of the matter in the clusters is dark matter.

The clumpy web of dark matter which underlies the visible web of galaxies can also be measured by observing the gravitational lensing (bending) of light from distant galaxies. The gravity of massive clumps of dark matter deflects the light coming to us from more distant galaxies, distorting the images of these galaxies. These distortions may be measured by JDEM and by JWST, allowing a 3-D map of the distribution of dark matter in our local universe to be constructed. Very recently the combined observations of Chandra, HST, and the European Southern Observatory (ESO) ground observatory of "the bullet cluster," formed by the collision of two large clusters of galaxies, have definitively established the existence of dark matter, ruling out alternative models that require modifications to Einstein's General Relativity.

Explore the Milky Way and Its Neighbors

We can gain crucial insights into galaxy formation by studying our own Milky Way galaxy and the neighboring galaxies that we can resolve star by star. Our Galaxy's main components are its gravitationally dominant dark matter halo, the thin disk in which the Sun resides, a puffier thick disk, the central bulge, and the diffuse stellar halo that extends to roughly 100 kiloparsecs, more than 10 times the Sun's distance from the Galaxy's center. Understanding the structure and origin of these components requires accurate measurements of chemical abundances, stellar distances, and stellar velocities, from which we can piece together the Galaxy's star formation and assembly history. Abundances and line-of-sight velocities can be measured with spectrographs on large ground-based telescopes, but the high angular resolution of space-based imaging makes it a uniquely powerful tool for geometric measurements of distances and proper motions (angular speeds).

Our view of the Galaxy's components close to the plane of the Milky Way is obscured by dust at wavelengths accessible to ground-based telescopes. Infrared surveys of portions of the Galactic plane with Spitzer have revealed an amazing variety of structures and physical processes. WISE will extend this over the entire Galaxy. The Space Interferometer Mission—PlanetQuest (SIM), currently engaged in mission risk-reduction activities, will transform this field by measuring the distances and motions of stars across the

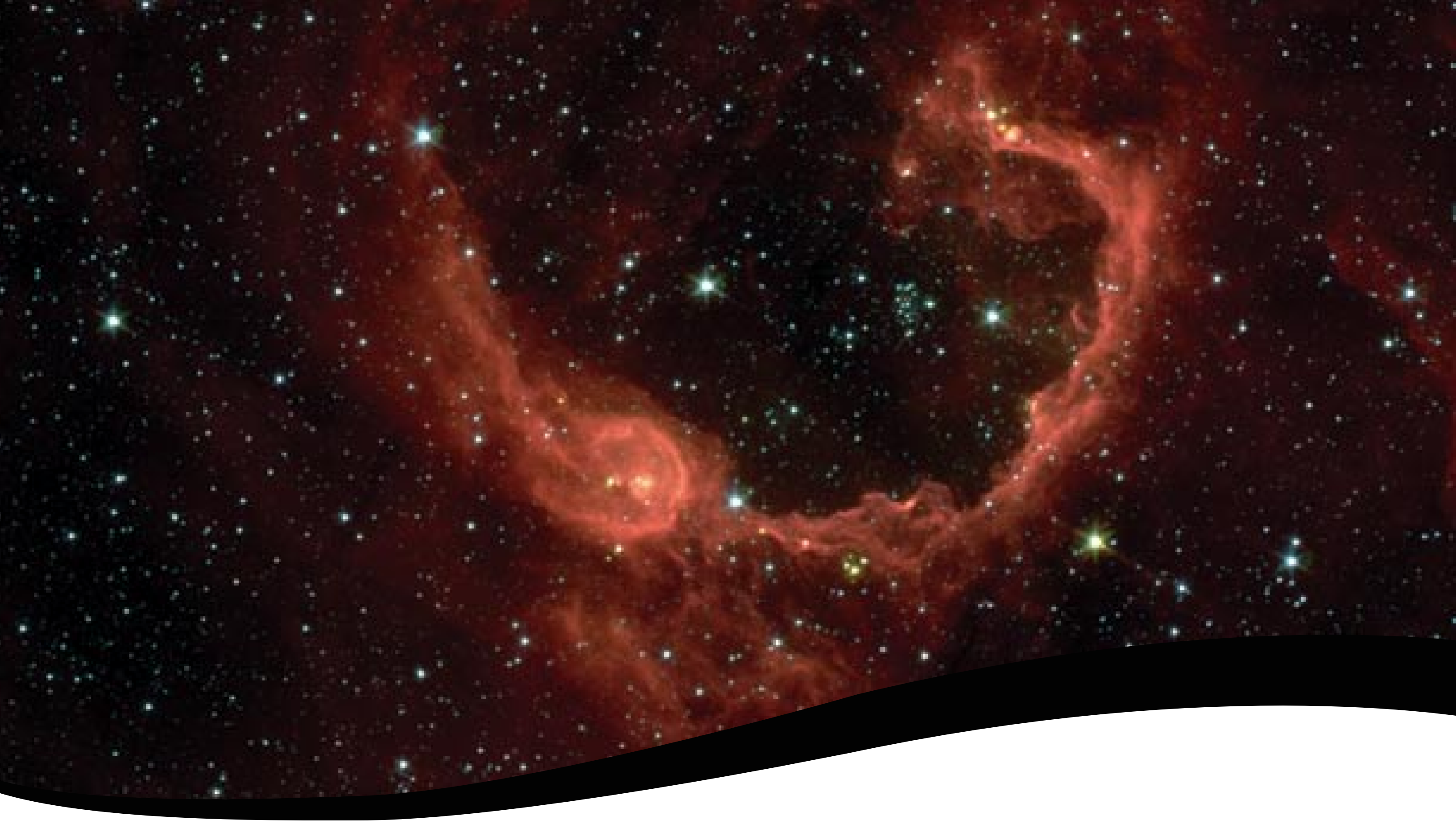


Figure 7.8 Star Formation

Spitzer Space Telescope image of massive star formation in the plane of our Galaxy. Stars are shown in blue and white, while the red color traces emission from interstel lar dust. The larger circular cavity, or bubble, has been created by winds and mass loss from a cluster of stars visible just to the right of the center of the image. On the surface of the bubble, a second bubble, seen to the left and below the center, has begun to expand. Perhaps the formation of the stars driving this second bubble was triggered by the pressure which excavated the first bubble. WISE will find many other bubbles—and other manifestations of massive star formation—in its survey of the entire Galactic Plane, while JWST and SOFIA will study the structure of the bubbles and the composition of the material composing them.

Milky Way and in its nearest galactic neighbors. SIM will be able to measure proper motions of stars more than 1,000 times fainter than the Hipparcos limit with precision as high as three microarcseconds per year. SIM's high-precision measurements of faint stars, roughly 20,000 over the anticipated mission lifetime, would perfectly complement the all-sky survey of brighter stars by ESA's Gaia mission. SIM would also be a unique tool for studying the nature of dark matter. The cold dark matter (CDM) hypothesis—that dark matter consists of massive, weakly interacting elementary particles—has had spectacular success in explaining structure from scales of the cosmic horizon down to individual galaxies. However, its success on subgalactic scales is an open and controversial question. The CDM scenario predicts dark matter halos that contain substantial amounts of lumpy substructure. SIM could map the gravitational potential of the Milky Way's dark halo, using the motions of individual stars, star clusters, and dwarf galaxies to pin down the halo's total mass, spatial extent, radial profile, and three-dimensional shape.

7.2.3 The Origin & Destiny of Stars

Stars are the furnaces that forge nearly all the atoms in the universe, other than the hydrogen and helium made during the Big Bang. From the death of a star come the atoms necessary for planets and life. Many fundamental aspects of the lives of stars have remained a deep mystery, but, with today's sophisticated space observatories, we can build the tools to determine how planetary systems form in the disks of gas and dust around young stars and evolve toward suitable sites for life. To explore the origin and destiny of stars we also need to know the nature of the exotic objects left by dying stars and how the heavy elements essential for life are created and cycled throughout the universe.

From Interstellar Clouds to Stars

We are immersed in a dilute sea of atoms of gas and grains of dust. Large-scale forces can compress this material into clouds so dense that atoms join into molecules. Turbulence and magnetic fields control the configuration of these molecular clouds, twisting and shredding them into sheets and filaments. These structures sometimes collapse, forming cold dense cores shielded by dust from damaging ultraviolet photons. Star formation begins deep within these cores. How can we peer inside such cold, dark clouds?

Visible light cannot escape from dusty stellar nurseries, but longer wavelength radiation can, in a manner similar to the penetration of radio waves through sunlight-blocking clouds on Earth. SOFIA and ESA's Herschel Space Observatory will probe the controlling influences on star formation by measuring the temperatures, densities, and velocity structures within molecular clouds and collapsing cloud cores. JWST will search for prebiotic molecules and probe the chemistry occurring in the central regions of the youngest protostars.

The Emergence of Stellar Systems

After a dramatic initial collapse, a protostar grows for a few hundred thousand years as gas and dust flow onto it from the surrounding cloud. Eventually the new star stabilizes, heated by the energy released as gravity continues to compress it. These processes are only vaguely understood. What sets the mass of the final star? Why are there more low-mass stars than high-mass ones? What conditions allow planet formation and determine the types of planets formed? Examining star formation over a wider range of elemental abundances, gas pressures, and magnetic field strengths will show how the starting conditions influence the resultant mass distribution. Millimeter-wavelength observations reveal that significant amounts of gas and dust, usually more than enough to form a planetary system, are left in disks around new stars.

The mid-infrared WISE survey will discover hundreds of objects which are in the earliest stages of gravitational collapse. The processes controlling the fragmentation of molecular clouds will be measured with the far-infrared spectroscopy of Herschel and SOFIA. These facilities will provide sufficient spatial and spectral resolution to measure the rotational velocities and masses in prestellar and star-forming cores. JWST will help us understand the formation of planet-forming disks and the related tendency of stars to form as binary or multiple star systems. Increasingly deeper understanding will come with finer resolution from SIM, the Keck and Large Binocular Telescope Interferometer, and the Terrestrial Planet Finder (TPF) mission.

The Extreme Physics at the End of Normal Stellar Lives

Neutron stars and black holes, the end states of massive stars, are unique environments with gravity, magnetic fields, and densities that are far beyond the range available on Earth. Although compact (a neutron star is only 15 miles wide), they become observable as they accrete matter from a surrounding disk, which gets extremely hot and glows brightly at high energies. These systems are important laboratories for studying extreme physics. Already they have provided indirect evidence of gravitational radiation and of frame-dragging, the twisting of spacetime around a rotating star predicted by general relativity. Spinning, highly magnetic neutron stars, also known as pulsars, radiate beams of light into the Galaxy and emit jets of material that energize their surroundings. Through detection of the gravitational redshift of X-rays from the surfaces of neutron stars, we may obtain a direct measure of the mass/radius ratio of neutron stars, potentially revealing exotic forms of ultradense matter, such as strange-quark matter.

