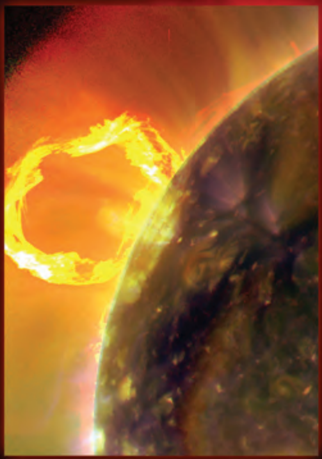
National Aeronautics and Space Administration

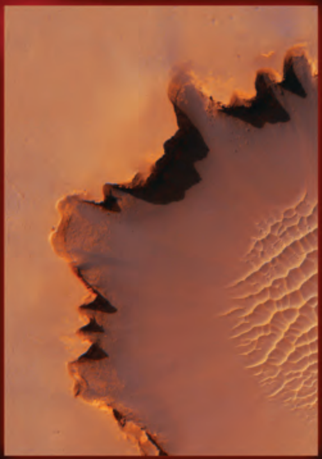
2010 Science Plan

For NASA's Science Mission Directorate

EARTH SCIENCE



HELIOPHYSICS



PLANETARY SCIENCE

ASTROPHYSICS

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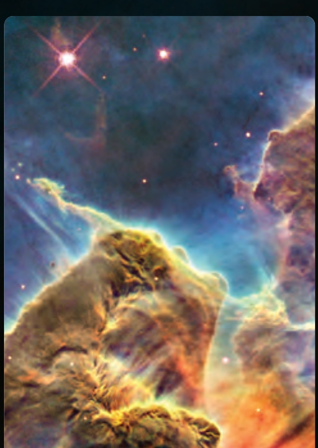
Science Plan

Table of Contents



Chapter 1

Our Journey of Discovery

NASA leads the nation on a great journey of discovery, seeking new knowledge and understanding of our planet Earth, our Sun and solar system, and the universe out to its farthest reaches and back to its earliest moments of existence. NASA's Science Mission Directorate (SMD) and the nation's science community use space observatories to conduct scientific studies of the Earth from space, to visit and return samples from other bodies in the solar system, and to peer out into our Galaxy and beyond.

Chapter 1

NASA's science program seeks answers to profound questions that touch us all:

- How and why are Earth's climate and the environment changing?
- How and why does the Sun vary and affect Earth and the rest of the solar system?
- How do planets and life originate?
- How does the universe work, and what are its origin and destiny?
- Are we alone?

Chapters 2 and 3 describe SMD's goals and processes in pursuit of the answers.

From space, researchers view the Earth as a planet and study it as a complex, interacting dynamic system with diverse components: the oceans, atmosphere, continents, ice sheets, and life itself. We observe and track global-scale changes, connecting causes to effects, and we study regional changes in their global context. We observe the role that human civilization increasingly plays as a force of change. Through our partnerships with other agencies (e.g., NOAA, USGS, EPA) that maintain forecast and decision support systems, we improve national capabilities to predict climate, weather, and natural hazards; to manage resources; and to develop environmental policy. NASA's Earth Science is an essential part of the national and international efforts to understand global change and use Earth observations and scientific understanding in service to society. The Earth Science program is described in Chapter 4.1.

At the dawn of the space age and the birth of NASA, we discovered that the Earth and its space environment were linked in unexpected ways. Explorer 1 and Mariner 2 discovered that planets are not simply illuminated and warmed by the Sun, but that planetary atmospheres and magnetospheres interact with the Sun through energetic particle showers and magnetic fields. We learned that Earth is embedded in the volatile atmosphere of the Sun, a main-sequence star midway through its life. Thus was born the scientific discipline of heliophysics. Solar radiation drives the climate system and sustains the biosphere of Earth. Solar particles and magnetic field fluxuations shape radiation belts, create high-altitude winds, heat the ionosphere, and alter the ozone layer. The resulting space weather affects radio and radar transmissions, gas and oil pipelines, electrical power grids, and spacecraft electronics and orbital dynamics. We seek to understand how and why the Sun changes over time, how planetary systems respond, and how in-space and terrestrial systems are affected. As our human presence expands beyond the confines of Earth, this science enables the space weather predictions necessary to safeguard the journeys of human and robotic explorers. The Heliophysics program in described in Chapter 4.2.

We extend humankind's virtual presence throughout the solar system via robotic space probes to Earth's moon, to other planets and their moons, to asteroids and comets, and to icy bodies of the outer solar system. We are continuing humankind's reconnaissance of the Solar System by sending missions to fly by Pluto and to visit two world-sized asteroids, Ceres and Vesta. We are also in the midst of a large-scale investigation of Mars, launching a series of ever more capable orbiters, landers, and rovers, with the long-term goal of a sample return mission. And we are focusing research on the moons of Jupiter and Saturn where we see intriguing signs of surface activity and of liquid water within, knowing that on Earth, where there is water and an energy source, there is also life. The Planetary Science program is described in Chapter 4.3.

We are learning wondrous things about our physical universe—the Big Bang and black holes, dark matter and dark energy, and the interrelated nature of space and time. Theories explaining these phenomena challenge NASA scientists to develop new observations that can test these theories and our understanding of fundamental physics. We have measured the age of the universe, and now seek to explore its ultimate extremes—its birth, the edges of space and time near black holes, and the mysterious dark energy filling the entire universe. Our space missions are using nearly the full spectrum of electromagnetic radiation to observe the cosmos, yet we plan to go even further. We will have *a wholly new spectrum* in which to observe the universe, that of gravitational radiation, waves of spacetime itself. We are seeking to understand the diversity of planets and planetary systems in our galaxy. With hundreds of large planets around other stars now found, we seek to find Earth-like planets in other solar systems, and then to look for the signs of life in these locations. The Astrophysics program is described in Chapter 4.4.

NASA's journey of scientific discovery also helps motivate, support, and prepare for human expansion into the solar system. Science missions characterize the radiation environment of deep space, the pressures and compositions of planetary atmospheres, the terrain and geology of planetary surfaces, and the nature and origin of small bodies. They identify the hazards and resources present as humans explore space and the science questions and regions of interest that warrant detailed examination by human explorers.

This is NASA's science vision: using the vantage point of space to achieve with the science community and our partners a deep scientific understanding of our planet, other planets and solar system bodies, the interplanetary environment, the Sun and its effects on the solar system, and the universe beyond. In so doing, we lay the intellectual foundation for the robotic and human expeditions of the future while meeting today's needs for scientific information to address national concerns, such as climate change and space weather. At every step we share the journey of scientific exploration with the public and partner with others to substantially improve science, technology, engineering, and mathematics (STEM) education nationwide. SMD's Education program is described in Chapter 5.