In recent years, supernovae from massive stars have been identified at the core of gamma-ray bursts (GRBs), among the most powerful explosions seen in the electromagnetic spectrum since the Big Bang. These once-mysterious GRBs are seen at great distances; some have occurred when the universe was less than half its present age. Due in part to the Swift satellite (an Explorer mission), we know much more about the origins of these bursts. Some of the GRBs have been identified with the death of a single massive star and creation of a black hole. Others have been identified with the merger of two compact objects (neutron stars or black holes). GLAST will study GRBs over a wider range of energies, some dating back to the earliest supernovae. A hard X-ray survey telescope, such as a candidate Black Hole Finder Probe of the Beyond Einstein program, would conduct a black-hole census.

How the Elements are Made and Distributed

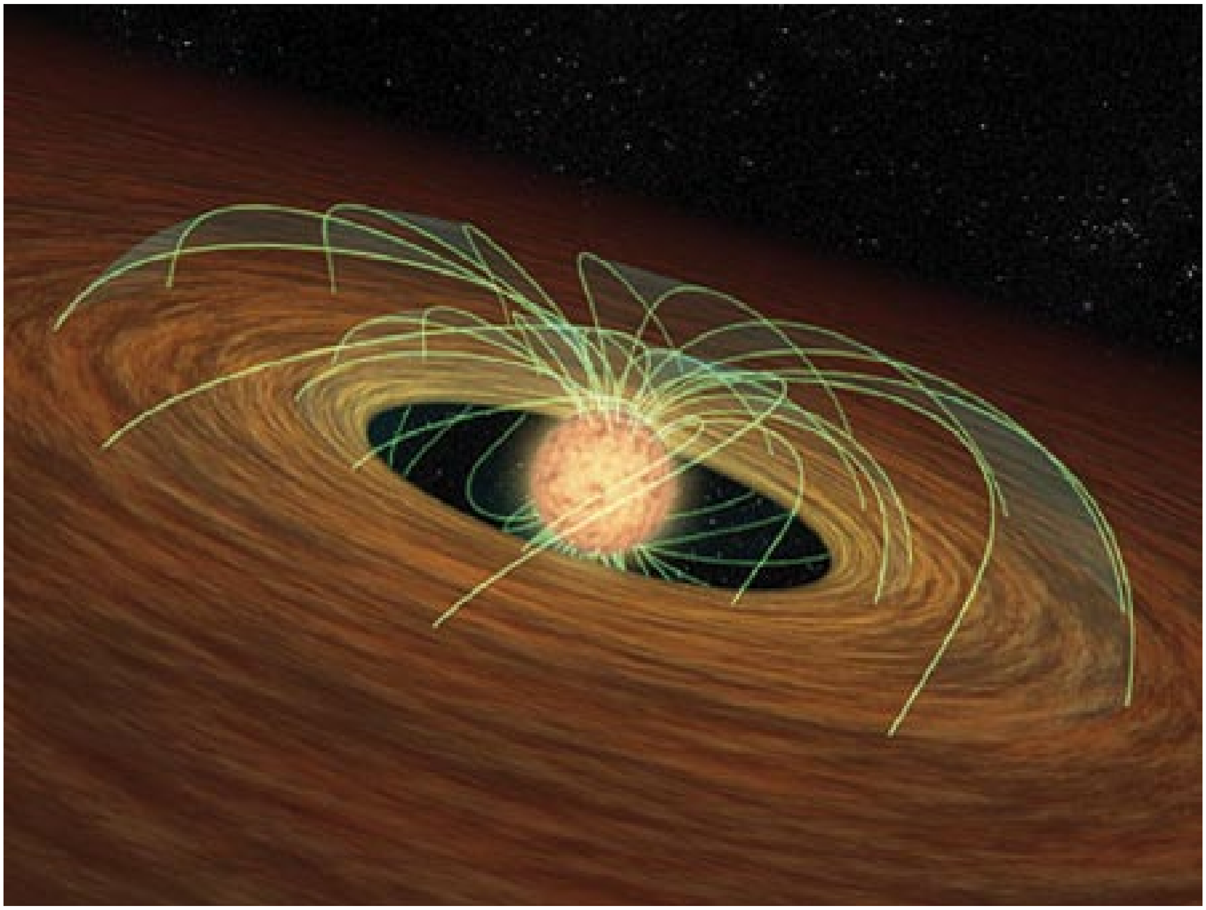
Although we have learned much about the neutron stars and black holes left behind by certain types of supernovae, we still do not understand exactly how the explosions occur. Elements are synthesized in the original star and during the supernova explosion. The resulting shocks from the blast wave heat and accelerate the surrounding gas, pumping significant amounts of energy into the interstellar medium, heating it, and even punching holes through a galactic disk and driving galactic winds. They drive turbulence in molecular clouds that may trigger star formation. In fact, there is evidence that a nearby supernova explosion might have played an important role in the formation of the Sun. Star death, star birth, and the generation and recycling of heavy elements into the interstellar medium are closely linked.

Herschel and JWST will build on results from Spitzer and Chandra to trace this process in the early universe as galaxies and quasars formed and evolved. The Japanese-led Suzaku X-ray mission and Con-X will probe the acceleration process and determine the maximum energy of cosmic rays that are produced in them. GLAST will map regions of particle acceleration through the gamma rays created by the particles moving at nearly the speed of light.

Determine How Planets Form in Dense Disks of Gas and Dust Around Young Stars

The heavy elements manufactured in massive stars and released into interstellar space by supernovae are the

Figure 7.9



Young Star and Disk

An artist's conception of the interaction between a young star and its planet-forming disk. The stellar magnetic field threads the disk, and the inertia of the disk slows the stellar rotation. This picture is based on observations from the Spitzer Space Telescope showing that stars with planet-forming disks rotate more slowly than do stars without disks. This illustrates how observations with JWST and SOFIA can probe the details of the planet-formation process. Image courtesy of the Spitzer Science Center.

raw material for Earth-like planets and for life. Planets form from a protoplanetary disk around a young star. The classic picture is that solid particles of dust coalesce early and stick to each other in collisions, slowly building a core around which a planet grows: gas giant planets grow quickly before the system loses most of its gas, and Earth-like planets grow over a longer period. This picture explains many characteristics of our solar system, but it is running into trouble elsewhere.

What governs the formation and evolution of gaseous and rocky planets? How does the flow of material inward to the star avoid carrying the nascent planets to a fiery doom? How are otherwise semi-inert, nonreactive molecules transformed into reactive radicals that drive the production of life's raw materials? Does early bombardment of planets by asteroids and comets deliver carbon-rich material and start the development of life? How do giant planets direct material from one part of the disk, perhaps water-rich, to the inner regions where Earth-size bodies are growing?

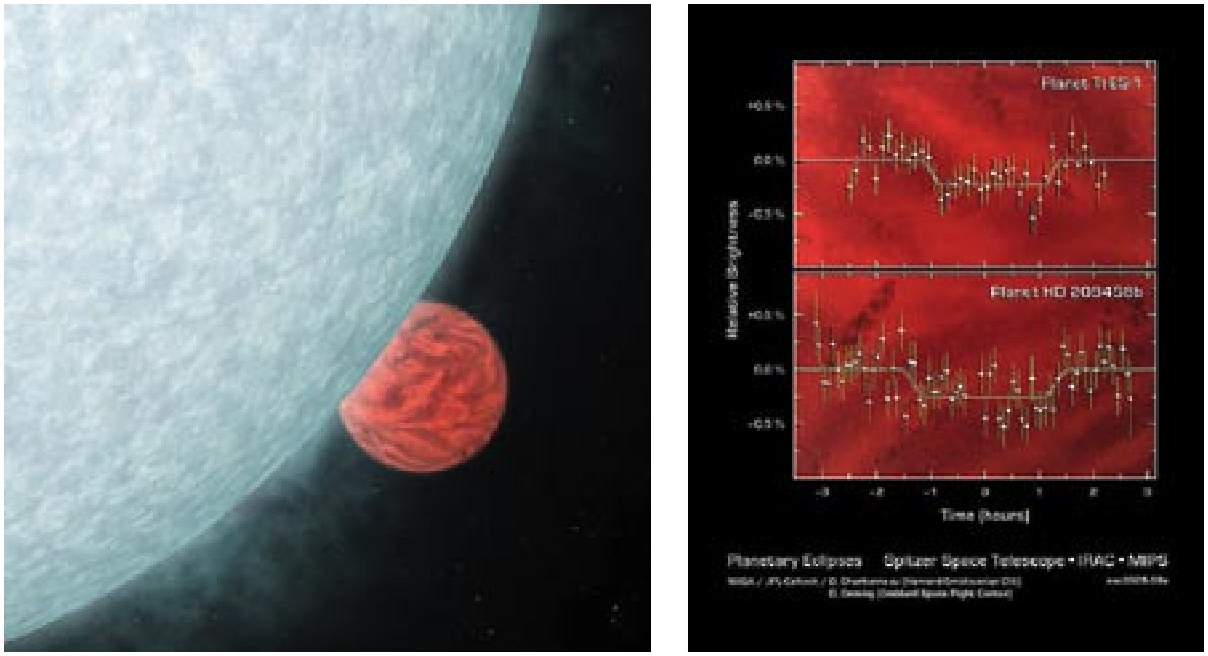
Studies of stellar clusters show that, at any given age, there is a wide range of disk masses, suggesting a broad variety in planetary system evolution. This is corroborated by the range of properties exhibited by the hundreds of planetary systems identified by radial velocity, transit, and microlensing studies. This allows for solar systems vastly different from ours with its four rocky planets followed by four gas and water giants. WISE, JWST, SOFIA, and Herschel, each in its own unique way, will observe protoplanetary disks to explore this variety. JWST, as well as the ground-based Keck Interferometer and Large Binocular Telescope Interferometer, will reveal ripples and gaps in disks that help locate a perturbing, young planet and provide estimates of its mass. TPF will go well beyond the capabilities of JWST and peer deeply within dust-enshrouded protoplanetary disks to cleanly separate planets, disk, and star. These missions will be the first to have the capability to directly detect the light from Earth-like extrasolar planets.

7.2.4 Exploring New Worlds

The search for extrasolar planetary systems is well underway, and we now know of more than 180 planets outside our solar system, many discovered by NASA-supported ground-based telescopes. However, most of the extrasolar planets discovered so far are not the terrestrial planets that could potentially be habitable, but rather are gas-giant planets like Jupiter and Saturn, hundreds of times more massive than Earth. As yet, no Earth-sized planets have been detected; this is because no current instruments possess the sensitivity and resolution needed for such a discovery.

The technology required to detect and characterize potentially habitable worlds is enormously challenging, and no

Figure 7.10



Extrasolar Planets

The panel on the left shows an artist's impression of extrasolar planets. The graph on the right shows data from NASA's Spitzer Space telescope of changes in the infrared light output of two star-planet systems (one above, one below) located hundreds of light-years away. The data were taken while the planets disappeared behind their stars. The dip seen in the center of each graph represents the time when the planets were eclipsed, and tells astronomers exactly how much light they emit.

Future missions will take the study of extra-solar planetary systems into a new era. The Kepler mission will detect and characterize Earth-like planets. Other missions such as JWST, WISE, SIM, and TPF will observe protoplanetary disks and planetary systems to explore different aspects of the planet formation process and the variety of planets that can form around stars.

single mission can provide all the measurement capabilities. Kepler, a Discovery mission, will be the first to detect and characterize terrestrial planets, measuring the reduction in starlight as a planet orbits and occludes its parent star. The flagship missions for exploring new worlds will be JWST, which will probe the initial stages of star and planet formation; SIM, which will survey nearby stars for candidate Earth-like planets, measuring their orbits and masses; and TPF, which will identify those terrestrial-type planets with atmospheres and study their potential for supporting life. Linking the flagship missions together will be precursor observations with a variety of space-based and ground-based telescopes, which will measure the statistics of exoplanet systems and determine whether Earth-mass planets are common or rare.

The Diversity and Frequency of Other Worlds

A comprehensive census of the planetary systems in our solar neighborhood using ground-based and space-based observations will enable investigation of the relationship among the main players in a planetary system: gas-giant and rocky planets, cometary systems (Kuiper Belts), and asteroid belts and zodiacal clouds. These studies will set the stage for follow-up observations to understand the properties of the planets that we find and allow us to understand the larger context of our own planetary system.

Giant planets, composed mostly of gas and unlikely to directly harbor life, dynamically constrain the orbits available for terrestrial planets and may affect their habitability. Giant planets are the older siblings—both the bullies and protectors—of the terrestrial planets. How they stir up the disk determines how many comets and asteroids survive to bombard smaller worlds with either sterilizing intensity or with life-bringing chemicals. Giant planets in eccentric orbits probably do not allow terrestrial planets to orbit stably in the habitable zone (the orbital region around a star within which liquid water may exist on a planet's surface). However, gas giants might be necessary for shielding terrestrials from life-damaging impacts of comets.

Kepler will measure the sizes, masses, and, hence, densities of both gas- and ice-giant planets. Observations of stars harboring giant planets with SIM will measure the eccentricity and inclinations of orbits for planets within five AU (Earth-Sun distances) of their parent stars. This will be our best tool for disentangling the dynamics of systems with multiple giant planets. TPF will be capable of detecting and spectroscopically analyzing both Earth-like and giant planets, which is of particular importance in understanding the chemical composition, physical structure, and overall evolution of these objects.

Being about ten times smaller in diameter than a Jupiter and a hundred times smaller than a Sun, Earth-size rocky planets are challenging to find. Observations suggest that rocky planets may be common, but their abundance is unknown. The information to date, however, is encouraging: Roughly seven percent of all nearby stars harbor a giant planet within three AU, and there are apparently more smaller planets than gas giants. Multiple planets are common, often in resonant orbits. And eccentric orbits, which are easier to observe, are the most common, with only 10 percent nearly circular.

Kepler will survey our region of the Milky Way Galaxy to detect and characterize hundreds of Earth-size and smaller planets in or near the habitable zone, and thousands in shorter period orbits. Planned follow-up by ground-based observatories, HST, and JWST will determine the masses and densities of the planets and whether they are rocky or icy in composition. Knowledge of the planetary period and the stellar properties determines whether the planet is in the habitable zone of its star. Both HST and Spitzer have already been used to observe a handful of planets, through comparison of the spectra of the star and planet together, the star hiding the planet, and the planet transiting the star. With its high-resolution infrared spectroscopy, SOFIA will be able to resolve planet formation within the habitable zone. SIM will perform the first census of Earth-like planets around the very nearest stars—planets that we will later be able to observe through direct detection of light—to learn more about their physical properties, accurately measuring their masses and orbits. SIM will locate targets suitable for subsequent observation by the TPF mission.

Brown dwarfs have masses too small to sustain nuclear fusion, but they emit infrared radiation. Jupiter itself lies at the lower end of the brown dwarf mass spectrum. Thus, studies of brown dwarfs either as isolated objects or as stellar companions can illuminate our understanding of the planet formation process. In addition, a growing body of data from Spitzer—to be greatly augmented by JWST—suggests that brown dwarfs may themselves host planetary systems. Because brown dwarfs are about as common as all other types of stars, it is quite possible that the extrasolar planetary system nearest our Sun orbits a brown dwarf. The WISE mission, with its sensitive all-sky infrared maps, may discover brown dwarfs even closer to the Sun than the known nearest star, Proxima Centauri.

Comparative Planetology

We are seeing an explosion in our understanding of extrasolar planetary systems, as results from Hubble, Spitzer, and a vigorous program of ground-based studies are revealing the composition, structure, and dynamics of these systems and the masses and locations of planetary objects within them. A comprehensive census of the planetary systems in our solar neighborhood using ground-based observations and observations from Spitzer, SOFIA, Herschel, JWST, SIM, TPF will enable investigation of the relationship between all the main components of a planetary system: gas-giant and rocky planets, cometary systems (Kuiper Belts), and asteroid belts and zodiacal clouds.

These studies often impinge upon studies of our own solar system, permitting, for example, comparison of the crystalline silicates orbiting nearby stars with those in Comet Hale-Bopp and Tempel I. Also, deep observations of the outer solar system from the ground and with JWST will enable direct comparison of our solar system with other systems. This is opening up the prospects for studies in comparative planetology, through which the wealth of understanding we have of our own solar system will inform our interpretation of data on extrasolar systems. Conversely, the study—now possible for the first time—of large numbers of extrasolar systems from a favorable external perspective may help to answer questions about the formation and evolution of our own solar system.

The Origin of Organic Molecules on Planets

The next big step in understanding the evolution of habitable planets is to study how terrestrial planets receive and store the materials required to foster life. The building blocks of life—organic molecules—likely permeate the Universe. However, their precise identification and details regarding their abundances and distribution are in need of further study. Research indicates that a complex series of processes are involved in generating a planetary environment that is hospitable to life. For example, while the amount of life-essential carbon present in a planet is determined early on by the planet’s birthsite within the young solar nebula, organics and volatiles such as water are accumulated throughout a planet’s history via cometary impacts.

Observations of ice and organic compounds in disks with JWST, SOFIA, TPF and Herschel can be combined with theories of organic chemistry, volatile processing, and orbital dynamics to place constraints on the formation and evolution of prebiotic compounds and their delivery to terrestrial planets.

The Search for Habitable Planets and Life

The search for life elsewhere in the universe begins with an understanding of the biosignatures of our own world. Earth has surface biosignatures due to vegetation, as well as several atmospheric biosignatures, including the characteristic spectra of life-related compounds like oxygen—produced by photosynthetic bacteria and plants—and its photochemical product, ozone. The most convincing spectroscopic

Astrophysics Opportunities Enabled by Human Exploration of the Moon

The return of human explorers to the surface of the Moon by 2020 creates additional opportunities for realizing the science priorities in astrophysics. During the period of time covered by this Science Plan, NASA will establish a “Lunar Exploration Ar-
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exp
timescale in which those capabilities will be available to support astrophysics exploration.

At the same time, NASA will conduct studies to identify potential investigations and projects that can realize priority astrophysics objectives from the Moon. The interim report on *The Scientific Context for the Exploration of the Moon* (NRC, 2006) identifies “determining the utility of the Moon as a platform for astrophysics observations” as one priority, and recommends that NASA evaluate the Moon’s potential as an observation platform. Beginning in 2006, NASA will sponsor workshops and an NRC study to identify those astrophysics science objectives that can be realized from the lunar surface, and to determine the additional studies necessary to establish their cost and benefit. In 2007, NASA will select several concept studies for science investigations that can be realized on the short sorties that will be the first human exploration missions. Also in 2007, the NASA Advisory Council will sponsor a Lunar Science Workshop aimed at establishing science objectives for the lunar exploration program.

In identifying astrophysics mission concepts that can be realized from the surface of the Moon and in establishing the priorities for those potential missions, SMD will use the same community-based processes that have been used to establish priorities in the current astrophysics program. Recognizing that newly enabled candidate missions must compete with other
miss
science objectives in astrophysics.

Table 7.1

Targeted Outcomes through 2016

What are the Origin, Evolution, and Fate of the Universe?	How Do Planets, Stars, Galaxies, and Cosmic Structures Come into Being?	When and How Did the Elements of Life and the Universe Arise?	Is There Life Elsewhere?
Test the validity of Einstein's General Theory of Relativity. Investigate the nature of spacetime through tests of fundamental symmetries (e.g., is the speed of light truly a constant?). Test the inflation hypothesis of the Big Bang. Precisely determine the cosmological parameters governing the evolution of the universe. Improve our knowledge of dark energy, the mysterious cosmic energy that will determine the fate of the universe.	Investigate the seeds of cosmic structure in the cosmic microwave background. Measure the distribution of dark matter in the universe. Trace the filamentary cosmic web of atomic matter in the universe. Discover the first stars, galaxies, and quasars (black holes). Determine the mechanism(s) by which most of the matter of the universe became reionized. Determine the history of cosmic star formation and the assembly of galaxies. Study the birth of stellar and planetary systems. Uncover the connection between galaxies and supermassive black holes.	Discover when complex organic molecules, the precursors of biology, first appeared in the universe. Measure the metal enrichment of the diffuse intergalactic and interstellar media. Improve our understanding of supernovae and their nucleosynthesis of heavy elements needed for life.	Determine the frequency with which planets are found within the habitable zones of other stars and characterize their physical properties, such as mass, diameter and orbital parameters. Determine what properties of a star (such as metallicity) are most strongly correlated with the presence of habitable Earth-like planets.

evidence for life as we know it is the simultaneous detection of large amounts of oxygen and a reduced gas, such as methane or nitrous oxide, which can be produced by living organisms.

To determine if a planet is habitable and in particular to discover if life exists there, we must build observatories capable of directly detecting the light from the planet, with the planet illuminated by the light of its parent star or glowing at infrared wavelengths by the warmth of the planet itself. The direct detection of Earth-like planets is an enormous technical challenge; telescopes are required that can suppress the overwhelming glare from a star so that its faint orbiting planets can be seen. Direct imaging detection and spectroscopic characterization of nearby Earth-like planets will be undertaken by TPF, either as a coronagraph (TPF-C), which would operate at visible wavelengths, or as an interferometer (TPF-I), operating in the mid-infrared. TPF will survey a large volume of our solar neighborhood, searching for terrestrial planets around hundreds of stars and measuring the atmospheric compositions of as many as dozens of candidate Earth-like planets. Transit spectroscopy with JWST and HST to follow up Kepler and other detections offers a nearer opportunity for planetary spectroscopy on large numbers of extra-solar planets.