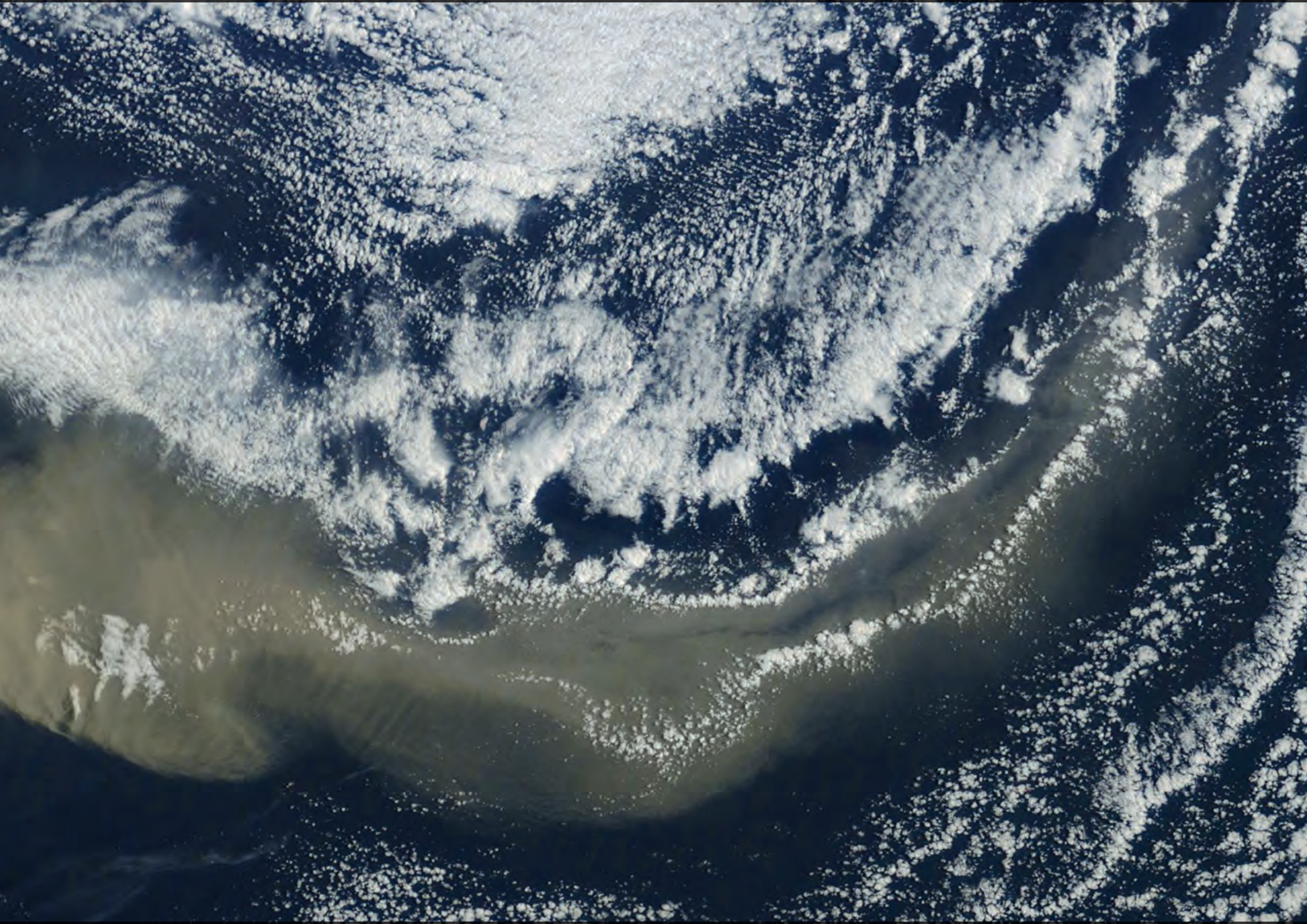
Over 55 NASA and NASA-partnered science missions are now in operation in space. Over 25 new science missions are currently in development, with several more being prepared to begin development. Scientific priorities for future missions are guided by decadal surveys produced by the National Research Council of the National Academy of Science. The first Earth Science decadal survey was published in early 2007. The next three years will see the release in succession of new decadal surveys in Astrophysics, Planetary Science, and Heliophysics. NASA will use these surveys as the principal source of science community input into its planning process.

As do other Federal agencies, NASA issues a Strategic Plan every three years. To complement the NASA Strategic Plan, NASA's Science Mission Directorate produces a Science Plan at the same pace. The prior Science Plan was published in January 2007. The next edition of the Science Plan is scheduled for early 2013, and will be informed by the results of the full set of new space science decadal surveys. Between the 2007 and 2013 editions, this edition serves as an update focusing on changes to the program planned for 2010 and beyond.

This 2010 Science Plan identifies the direction NASA has received from the Administration and Congress, advice received from the nation's science community, principles and strategies guiding the conduct of our activities, and challenges we face. The plan that results enables NASA, as Administrator Bolden says, to "do the ***best*** science, not just more science."

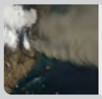
Chapter 2

The National Agenda for Science at NASA



NASA science contributes directly and substantially to current national priorities:

Leadership in Fundamental Research: NASA is a leading scientific research organization working in and across the fields of Astrophysics, Planetary Science, Heliophysics, and Earth System Science. NASA's Science Mission Directorate operates over 55 space missions, with over 25 more in development and a half-dozen mission concepts being readied to enter the development process, generating science data accessible to researchers everywhere. Over 10,000 U.S. scientists in academia, industry, and Government laboratories funded by 3,000 competitively-selected research awards are working to answer fundamental science questions of societal importance. The U.S. science community's drive for innovation is



Chapter 2

unwavering and is ready to produce the new discoveries and technologies that feed a strong economy.

Enhancing Environmental Stewardship: Understanding the causes and consequences of climate change is one of the grand challenges of the 21st century. NASA combines advanced space missions with a major Earth science and applications research program. NASA observations and research are essential contributions to the national and international scientific assessments of climate change that governments, businesses, and citizens the world over rely on in making many of their largest investment and policy decisions. NASA's work to determine the relative contributions of human-induced and naturally occurring climate change is an important scientific challenge with significant societal benefit, realized through NASA's partnerships with many other Federal agencies through the U.S. Global Change Research Program.

Educating the Next Generation and Creating a World-class Workforce: Stunning imagery from Hubble, the Solar Dynamics Observatory, Cassini, the exploits of the Mars rovers, and the successes of other space and Earth science missions fire the public imagination and inspire students to pursue STEM educations and career fields. The thousands of scientists funded by NASA are in turn training graduate students, teaching undergraduates, and providing research results for use in teacher-tested education tools. They and a like number of engineers, both at NASA and its industrial and university partners, are training their junior peers, teaching and volunteering in K-12 and informal settings, and inventing new design tools for the workforce of the future. A solid foundation in our premier Earth and space science and technology laboratories and space and suborbital missions feeds the broader U.S. technical workforce with employees that embody the values of competence, innovation, and service.

Driving Technological Innovation: NASA science missions are engines of innovation, and NASA invests in technology development in each of its four Science areas. These technologies enable the advanced space missions of the future and also find myriad applications in the broader economy, particularly in fields such as health care that rely on imaging, data mining and visualization technologies. For example, technologies and techniques developed for Hubble are now used to enhance breast cancer imaging.

Extending Partnerships Internationally and Domestically: SMD partners with a dozen U.S. Federal agencies and over 60 different nations and international research organizations to leverage resources and extend the reach of our science results. In Astrophysics, NASA and NSF collaborate to advance the science, with NASA providing the space-based observatories and NSF the ground-based observatories. NASA and the DOE partner on selected space missions to study high energy physics. In Planetary Science, NASA partners with established and emerging spacefaring nations to send spacecraft to asteroids, comets, and other planets, and NASA-funded scientists commonly collaborate with foreign colleagues in mission-enabling research. In Heliophysics, NASA develops observations and models of space weather, and collaborates with NOAA and DoD through the National Space Weather Program to enable use of those advances in operational systems. In Earth Science, NASA manages development and launch of weather satellites for NOAA on a reimbursable basis and works with NOAA as they adopt data and measurement technologies into operational observing systems. USDA, FAA, EPA, USGS, and many other federal agencies are users of NASA's Earth Science data. SMD collaborates with the NSF on research in, from, and about Antarctica spanning all four SMD science areas. Like the International Space Station, NASA's constellation of the Sun, Earth and Solar System observatories are models of international cooperation and serve to further common scientific interests.

Research projects like airborne science campaigns in Earth science and the recent international solar eclipse expeditions to China and Libya bring together a diverse range of United Nations member states.

2.1 National Policy Direction on Earth and Space Science

As a Federal agency, NASA implements Executive and Legislative Branch policy direction. As a science organization, NASA seeks advice from the broad national science community on posing important scientific questions and on defining and prioritizing the scientific research programs that most effectively address those questions. Based on this direction and advice, NASA defines its science plan.

The Space Act and 2008 Congressional Authorization

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

- "Arrange for participation by the scientific community in planning scientific measurements and observations to be made through use of aeronautical and space vehicles, and conduct or arrange for the conduct of such measurements and observations" and;
- "Provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

Through the NASA Authorization Act of 2008, the Congress stated several findings regarding science programs at NASA:

- "NASA is and should remain a multi-mission agency with a balanced and robust set of core missions in science, aeronautics, and human space flight and exploration."
- "NASA should assume a leadership role in a cooperative international Earth observations and research effort to address key research issues associated with climate change and its impacts on the Earth system."
- "Human and robotic exploration of the solar system will be a significant long-term undertaking of humanity in the 21st century and beyond, and it is in the national interest that the United States should assume a leadership role in a cooperative international exploration initiative."

The Congress has also mandated some specific programmatic activities for NASA, including:

- Monitoring and assessing the health of Earth's stratosphere;
- Participating in an interagency program to provide land remote sensing data; and
- Tracking and characterizing Near Earth Objects greater than 140 meters in diameter.

The 111th Congress is anticipated to enact new authorization legislation for NASA in 2010 in response to the President's proposals for the nation's civil space program.