Navigator Program: Exploring New Worlds

To realize this bold exploration agenda, NASA has established the Navigator program, a suite of interrelated missions to explore and characterize new worlds. The program embodies the Presidential directive to enable advanced telescope searches for Earth-like planets and habitable environments around neighboring stars. The Navigator program is structured in a cohesive effort of precursor and supporting science and technology development and moderate scale facilities leading toward TPF, which serves as the focus of the program. The search, begun with HST and Spitzer, will continue with Kepler, Keck, the Large Binocular Telescope Interferometers, and JWST, which will observe nearby stars to probe preplanetary and exozodiacal dust disks, revealing gaps and features created by planets that have so far remained undetected. SIM will survey the nearest stars, fully characterizing nearby planetary systems to provide targets for the more powerful TPF to examine.

7.3 Mission Summaries

Figure 7.11 gives the mission timelines for all currently operating missions through those for which formulation begins by 2016. The blue bar begins at the beginning of formulation; the triangle marks the launch date; the tan bar shows the prime mission lifetime, while the green bars represent mission lifetime extensions. The timeline extends to 2025 to show the run-out of all the listed missions. Note that missions whose formulation begins after 2016 are **not** shown here, even though there will be missions inaugurated between 2016 and 2025.

Table 7.2 provides succinct descriptions of the Astrophysics Division missions which have yet to be launched—their purposes, primary science goals, and basics of implementation.

Figure 7.11

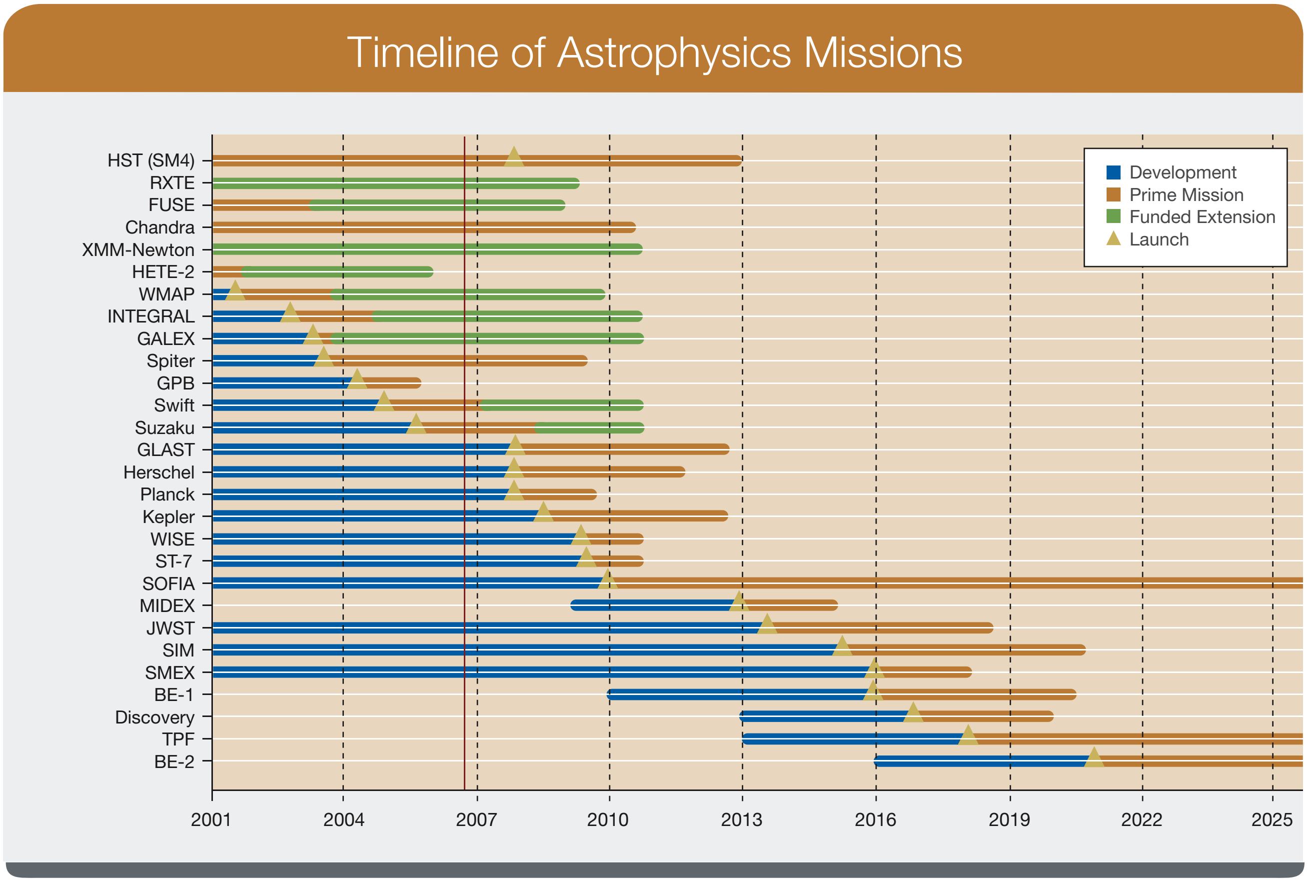


Table 7.2

Astrophysics Future Mission Summary

Program	Mission	Objective (See Table 2.1)				Mission Objectives and Features
		1	2	3	4	
Flagship	James Webb Space Telescope (JWST)	●	●	●	●	Infrared successor to the HST; 6.5 meter telescope with four infrared instruments at L2; partnership between NASA, the European Space Agency (ESA), and the Canadian Space Agency.
Flagship	Hubble Space Telescope - Servicing Mission 4 (HST-SM4)	●	●	●	●	Enhance Hubble's range and dramatically increase both the survey power and the panchromatic science capabilities. Space Shuttle servicing to add two instruments: Cosmic Origins Spectrograph operating at near ultraviolet wavelengths and Wide Field Camera 3 (WFC3) operating at near infrared wavelengths.
Strategic mission	Gamma-ray Large Area Space Telescope (GLAST)	●	●	●		Observations of celestial high energy gamma-ray sources. Joint NASA/DOE mission with a large area telescope for an all sky survey in the highest-energy gamma rays.
ISSC	Herschel Space Observatory)		●	●		Completely cover the peak of the spectrum of galaxies and of star-forming regions out to redshifts of six. Fills wavelength gap between JWST and Spitzer. ESA mission with NASA contribution.
ISSC	Planck Surveyor	●				The third-generation space mission to measure the anisotropy of the cosmic microwave background radiation. An ESA mission with major contributions from NASA.
Discovery	Kepler				●	Monitor 100,000 stars continuously for four years to detect Earth-sized planets using transit photometry. Discovery PI-led mission; sensitive detectors capable of detecting a change in a star's brightness as small as 20 parts-per-million.
Explorer	Wide-field Infrared Survey Explorer (WISE)		●	●		Survey the whole sky in four mid-infrared bands to sensitivities 500 or more times better than previous all-sky surveys. The survey will provide an important catalog for JWST. Explorer MIDEX PI-led mission; 40 cm telescope continuously scanning spacecraft with scan mirror to freeze images on arrays for 8.8 second exposures.
Flagship	Stratospheric Observatory for Infrared Astronomy (SOFIA)		●	●	●	Infrared and submillimeter observations of stellar and planet-forming environments. Joint NASA/DLR (Germany) airborne 2.5-meter telescope on a Boeing 747; nine first-generation instruments.
Explorer	Explorer (MIDEX)	○	○	○		Competitively selected PI mission; could address any of the first three objectives.
Explorer	Explorer (SMEX)	○	○	○		Competitively selected PI mission; could address any of the first three objectives.

Astrophysics Future Mission Summary—Continued

Program	Mission	Objective (See Table 2.1)				Mission Objectives and Features
		1	2	3	4	
Navigator	Space Interferometry Mission (SIM)		●	●	●	Detect and characterize other planetary systems; measure the mass of planets and stars; measure the internal dynamics and external motions of galaxies in the Local Group and beyond; investigate quasar physics and establish the successor to the International Celestial Reference Frame. A 9-m baseline interferometer in Earth-trailing solar orbit.
BE	Constellation-X (Con-X)	●	●	●		X-ray imaging and spectroscopy for the study of black holes, dark matter, dark energy and neutron stars. Single spacecraft carrying a constellation of four telescopes placed in an L2 orbit with a combined collecting area of 1.5 square meters.
BE	Joint Dark Energy Mission (JDEM)	●				Measure the cosmological parameters of the expanding Universe. Joint NASA/DOE mission; three mission concept studies (ADEPT, DESTINY, SNAP) have been selected by NASA to examine differing mission implementations.
BE	Laser Interferometry Space Antenna (LISA)	●	●	●		First measurement of low-frequency gravitational waves. Three independent, free-flying, drag-free spacecraft provide for three-arm interferometry of a variety of astrophysical sources. Collaboration with ESA.
BE	Black Hole Finder Probe (BHFP)	●				Conduct a thorough census of black holes in the universe.
BE	Inflation Probe (IP)	●				Provide a stringent test of inflationary cosmology, the physics of the universe at less than a trillionth of a second after the Big Bang. This is a PI-class mission that will be selected by competition.
Navigator	Terrestrial Planet Finder—Interferometer (TPF)		●	●	●	*Interferometer*—Detect and characterize all components of other planetary systems, including terrestrial planets, gas-giant planets, asteroid belts; search for signs of life in terrestrial planets. Four 3-4 m passively cooled telescopes on separate formation flying spacecraft feeding light to a nulling interferometer on a fifth spacecraft; Proposed joint project with ESA's Darwin mission. *Coronagraph*—Image Earth-like planets, giant planets, and zodiacal dust around nearby stars; search for signs of life on Earth-like planets; carry out general astrophysics observations probing dark energy and dark matter. Single telescope at L2 with a narrow-field coronagraph and spectrometer to observe planets 10^{-10} as bright as their stars, and a wide-field camera for general astrophysics in the visible and near-infrared.

● Applies to the objective ○ Could apply to any objective

7.4 Program Elements

7.4.1 Research and Analysis

In a 2000 report, the Association of American Universities described the R&A line as "one of the most efficiently used funding lines in space science research." R&A supports scientific exploration outside budget lines of individual missions. It represents a small fraction of the NASA space-science budget, but it is this fraction that leads to ideas for new missions, incubates the critical early phases of technology development, and transforms the raw data from satellite instruments into answers to scientific questions. Its technology and detector development, theoretical research and modeling, laboratory astrophysics, ground-based observation, and archival research components, together with the suborbital and Explorer programs, constitute the scientific and technical foundations upon which major NASA missions grow.