U.S. National Space Policy

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

- Maintain a sustained robotic presence in the solar system to: conduct scientific investigations of other

Chapter 2

planetary bodies; demonstrate new technologies; and scout locations for future human missions;

- Continue a strong program of space science for observations, research, and analysis of our Sun, solar system, and universe to enhance knowledge of the cosmos, further our understanding of fundamental natural and physical sciences, understand the conditions that may support the development of life, and search for planetary bodies and Earth-like planets in orbit around other stars;
- Pursue capabilities, in cooperation with other departments, agencies, and commercial partners, to detect, track, catalog, and characterize near-Earth objects to reduce the risk of harm to humans from an unexpected impact on our planet and to identify potentially resource-rich planetary objects;
- Conduct a program to enhance U.S. global climate change research and sustained monitoring capabilities, advance research into and scientific knowledge of the Earth by accelerating the development of new Earth observing satellites, and develop and test capabilities for use by other civil departments and agencies for operational purposes;
- Work with NOAA to support operational requirements for environmental Earth observation and weather, including transitioning of mature research and development satellites to long-term operations. NOAA will primarily utilize NASA as the acquisition agent for operational environmental satellites for these activities and programs.
- Work together with the U.S. Geological Survey in maintaining a program for operational land remote sensing observations.

For the authoritative text, access the National Space Policy at http://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf.

2.2 Recommendations from the U.S. Scientific Community Through NRC Decadal Surveys

In planning its science programs, NASA works to implement, along with national policy direction, the priorities defined by the National Academy of Sciences in NRC decadal surveys and other reports. These reports result from a process whereby broad community input is gathered into representative committees that then prioritize that input with the goal of articulating community priorities within the scientific scope of each survey. As such, decadal surveys represent the broad consensus of the nation's scientific communities, and thus they are the starting point for NASA's strategic planning process in the arenas of Earth and space sciences.

NASA now has decadal surveys in hand for each of its four major science areas, some more current than others.

- *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, was received in January 2007 (NRC, 2007).
- *Astronomy and Astrophysics in the New Millennium* (NRC, 2001) is succeeded by a new survey in August 2010.
- The current decadal survey in Planetary Science is *New Frontiers in the Solar System: An Integrated Exploration Strategy* (NRC, 2003).
- In Heliophysics, it is *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (NRC, 2003).

Progress in implementing the missions recommended in current decadal surveys is described in Appendix 3. In some areas, other reports by the NRC provide additional recommendations on matters arising since the publication of the last decadal survey. This is true in the case of the *Connecting Quarks with the Cosmos* report (NRC, 2003) in Astrophysics and the *Scientific Context for Exploration of the Moon* report (NRC, 2007) in Planetary Science. New decadal surveys in Astrophysics, Planetary Science, and Heliophysics are expected in 2010, 2011, and 2012, respectively. The new round of decadal surveys will integrate the NRC advice received since the prior round with intervening accomplishments and identification of new scientific challenges.

NASA also receives ongoing tactical-level advice from the science community through the NASA Advisory Council and its Science Committee and Subcommittees. This includes the development of community-based roadmaps that define approaches to implementing the decadal survey science priorities, factoring in technology readiness and synergies among destinations and measurement types. Information on the Science Subcommittees, including their reports and findings, can be accessed at: http://science.nasa.gov/about-us/NAC-subcommittees. In addition, NASA receives advice from the Astronomy and Astrophysics Advisory Committee chartered by Congress to convey community input on collaborative program opportunities for NSF, NASA, and DOE.

2.3 Agency-level Goals

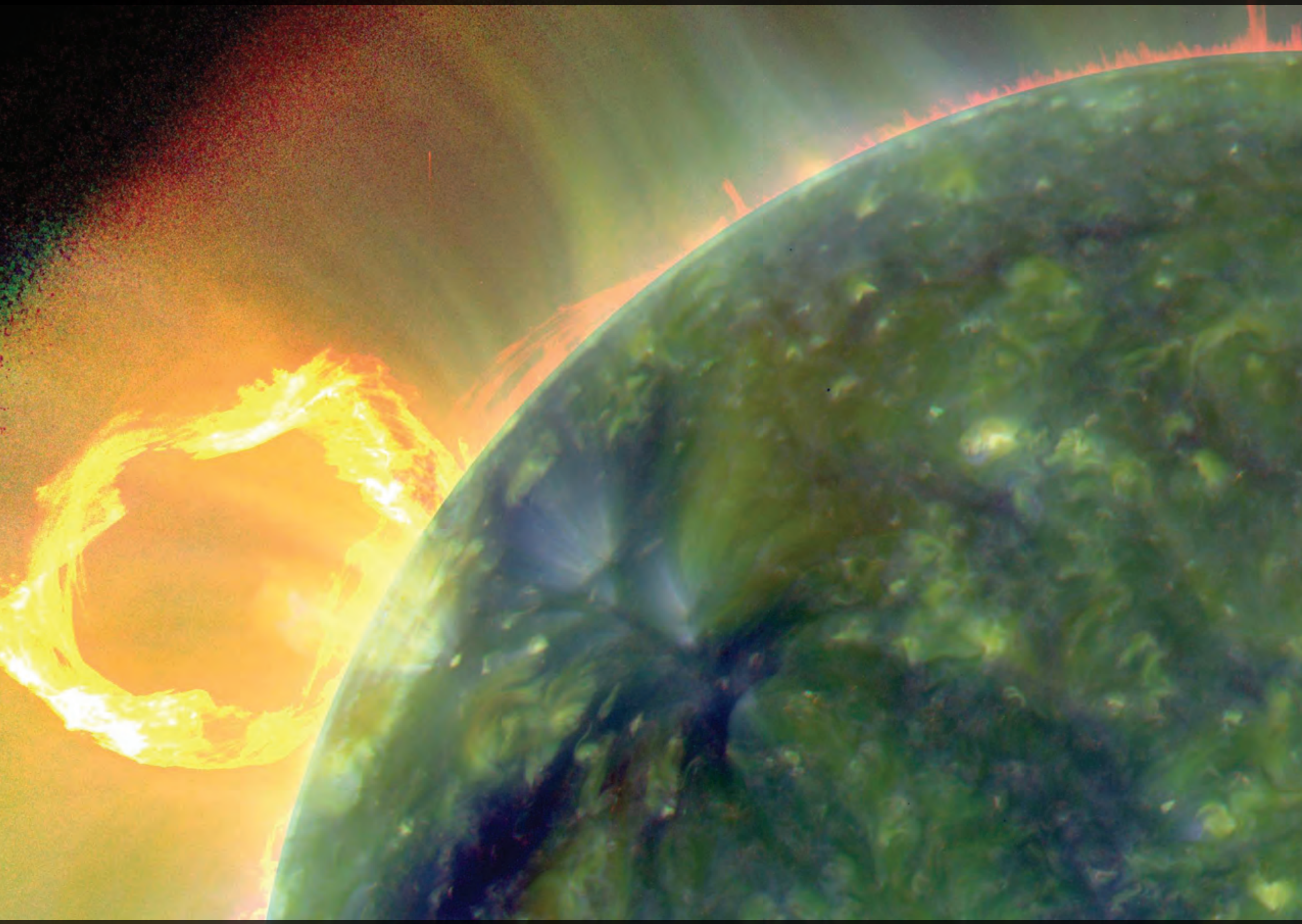
The 2010 NASA Strategic Plan succinctly articulates the Goal of the Agency in Science:

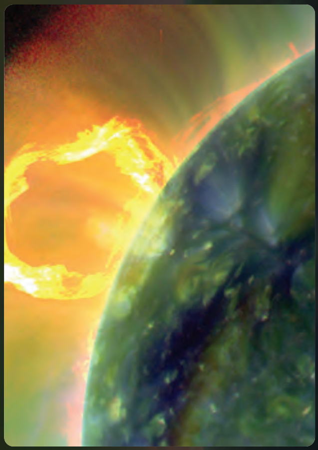
Expand scientific understanding of the Earth and the universe in which we live.

The Agency, through SMD, implements its goal of scientific discovery in four broad scientific component goals, identified as "outcomes" in the Agency plan:

- **Earth Science:** Advance Earth System Science to meet the challenges of climate and environmental change;
- **Heliophysics:** Understand the Sun and its interactions with Earth and the solar system;
- **Planetary Science:** Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere;
- **Astrophysics:** Discover how the universe works, explore how the universe began and evolved, and search for Earth-like planets.