Technology Incubation

The R&A program has supplied NASA missions with many technologies that were later incorporated into major missions in a process which continues to this day. Example capabilities are holographic gratings, extreme ultraviolet filters, and X-ray calorimeters. Microchannel plate detectors and their associated readouts, both developed under the Astronomy and Physics R&A program, have been the cornerstone of missions such as the Extreme Ultraviolet Explorer (EUVE), Chandra's High-Resolution Camera, the Hubble Space Telescope/Space Telescope Imaging Spectrograph (HST/STIS), the Far-Ultraviolet Spectroscopic Explorer (FUSE), Galaxy Evolution Explorer (GALEX), and the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS), as well as many rocket payloads. In the near- and mid-infrared regimes, new large-format, low-readout-noise arrays now under development will be vital to the success of JWST. At submillimeter wavelengths, the class of spiderweb micromesh bolometers that enabled BOOMERANG's image of the CMB sky will be used both on Planck Surveyor to obtain the definitive CMB map and on the Spectral and Photometric Imaging Receiver (SPIRE) instrument on Herschel to gain a new view of the universe. The effort to develop silicon pop-up detectors has led to the large-format arrays on the High-resolution Airborne Wide-bandwith Camera (HAWC) of SOFIA and the development of new cutting-edge instruments on the ground-based Submillimeter High Angular Resolution-2 (SHARC-2) instrument at the Caltech Submillimeter Observatory. The heterodyne superconducting-insulating-superconducting mixers with heritage in the R&A program will fly on both SOFIA and Herschel. High-accuracy clocks, drag-free gravitational reference systems, and laser-transponders will be flown on the LISA mission.

Supporting Theoretical Research and Modeling

Science seeks to advance human knowledge by explaining and understanding the universe in all its particulars. Theoretical research plays a fundamental role in this endeavor: it is the central process whereby data are converted into scientific understanding. Theory provides the framework for structuring science, the language we use to describe the world, and the tools we use to interpret data.

The National Academy of Sciences decadal survey, *Astronomy and Astrophysics in the New Millennium* (NRC, 2000), recognized theoretical studies as a central component of modern mission and technology development. Theoretical imagination conjured white dwarfs, neutron stars, black holes, the CMB, and accretion disks, all of which have since been verified as fact. Theory has provided the fundamental techniques and tools of atomic physics, nuclear physics, quantum physics, general relativity, physical chemistry, statistical physics, radiative transfer, and hydrodynamics. In recent years, theoretical studies include the development of software technologies supporting data exploration, astrophysical simulations, and the combinations of these that now enable a deeper understanding of complex systems. Theoretical research is crucial to progress because it establishes the framework within which the basic science questions are formulated, predictions are made, and data are interpreted and analyzed. It is the wellspring of new missions. A strong, stable, and sustained commitment to theory funding is needed for a healthy and balanced Astrophysics Science Program.

There are currently two prominent components of NASA support for theoretical research. The first is comprised of the broad-based Astrophysical Theory Program (ATP), the Beyond Einstein Foundation Science (BEFS) program, and the NASA Astrobiology Institute. All proposals to these programs are required to demonstrate their relevance to NASA's mission, but much research cuts across mission lines, synthesizing results from different wavelengths or from imaging and spectroscopy. The ATP component of NASA theory support is crucial to envisioning and defining missions, identifying novel techniques that could be used to address Astrophysics science objectives, and studying capabilities needed to achieve those objectives.

The second component of NASA support for theoretical research arose from the recommendation of the 2000 decadal survey that theoretical research be explicitly funded as part of each mission funding line, allocating a small fraction of its budget to theory challenges critical to the mission's key goals. The decadal survey made this recommendation because detailed modeling connecting the elements of a mission to the system under investigation is critical to conceive and implement successful and cost-effective missions. Rigorous modeling reduces mission risk and is essential for evaluating competing mission strategies, and simulations can vividly demonstrate mission goals. With a small incremental investment, mission-oriented theory challenges multiply the science obtained by each new probe and space telescope. Together with a vigorous ATP to address cross-cutting and basic astrophysical research that points to the next generation of missions, the theory challenge model ensures that the return on NASA's investments is optimized.

Laboratory Astrophysics

By using a combination of laboratory experiments, modeling, and theoretical calculations, the laboratory astrophysics program provides the fundamental knowledge needed to make sense of data collected by space missions and to plan them initially. Laboratory measurements are often an essential link between observations and scientific conclusions. The program explores a tremendous breadth of topics, from the very coldest regions deep in molecular clouds, to the extraordinary environments around supermassive black holes, and to the surfaces of icy bodies at the edge of our solar system. It supports NASA's space missions from conception to completion, defining mission parameters, providing post-flight analysis, and opening new discovery space for future observations.

Ground-Based Observations in Support of NASA Missions

Missions frequently require ground-based data to devise observing strategies, assess necessary instrumental capabilities, or allow proper interpretation of data. The Keck program to characterize planet populations, for example, complements and helps define the goals for Kepler, SIM, and TPF. The Large Binocular Telescope Interferometer is tasked with determining the brightness of the exozodiacal light in other stellar systems to gauge the backgrounds TPF will encounter. The high-resolution spectroscopy planned in support of Kepler will be critical for determination of the masses and densities of Earth-like planets. The ground-based Near-Earth Asteroid Tracking (NEAT) system on Mt. Haleakala, supported by NASA, in addition to its asteroid surveys is performing studies of nearby Type Ia supernovae as part of a larger program to probe the nature of dark energy. The ground-based Robotic Optical Transient Search Experiment (ROTSE) detected the first prompt optical transient associated with a gamma-ray burst, some of which are now followed up with HST. At higher gamma-ray energies, ground-based observations of the atmospheric Cerenkov radiation from gamma-ray-induced showers at teravolt energies will complement observations by GLAST and provide critical information about the emission models. At radio and optical wavelengths, significant progress has been made in identifying the counterparts of hitherto unidentified EGRET gamma-ray blazars. A combined Very Large Array and Very Long Baseline Array radio astronomy program has begun in order to assess likely candidates for GLAST detections and to provide radio properties and reference milliarcsecond-scale images in advance of GLAST's launch.

Archival Research

Until about 25 years ago, data were collected by an investigator for a single purpose, and the investigator rarely made the data available to others. NASA changed this model by archiving space-based data, thereby making it available to all interested parties. The data are saved in standard formats, making them easy to work with, and the result is that the same data sets are used for many purposes. These data archives have proven so important that most completed missions are archived and all new missions are required to have a thoughtful archiving plan. These data reside in archive centers with expertise in specific wavebands (e.g., infrared, X-ray). The centers not only archive the data, but have helped develop software to analyze the data and extract data products that are broadly used, such as catalogs of sources.

7.4.2 The Explorer Program

Explorers offer frequent access to space and opportunities for small and medium-sized missions (SMEX and MIDEX) that can be developed and launched in an approximately four-year timeframe. These focused, cost-capped, peer-reviewed and competed missions address important science questions and respond quickly to new scientific and technical developments. The Mission of Opportunity option enables collaborations with other agencies, both National and international.

Explorer missions currently in operation address high-priority science objectives of the Astrophysics Division. WMAP, a MIDEX mission launched in 2001, is answering fundamental questions about the age and early development of the universe; WMAP is also a vital precursor to the Inflation Probe of the Beyond Einstein program. GALEX, a SMEX mission launched in 2003, is mapping the ultraviolet emission from the local universe. This provides a baseline for understanding the observations made by HST, and in the future by JWST, of ultraviolet emissions from the distant universe that have been redshifted into the optical and infrared. Swift, a MIDEX mission launched in 2004, is providing observations of gamma-ray bursts that are finally allowing us to understand the origin of these once-mysterious phenomena. These intense transient events, for a short time the most luminous sources in the universe, serve as beacons allowing the study of the universe on the largest scales and the nature of matter under extreme conditions. These are excellent targets for HST and future JWST followup. WISE, a MIDEX well into development and slated for launch in 2009, will survey the whole sky in four mid-infrared bands to sensitivities 500 or more times better than previous all-sky surveys. WISE should find the nearest stars [brown dwarfs] to the Sun and identify the most luminous galaxies in the distant universe.

Future Explorers are relevant to Beyond Einstein, including both missions of opportunity and dedicated missions. For example, laser-ranging equipment on interplanetary probes may provide precision tests of relativity in the solar system. Dedicated physics platforms could provide both precision tests of general relativity and physics beyond the standard model of particles and fields.

7.4.3 Suborbital Program: Balloons and Sounding Rockets

The Suborbital Program, comprising the sounding rocket and high-altitude balloon programs, provides unique opportunities for high-priority science; detector and instrument development; and training of students, engineers, and future PIs. Small standalone space missions like SMEX cost in excess of $100M per project, which requires low risk with a high certainty of science return. Untested technologies and high-risk science need a lower-cost avenue to space. The Suborbital Program provides an opportunity for creativity, ingenuity, and the serendipity that are essential ingredients both in scientific progress and in motivating and training the next generation. Because of its flexibility, the Suborbital Program produces a steady stream of new instrumentation and new science that leads to new questions and the evolution of new missions.

Helium-filled balloons have the capability to lift multi-ton payloads to altitudes in excess of 120,000 feet for 30-day flights and have demonstrated the capability to launch a 200-kilogram payload to 160,000 feet. A 100-day ultralong-duration flight capability is being developed. This will provide useful flight opportunities for observing campaigns associated with Beyond Einstein and for multiwavelength observing campaigns involving correlated spacecraft and ground observations.

Balloon missions are prototyping optics and detectors to extend X-ray and gamma-ray measurements in space to higher energies than are currently possible. CMB balloon flights in the 1970s to the 1990s led directly to the design of COBE and WMAP. Instruments on the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI), ACE, and EOS-Aura space missions all were developed and tested on high-altitude scientific balloon flights. Finally, coded-aperture imagers and position-sensitive gamma-ray detectors developed for hard X-ray and gamma-ray astronomy have found applications to medical imaging and national security. Future balloon launches will be needed to test room-temperature cadmium zinc telluride semiconductor detectors, X-ray focusing optics, megapixel coded-aperture gamma-ray imagers, and fast low-power multichannel electronics for Beyond Einstein's Con-X and a candidate Black Hole Finder Probe.

The sounding rocket program has a history of cutting-edge science and detector development leading up to future space missions. In over a hundred missions since 1995, the sounding rocket program's success rate has been 99 percent. High-altitude rocket flights initiated X-ray astronomy and led to the current Chandra mission and a share of the 2002 Nobel Prize for Riccardo Giacconi. Initial rocket observations of the soft X-ray cosmic background led to later measurements with Chandra, the Italy–Netherlands Satellite per Astronomia X (BeppoSAX), and the Germany–U.S.–U.K. Roentgen Observatory Satellite (ROSAT).