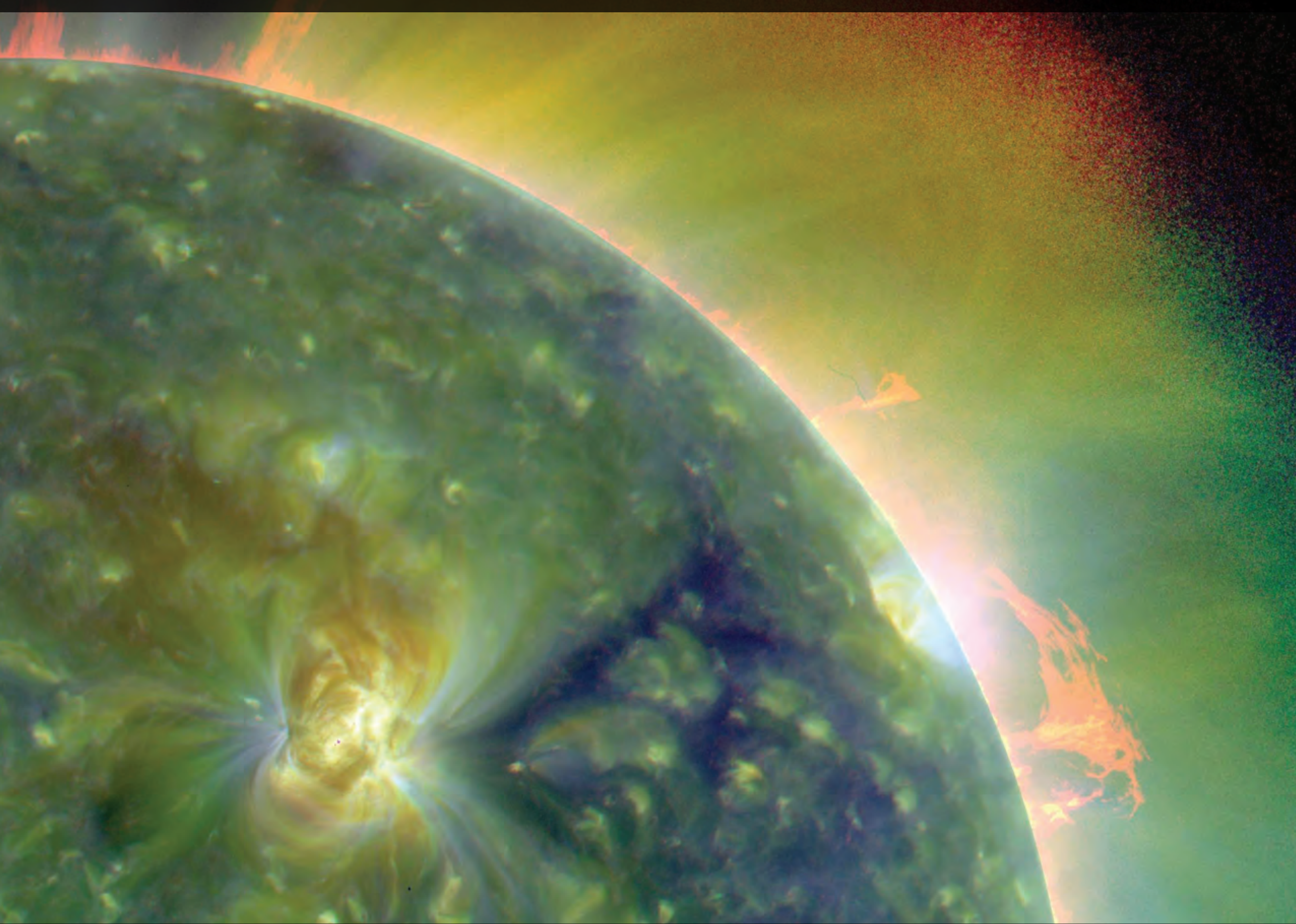
Building on the NRC decadal surveys and interaction with its science advisory committee and subcommittees, SMD has defined a set of science questions and research objectives upon which to base its research and mission programs. These questions and objectives are listed in Appendix 1.





Chapter 3

A Plan for Science at the Frontiers



The set of principles, strategies, and challenges described in this chapter shape SMD's plans for progress in all of its science areas. The Principles (3.1) are enduring over long periods and guide SMD activities. The Strategies (3.2) are also long range in nature but adapt to changing national goals, new scientific understanding and technologies, and evolving Agency policies. SMD must also overcome several daunting Challenges (3.3), and this plan incorporates our approaches to doing so.

Chapter 3

3.1 Principles

Substantial progress on NRC decadal surveys in all four Science areas is the measure of success. SMD is committed to maintaining a balance across the four major science areas so as to enable substantial progress on their decadal surveys and on national mandates over a decadal time frame. Progress in answering the science questions and implementing the priorities of the decadal surveys and the direction of the Congress and the President is the fundamental success criterion for SMD. SMD engages Science Subcommittees of the NASA Advisory Council annually to rate scientific progress. In addition, the Congress has directed that "the performance of each division in the Science directorate of NASA shall be reviewed and assessed by the National Academy of Sciences at 5-year intervals." NRC assessments, and NASA responses, have been completed thus far for Astrophysics, Planetary Science, and Heliophysics. These will be taken into account as the NRC conducts the next decadal surveys in each of these areas (due successively in 2010, 2011, and 2012).