7.4.4 Technology Enables Discovery

NASA missions incorporate extraordinary technologies that allow them to accomplish extraordinary science. The technological demands of future missions are even more rigorous, and the scientific goals more ambitious. Studying the first objects and most distant supernovae, peering into a black hole, detecting gravitational waves, penetrating star-forming cocoons and finding other Earths require significant advances in key space technologies. JWST will carry a mirror with seven times the area of HST's that will open like the leaves of a folding table on the way to its distant orbit. Its light-gathering power will enable JWST to discover the first galaxies and quasars. SIM will detect the tiny wobble of a distant star being tugged by an orbiting planet. Con-X will operate new-technology array detectors, cooled to just 0.05 degree above absolute zero, to track X-ray-emitting plasma falling into the event horizon of a black hole. LISA will sense the relative positions of its component telescopes, measuring their 5-million-kilometer separations with phenomenal accuracy—to within a fraction of an atomic diameter—to detect the ghostly signal of a passing gravitational wave as it ripples spacetime.

Strategic Technologies

Astrophysics science missions require advances in four strategic technology areas: telescopes—the structures, optics, and wavefront controls to focus electromagnetic radiation with superb accuracy and minimum mass; detectors—devices that convert light to countable units; coolers—methods for cooling telescopes and detectors to achieve very low noise and correspondingly high sensitivity; and distributed spacecraft—the ability to fly spacecraft in coupled formations, measuring and maintaining their relative positions to extraordinary precision to synthesize very-large-aperture telescopes using an interferometer configuration.

Many of NASA's most challenging technology needs are, at least initially, unique to the NASA application. The Astrophysics Division can point to a proud tradition of pioneering technology developments: examples are the charge-coupled device (CCD) detectors used on HST, the super-polished X-ray mirrors which enable Chandra, and the ingenious radiative-cryogenic cooling system which makes Spitzer possible. In each of these cases, and in many more, the flight development was done in partnership with the aerospace industry. This partnership therefore results not only in timely availability of the newly developed items to NASA but also in a transfer of the technical expertise to the private sector. Future progress in Astrophysics depends on continued technology developments, as outlined below. Robust support for this development through a mix of NASA Center, University-based, and industrial activities must continue to be a part of the Astrophysics Division's activities. This requires funding both for low TRL activities through R&A programs and development of technologies for flight through either program level or mission-specific investments.

Telescopes

Telescopes consist of optics to collect and concentrate radiation, wavefront sensing and control technologies to compensate for unwanted surface irregularities, and metrology and structures technologies to control the separation of the optical elements. In some cases, the deployment of large telescope structures requires that they be lightweight and fold up within a launch vehicle shroud. For telescopes of all types, there is a premium on lightweight optics because the mass of the telescope drives the mass of the entire spacecraft. Thus, Con-X requires lightweight grazing incidence X-ray optics with a tenfold increase in the effective area-to-mass ratio. The mirrors must be smooth to an accuracy of 0.04 nanometer with hundreds of nested shells aligned to tolerances less than a micron, requiring new methods of assembly and metrology. Very precise wavefront control and straylight control are demanded by missions like the coronagraphic realization of TPF, which requires the suppression of starlight by more than nine orders of magnitude so that a faint nearby planet can be not only detected but also studied in detail.

Many applications require high angular resolution. In this case, individual mirrors are arrayed to synthesize a large-aperture telescope system called an interferometer. Angular resolution 10 to 1,000 times that available with single-aperture telescopes is possible using an array of formation-flying telescopes in the configuration of an interferometer. Telescopes and interferometers are central technology challenges to the science goals for imaging black hole horizons and galaxies near the edge of the universe; interferometers can also be used to test the foundations of general relativity.

Detectors

In the optical and near-infrared regimes, NASA leverages well-developed commercial capabilities to realize large, high-quantum-efficiency focal planes with up to the one billion pixels that may be needed to discover and monitor distant supernovae for one candidate implementation of the Dark Energy Probe. At mid- and far-infrared wavelengths, SOFIA will require large format arrays of photo-conductors, bolometers, and heterodyne mixers for high spectral resolution imaging of interstellar lines from star and planet forming regions. In the millimeter-wave spectral region, the Inflation Probe may require arrays of superconducting detectors to measure the faint polarization of the cosmic microwave background radiation produced by inflation. Minimizing detector system mass and power dissipation are essential technologies for operating these detectors in a space mission. Here NASA's requirements are unique and demand the type of targeted technology development highlighted earlier.

Synergy exists between X-ray and far-infrared/submillimeter-wave detectors. Con-X, SOFIA, and one Inflation Probe candidate need multiplexed calorimeter and bolometer arrays to meet the energy resolution and sensitivity requirements in the soft X-ray band and to realize large-format, high-sensitivity polarimeters for the submillimeter. Multiplexing readout electronics enable the construction of focal plane arrays by combining signals directly at the low-temperature focal plane. Both regimes are developing transition-edge sensors and superconducting quantum interference device multiplexers. Kinetic inductance detectors also hold promise and may be multiplexed with room-temperature electronics.

Coolers

A telescope on Earth's surface, operating at room temperature, glows brightly at infrared-to-millimeter wavelengths, masking the faint incoming celestial radiation. By cooling the entire observatory, a spaceborne facility is orders of magnitude more sensitive than a ground-based telescope. A key element of the cooling systems for future telescopes will be extensive use of radiative cooling, as implemented by Spitzer. This can be readily implemented in the L2 or other heliocentric orbits envisioned for future missions such as JWST. This will make it that much easier for multistage systems culminating in new subkelvin coolers to reach the ultralow temperatures required for calorimeter and bolometer focal planes, providing more heat lift, continuous operation, and high-temperature stability. Adiabatic demagnetization refrigerators, ^{3}He sorption coolers, and open-cycle dilution refrigerator precursor technologies show many of the attributes needed to meet these requirements. In the future, mechanical coolers, including microfabricated focal-plane coolers, which may cool just the detectors themselves, will be of increasing importance.

Distributed Spacecraft

Higher angular resolutions can be realized only with optical elements spaced so far apart that they can no longer be fabricated as a single aperture. Deployment of optical components and sensors on separate spacecraft, each of which may be launched separately, can form optical systems with large baselines and high resolution. Formation-flying techniques hold the components in alignment, using precision control of the spacecraft motions to form images. Carrying out this type of spacecraft coordination requires extremely stable gyros, precise star trackers, laser ranging systems between spacecraft referenced to highly accurate frequency standards, and micronewton-force thrusters to perform minute positional adjustments. Spacecraft-control algorithms need to be developed for continuous high-reliability monitoring, formation flying, reconfiguration, reorientation, and autonomous recovery. LISA will demonstrate advanced formation-flying techniques in order to detect the minute warping of spacetime as gravitational waves move through the solar system. LISA will sense gravitational waves by measuring the relative displacements of inertial test masses contained in each spacecraft separated by millions of kilometers to *picometer* accuracy. The three spacecraft that make up the LISA interferometer will use newly developed micronewton thrusters to control the spacecraft position and lasers with output stabilized to 1,000 times the stability of commercial lasers.

7.4.5 Education and Public Outreach

In studying the origin and evolution of the universe, Astrophysics tells a story that is fascinating to the public. The missions carried out by the Astrophysics division address profound questions that intrigue all: How did the universe begin and evolve? How did life arise? Are we alone? These questions easily lend themselves to engaging the public in our quest for knowledge.

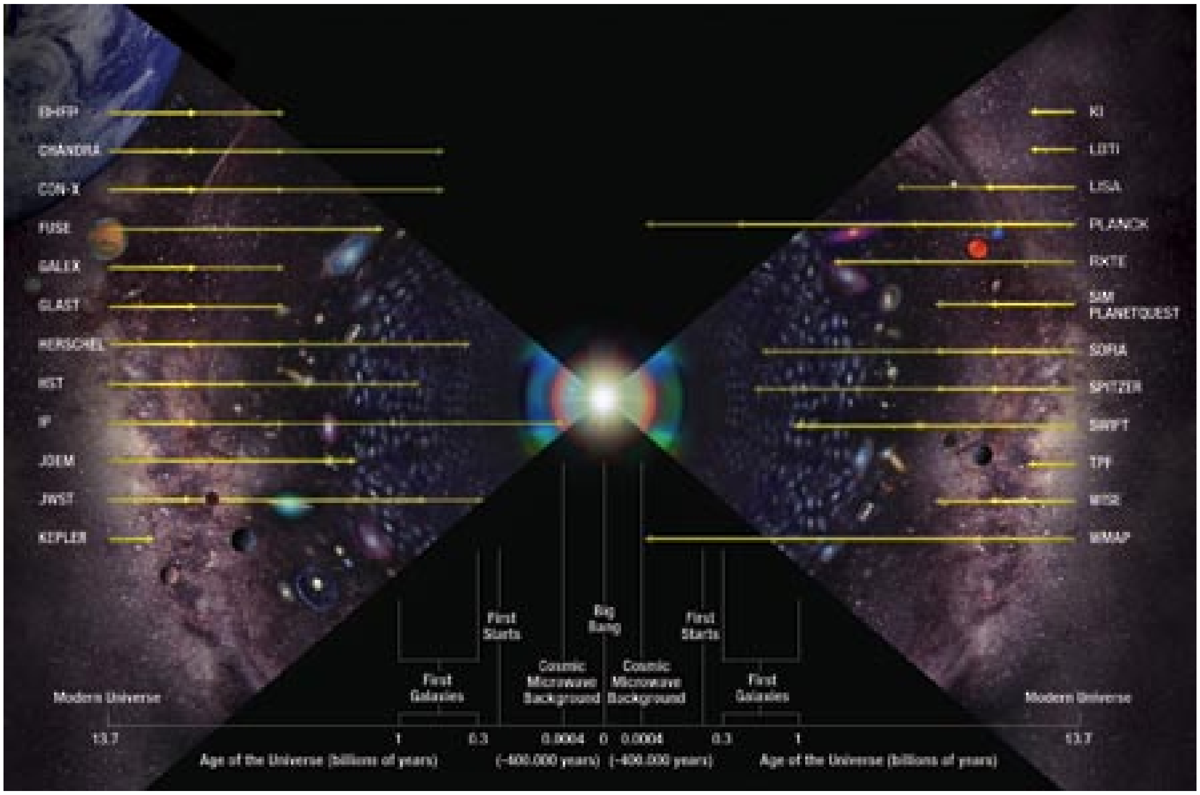
The Astrophysics Division's E/PO programs for existing missions such as Hubble, Chandra, and Spitzer have already blazed trails in increasing public engagement and student involvement in astrophysics. Astrophysics E/PO programs reach millions of Americans and serve to increase interest and participation in STEM subjects, thus strengthening NASA and the Nation's future workforce. The exciting suite of future missions described above shows that we are standing today at the edge of discoveries that could reveal in detail how the universe began, trace its evolution, and even discover whether we are truly alone in the universe. This offers tremendous potential to meaningfully engage the public in the process of scientific endeavor and take them along on this exciting journey. One means is to enable active participation by the public and students in mission development and operations—perhaps via student experiments or through involvement in helping to analyze data. For example, the SOFIA mission may offer a unique opportunity to engage teachers and students in real-time observing experiences by permitting them to fly on the SOFIA airplane alongside scientists. Students will learn the scientific process of designing experiments and obtaining, analyzing and interpreting data. Programs such as Beyond Einstein and Navigator offer the opportunity to develop thematic E/PO programs that can tell a large variety of audiences the story of the universe and how all the various pieces fit together—the study of our origins, the study of black holes and galaxies, what the universe is made of, and a census of extrasolar planets and which of those might harbor life. As they are multimission programs spanning decades, they offer the opportunity to involve young students in missions that they might one day also be a part of as adults.

Astrophysics missions continue to capitalize on high-visibility events, such as professional meetings of scientists, engineers, and school teachers, by organizing booths and related activities to engage the participants and the press. Exhibitions in museums and planetaria have also been highly popular and reach a vast audience. The Astrophysics Division is also participating in the International Year of Astronomy (IYA), sponsored by the United Nations for the year 2009, and is planning educational activities coordinated with that event.

7.5 Astrophysics Beyond 2016

The larger part of the Beyond Einstein program and the TPF missions will be implemented beyond 2016. In addition, a set of "vision missions" concepts have been identified for the decade beyond 2016 as a means of helping to identify future directions for Astrophysics research and technology challenges to be overcome on the way.

Figure 7.12



Looking Far Away and Long Ago

As we look at more deeply into the universe, we are peering back in time. Astrophysics missions allow us to study the universe at various stages of its existence, from close to its birth to the present.

The James Webb Space Telescope

Over 1000 people in more than 17 countries are developing the James Webb Space Telescope. Shown here are team members in front of the JWST full-scale model at the Goddard Space Flight Center in Greenbelt, Maryland.

8 Science and Human Exploration

The United States, led by NASA, is accelerating a journey of exploration into the solar system and beyond. Human explorers will return to the Moon by 2020, then will venture further into space, ultimately to Mars and beyond. The fundamental goal of the *Vision for Space Exploration* is "to advance U.S. scien tific, security, and economic interests through a robust space exploration program." The Science Mission Directorate leads the Agency in pioneering scientific discovery and plays a vital role in advancing U.S. Earth and space science interests in the context of the *Vision*.

Chapter 8

Science and Human Exploration

The expansion of the human sphere beyond low Earth orbit will create opportunities for scientific discovery at every step. This Science Plan provides the framework and direction for realizing those opportunities.

There is extensive cross-fertilization between human exploration and science. The report of the President's Commission on Implementation of U.S. Space Policy found that "Science has held key position in America's space program since its inception nearly 50 years ago and remains an integral reason for exploring space. Science and exploration are synergistic: science is the attempt to explain nature, while exploration is the establishment and pushing back of a frontier. New frontiers reveal new and unprecedented natural phenomena, for which science is called upon to offer explanations. The Commission finds implementing the space exploration vision will be enabled by scientific knowledge, and will enable compelling scientific opportunities to study Earth and its environs, the solar system, other planetary systems, and the universe. Science in the space exploration vision is both *enabling* and *enabled*."

New scientific understanding is critical to enable the successful human exploration of the Moon and other destinations. One of the objectives of NASA's Heliophysics Science Program is to *Safeguard the Journey of Exploration*. NASA is undertaking the science investigations necessary to maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space. The Planetary Science Program is addressing the question, *What are the potential hazards to humans in the space environment and are there resources that would enable a human presence away from the Earth?* Instruments and techniques designed to conduct robotic scientific investigations of the planets and other bodies in the solar system are now being turned toward the Moon in preparation for the scientific exploration of the Moon by humans.

This Science Plan includes precursor science investigations that are important for achieving the Vision for Space Exploration, including research and analysis, data analysis, and mission developments that have already begun. Some examples include the Moon Mineralogy Mapper experiment on Chandrayaan-1, the Mars Science Laboratory, the Solar Dynamics Observatory, and the research and data analysis programs in planetary science, heliophysics, and other disciplines. Additional precursor science investigations are also underway, but are beyond the scope of this Science Plan. The Exploration Systems Mission Directorate (ESMD) is undertaking the exploration research required to enable human exploration. One example is research required to ensure human health and safety. Further, ESMD is contributing the Radiation Assessment Detector instrument on the SMD's Mars Science Laboratory mission.

NASA is in the process of engaging the science community in developing and prioritizing the scientific studies that will form the backbone of the exploration science program. We are identifying the opportunities available to the scientific community—all branches—to do things that would not previously have been possible now that we are returning humans to the Moon, will be going to Mars, and will be creating the option to explore and utilize the near-Earth asteroids. The program of human exploration allows provides new venues for scientific discovery. We are now asking the question *what will we do at these places that we could not previously have planned to do?*

NASA is also developing the exploration architectures and systems necessary to enable both human exploration and new science opportunities. ESMD leads these activities; SMD participates in both strategy and architecture development to ensure compatibility and opportunity for science. The Mission Directorates are working closely together to undertake the high-priority science investigations that will enable the exploration program as well as the compelling science investigations that are enabled by the human and robotic exploration program.

A near-term priority is the identification of high-priority science investigations enabled by the first stop on the journey of exploration, the Moon. NASA has requested a study by the NRC Space Studies Board on lunar science priorities. NASA is also conducting and participating in community-based workshops and roadmapping activities, including a NAC sponsored workshop in early 2007. Funded opportunities for both studies and investigations will be openly competed and peer reviewed, consistent with SMD practices described in this Science Plan, beginning with a solicitation in 2006 for proposals from the science community for concepts for lunar surface science. When the time is right, a solicitation for scientific analysis of Lunar Reconnaissance Orbiter data will be issued. The potential range of science investigations is quite broad, but generally falls into four categories: science of the Moon (research with the Moon as the subject), science on the Moon (use of the Moon as a laboratory), science from the Moon (use of the Moon as a platform), and science near the Moon (research concerning the trans- and cis-lunar space environment). These activities and studies will identify compelling science investigations that are enabled by human exploration and address NASA's strategic science objectives. NASA, under the leadership of SMD, will undertake the highest-priority science investigations.

NASA has well-established, community-based processes to ensure that its science investigations are effective, relevant, and of the highest science quality. SMD will use these processes to identify science opportunities and establish priorities for exploration-enabled science activities. Recognizing that exploration-enabled science opportunities must compete with ongoing and planned science activities for resources, it is important to prioritize exploration-enabled science activities in the context of the rest of the SMD program. An important question to answer during the time period covered by this Science Plan is whether the science activities enabled by the human exploration program and identified as compelling by the science community have greater or lesser priority than activities previously planned by SMD.

The *Vision for Space Exploration* provides both the impetus and the opportunity for the science that enables exploration and for the science that is enabled by exploration. Human exploration of space beyond low Earth orbit is a core element of the Vision and, hence, of this Science Plan. NASA's Science Mission Directorate has a vital role in advancing the scientific interests of the United States as part of this national vision.

9 Summary

At the Brink of Understanding

Chapter 9

Summary—At the Brink of Understanding

At the beginning of the 20th century, whole new vistas opened in scientific knowledge. Einstein's theories of relativity and Planck's quantum mechanics opened new ways of thinking about the universe. The work of Rutherford, Bohr, Thomson and others peered inside the atom. Bethe discovered that the fusion of hydrogen atoms powers the Sun. Ever-larger telescopes revealed the amazing diversity of planetary bodies in our solar system and the wonders of stars and galaxies beyond. Swedish scientist Svante Arrhenius asked the important question "Is the mean temperature of the ground in any way influenced by the presence of the heat-absorbing gases in the atmosphere?" For the past nearly 50 years, NASA has used its unique capabilities in space exploration and aeronautics to test and build upon these discoveries. NASA's ability to provide the vantage point of space and to attack scientific questions in a program management mode has led to substantial progress, with a stream of new discoveries that has become a veritable river in recent years.

Now at the beginning of the 21st century, humanity is poised for another great era of discovery. NASA and its partners are leading many of these paths of inquiry. We have measured the age of the universe, and we are close to being able to read its history and project its future. We have discovered over 180 planets around other stars, and we can conceive of means to survey our neighborhood in the galaxy and detect, if they exist, Earth-like planets. We have discovered water in what were thought to be unlikely places in our solar system, and we can devise probes to explore those places in search of life or its precursors. We have observed violent solar flares and their impacts in Earth's neighborhood and beyond to the edge of the solar system, and we can envision the potential to "instrument the solar system" to enable monitoring and prediction of events and phenomena that may affect human and robotic explorers. We have put in place the first capability to observe all the major components of the Earth system, and we can see a way forward to understanding and predicting the causes and consequences of Earth system change.

In short, we are at the brink of understanding. While we do not yet see the answers, the pathways to many of them lie open before us. We are limited by resources, not navigation. Other National endeavors lay claim on the same pool of resources, and it is incumbent upon NASA's Science Mission Directorate to exercise wise stewardship of the American taxpayers' investment. This Science Plan describes how we will use those resources to return the new scientific understanding and benefits anticipated in the Vision for Space Exploration, other Presidential initiatives, and Congressional direction. And if the past is prologue, our discoveries will lead us to yet greater vistas beyond.

Appendices

Appendix 1: Strategic Goals and Decadal Outcomes

These outcome statements serve as benchmarks against which our sponsors in the Executive and Legislative branches and our stakeholders in the science community measure our progress (augmented by subordinate annual performance goals).

Strategic Goal 3.1: Study planet Earth from space to advance scientific understanding and meet societal needs

1. Progress in understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition.
2. Progress in enabling improved predictive capability for weather and extreme weather events.
3. Progress in quantifying global land cover change and terrestrial and marine productivity, and in improving carbon cycle and ecosystem models.
4. Progress in quantifying the key reservoirs and fluxes in the global water cycle and in improving models of water cycle change and fresh water availability.
5. Progress in understanding the role of oceans, atmosphere, and ice in the climate system and in improving predictive capability for its future evolution.
6. Progress in characterizing and understanding Earth surface changes and variability of the Earth's gravitational and magnetic fields.
7. Progress in expanding and accelerating the realization of societal benefits from Earth system science.

Strategic Goal 3.2: Understand the Sun and its effects on Earth and the solar system

1. Progress in understanding the fundamental physical processes of the space environment from the Sun to Earth, to other planets, and beyond to the interstellar medium.
2. Progress in understanding how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields.
3. Progress in developing the capability to predict the extreme and dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers.

Strategic Goal 3.3: Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space.

1. Progress in learning how the Sun's family of planets and minor bodies originated and evolved.
2. P
   origin and evolution of Earth's biosphere and the character and extent of prebiotic chemistry on Mars and other worlds.
3. Progress in identifying and investigating past or present habitable environments on Mars and other worlds, and determining if there is or ever has been life elsewhere in the solar system.
4. Progress in exploring the space environment to discover potential hazards to humans and to search for resources that would enable human presence.

Strategic Goal 3.4: Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets

1. Progress in understanding the origin and destiny of the universe, phenomena near black holes, and the nature of gravity.
2. Progress in understanding how the first stars and galaxies formed, and how they changed over time into the objects we recognize in the present universe.
3. Progress in understanding how individual stars form and how those processes ultimately affect the formation of planetary systems.
4. Progress in creating a census of extra-solar planets and measuring their properties.

In the Executive branch, assessment of progress is conducted by the Office of Management and Budget with its Performance Assessment and Rating Tool (PART). In the Legislative branch, the assessment is conducted via the annual Performance Plan and Performance Report required under the Government Performance and Results Act (GPRA). For the latter, a panel of external scientific experts reviews and rates NASA's progress annually against its plan. In addition, the NASA Authorization Act of 2005 requires that the National Research Council review and assess the performance of each division in NASA's Science Mission Directorate, and requires NASA to report to the Congress each year on the results of these and other external reviews and actions NASA has taken in response.

Appendix 2*: Missions Identified in Recent NRC Decadal Surveys

Earth Science and Applications from Space (NRC, 2005; Interim report) (Earth Science)	Status in Plan
Global Precipitation Measurement (GPM)	In development
Atmospheric Soundings from Geostationary Orbit (GIFTS)	No
Independent studies for:	
Ocean Vector Winds	No
Landsat Data Continuity	In development
Glory	In development
Earth System Science Pathfinder missions at a rate of 1 per year	Yes, at greatly reduced rate

The Sun to the Earth and Beyond (NRC, 2002) [Heliophysics]	Status in Plan
Large Missions	
Solar Probe	Future strategic mission
Medium Missions	
Magnetospheric Multiscale	In development
Geospace Network	RBSP in development; ISTP is future strategic mission
Jupiter Polar Mission	Juno mission in development
Multispacecraft Heliospheric Mission	Future strategic mission
Geospace Electrodynamic Connections	Future strategic mission
Suborbital Program	Yes
Magnetospheric Constellation	No
Solar Wind Sentinels	No
Stereo Multispheric Imager	No

*The missions are presented in the order in which they appear in the NRC decadal survey documents noted, which reflect the NRC priorities given the conditions and constraints relevant at the time of publication.

Appendix 2: Missions Identified in Recent NRC Decadal Surveys—Continued

Small Flight Missions	
Endorsed Explorer-class missions	Yes, at reduced rate
Endorsed University-Class Explorers	No
Endorsed Approved NASA Missions	
Solar Dynamics Observatory	In development

New Frontiers in the Solar System (NRC, 2003) [Planetary Science]	Status in Plan
Solar System:	
Large Flight Missions	
Europa Geophysical Explorer	Future strategic mission
Medium Flight Missions	
Kuiper Belt-Pluto Explorer	Mission launched in 2006
South Pole-Aitken Basin Sample Return	New Frontiers mission candidate[2]
Jupiter Polar Orbiter with Probes	Juno mission in development
Venus In-situ Explorer	New Frontiers mission candidate[2]
Comet Surface Sample Return	New Frontiers mission candidate[2]
Small Missions	
Discovery missions at one launch every 18 months	Yes, at reduced rate
Cassini extended	Subject to 2007 Senior Review
Mars:	
Large Missions	
Mars Sample Return	No
Medium Missions	
Mars Science Laboratory	In development
Mars Long-lived Lander Network	In consideration for 2016 opportunity

Appendix 2: Missions Identified in Recent NRC Decadal Surveys—Continued

Small Missions	
Mars Scout line	Yes
Mars Upper Atmosphere Orbiter	May be fulfilled by MSO

Astronomy and Astrophysics in the New Millennium (NRC, 2001) [Astrophysics]	Status in Plan
Major Initiatives (space-based)	
Next Generation Space Telescope (now James Webb Space Telescope)	In development
Constellation-X Observatory	Beyond Einstein candidate[1]
Terrestrial Planet Finder (TPF)	Future strategic mission
Single Aperture Far Infrared (SAFIR) Observatory	No
Moderate Initiatives (space-based)	
Gamma-ray Large Area Space Telescope (GLAST)	In development
Laser Interferometer Space Antenna (LISA)	Beyond Einstein candidate[1]
Solar Dynamics Observatory (SDO)	In development
Energetic X-ray Imaging Survey Telescope (EXIST)	Beyond Einstein candidate[1]
Advanced Radio Interferometry between Space and Earth (ARISE)	No
Reaffirms Missions from Previous Decadal Survey:	
Stratospheric Observatory for Infrared Astronomy (SOFIA)	In development
Space Interferometry Mission (SIM)	Future strategic mission
Hubble Space Telescope 4th Servicing Mission	In development
Endorsed continuation of vigorous Discovery and Explorer programs	Yes, at reduced rate
From Quarks to the Cosmos (NRC, 2003) [Astrophysics – not a decadalsurvey, but the source of the Beyond Einstein program]	
"wide field telescope in space...to fully probe the nature of dark energy" –NASA/DOE implementation: Joint Dark Energy Mission (JDEM)	Beyond Einstein candidate[1]
"measure the polarization of the cosmic microwave background" – NASA implementation: Inflation Probe	Beyond Einstein candidate[1]

Appendix 3: References

The following documents were used in development of this Science Plan:

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Other Reviews of the draft Science Plan

Letters forwarding recommendations of the NASA Advisory Council Science Subcommittees;
all available at: *http://science.hq.nasa.gov/strategy/NAC_sci_subcom/index.html*

Letters forwarding recommendations of the NASA Advisory Council; all available at:
http://www.hq.nasa.gov/office/oer/nac/minsmenu.html

Industry Comments (available upon request)
NASA Science Associates Group
- Consensus Views
- Consolidated Comments Submitted

Appendix 4: Abbreviations and Acronyms

Abbreviations and Acronyms	Definition
AFL	Astrobiology Field Laboratory
AGN	Active Galactic Nuclei
AIRS	Atmospheric InfraRed Sounder
AIST	Advanced Information System Technology
ALP	Alternate Launch Providers
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AMSU	Advanced Mircowave Sounding Unit
AO	Announcement of Opportunity
ATI	Advanced Technology Initiative
AVGR	Ames Vertical Gun Range
BHFP	Black Hole Finder Probe
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CCD	Charge-coupled device
CCSP	Climate Change Science Program
CDM	Cold Dark Matter
CENR	Committee on Environment and Natural Resources
CERES	Cloud and the Earth’s Radiant Energy System
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CMB	Cosmic Microwave Background
CME	Coronal Mass Ejection
CNES	French Space Agency (Centre National d’Etudes Spatiale)
CO	Carbon monoxide
CO_2	Carbon dioxide
CONTOUR	Comet Nucleus Tour
Con-X	Constellation-X
COSPAR	Committee on Space Research of the International Council of Scientific Unions
DAAC	Distributed Active Archive Center
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Rahmfahrt)
DoD	Department of Defense
DOE	Department of Energy
DSN	Deep Space Network
EDL	Entry, Descent and Landing
EPA	Environmental Protection Agency
E/PO	Education and Public Outreach
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
ESA	European Space Agency
ESMD	Exploration Systems Mission Directorate (NASA)

Appendix 4: Abbreviations and Acronyms

Abbreviations and Acronyms	Definition
ESSP	Earth System Science Pathfinder
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FTS	Fourier Transform Spectrometer
FY	Fiscal Year
GALEX	Galaxy Evolution Explorer
GEC	Geospace Electrodynamic Connections
GEO	Geostationary orbit
GEOSS	Global Earth Observation System of Systems
GLAST	Gamma-ray Large Area Space Telescope
GN	Ground Network
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery And Interior Laboratory
HAWC	High-resolution Airborne Wide-bandwith Camera
HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
ICESat	Ice, Clouds and land Elevation Satellite
IDS	Interdisciplinary Science
IGM	Intergalactic Medium
IHS	Inner Heliospheric Sentinels
IIP	Instrument Incubator Program
IP	Inflation Probe
IPO	Integrated Program Office
IPCC	Intergovernmental Panel for Climate Change
ITSP	Ionosphere/Thermosphere Storm Probes
JAXA	Japanese Space Agency (Japan Aerospace Exploration Agency)
JDEM	Joint Dark Energy Mission
JIMO	Jupiter Icy Moons Orbiter
JWG	Joint Working Group
JWST	James Webb Space Telescope
L1	Lagrange point 1
LAGEOS	Laser Geodynamic Satellites
LDCM	Landsat Data Continuity Mission
LEAG	Lunar Exploration Analysis Group
LEO	Low Earth Orbit
LASCO	Large Angle and Spectrometric Coronagraph Experiment

Appendix 4: Abbreviations and Acronyms

Abbreviations and Acronyms	Definition
LISA	Laser Interferometer Space Antenna
LPRP	Lunar Precursor Robotic Program
LWS	Living With a Star
M3	Moon Mineralogy Mapper
MEO	Medium Earth Orbit
MEPAG	Mars Exploration Planning and Analysis Group
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MIDEX	Medium Explorer
ML^3N	Mars Long-lived Lander Network
MMS	Magnetospheric Multiscale
MODIS	Moderate Resolution Imaging Spectrometer
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NEAR	Near-Earth Asteroid Rendezvous
NEWS	NASA Energy and Water cycle Study
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NIMA	National Geospatial-Intelligence Agency
NPP	NPOESS Preparatory Project
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OCO	Orbiting Carbon Observatory
OPAG	Outer Planets Analysis Group
ORISIS	Origins Spectral Interpretation, Resource Identification, and Security
OSTM	Ocean Surface Topography Mission
NEAR	Near Earth Asteroid Rendezvous
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PDS	Planetary Data System
PI	Principal Investigator
OSTP	Office of Science and Technology Policy
R&A	Research and Analysis
RBSP	Radiation Belt Storm Probes
RF	Radio Frequency

Appendix 4: Abbreviations and Acronyms

Abbreviations and Acronyms	Definition
ROSES	Research Opportunities in the Space and Earth Sciences
SAR	Synthetic Aperture Radar
SDO	Solar Dynamics Observatory
SESWG	Solid Earth Sciences Working Group
SFA	Science Focus Area
SHARC	Submillimeter High Angular Resolution
SIM	Space Interferometry Mission
SMBH	Super Massive Black Holes
SMD	Science Mission Directorate (NASA)
SMEX	Small Explorer
SOFIA	**Stratospheric Observatory for Infrared Astronomy**
SOHO	Solar and Heliospheric Observatory
SOMD	Space Operations Mission Directorate (NASA)
SORCE	Solar Radiation and Climate Experiment
SPIRE	Spectral and Photometric Imaging Receiver
STEM	Science, Technology, Engineering and Mathematics
STIS	Space Telescope Imaging Spectrograph
STP	Solar Terrestrial Probes
TIROS	Television InfraRed Observation Satellite
TPF	Terrestrial Planet Finder
TRACE	Transition Region and Coronal Explorer
TRMM	Tropical Rainfall Measuring Mission
TR&T	Targeted Research and Technology
USAF	United States Air Force
USGS	United States Geological Survey
VExAG	Venus Exploration Analysis Group
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe
XMM	X-ray Multi-Mirror