Investment choices are based on scientific merit via peer review and open competition. SMD uses open competition and scientific peer review as the means for establishing merit for selection of research and flight programs. SMD solicits individual scientist lead research investigations primarily via the annual Research Opportunities in Space and Earth Sciences (ROSES) omnibus NASA Research Announcement (NRA) released February of each year. Occasional amendments to ROSES are also issued, as needed, for new opportunities unanticipated at the time of the ROSES NRA release. For competed missions, NASA solicits complete scientific investigations involving new space missions via Announcements of Opportunity (AO). For strategic missions, NASA solicits scientific instruments via AOs. Strategic missions are defined based on NRC decadal surveys and national policy direction; the former is itself a competitive, peer-review process of sorts, run by the National Academy of Sciences. A guide to current and forecasted future solicitations is maintained at: http://soma.larc.nasa.gov/StandardAO/index.html. Occasionally, NASA issues Cooperative Agreement Notices for the establishment of virtual research institutes. Current active institutes are the NASA Astrobiology Institute and the NASA Lunar Science Institute.

Active participation by the research community beyond NASA is critical to success. SMD engages the external science community in establishing science priorities, preparation and review of plans to implement these priorities, analysis of requirements and trade studies, conduct of research, and evaluation of program performance. Strategic-level science advice on priorities is sought primarily from the NRC. Tactical-level advice on implementing priorities is sought primarily via the Science Committee and Subcommittees of the NASA Advisory Council (NAC). Community engagement in technical analyses such as mission architectures prior to conceptual design are often performed by Analysis Groups, whose Chairs sit as members of the Science Subcommittees. Information on the NAC Subcommittees and Analysis Groups can be obtained at: http://nasascience.nasa.gov/about-us/NAC-subcommittees. Informal interaction with the science community occurs through meetings of the community's professional societies, such as the American Astronomical Society and the American Geophysical Union.

Effective international and interagency partnerships leverage NASA resources and extend the reach of our science results. International and interagency partnerships have long been a means to leverage SMD resources to accomplish shared science objectives. Over half of SMD's space missions involve co-investing partners. These partnerships range from provision of science instruments, spacecraft buses, and launch vehicles to data sharing arrangements. NASA holds periodic bilateral meetings with major partners to discuss the full range of current and potential future partnerships. For example, NASA is currently expanding partnerships with ESA in planetary science, since both agencies' science objectives require flagship-class missions that neither can afford to implement on its own, such as Mars sample return and precursor missions.

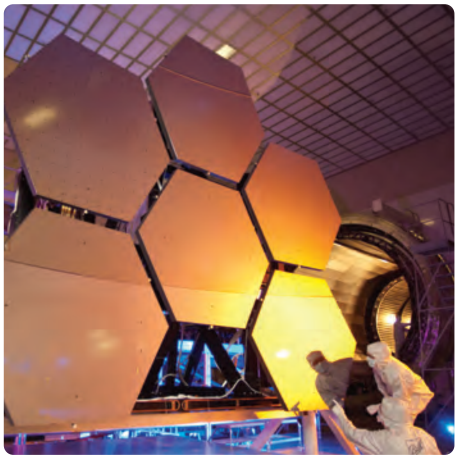
NASA partners with other Federal agencies, as well as with State and regional organizations, to enable satellite observations and research to improve the tools used by these organizations to advance scientific understanding and deliver essential services to the nation. These services include weather forecasting, wildfire fighting, coastal zone management, agricultural crop yield forecasting, air quality assessment, Near Earth Object tracking, and space weather monitoring.

Specific major partnerships are identified in the Division-specific portions of this document (Chapter 4).

A balanced portfolio of space missions and mission-enabling programs sustains progress toward NASA's science goals. Sustained progress requires particular attention to a balanced science portfolio, including basic research, technology development, missions, mission data analysis, and data and information systems. A recent NRC report, *An Enabling Foundation for NASA's Earth and Space Science Missions* (NRC, 2009) highlighted the importance of mission-enabling programs in meeting NASA's science goals. At NASA, space missions are the largest category and compose distinct size classes (Appendix 2). Large missions offer a high, broad, and long-range science return and use the scientific, engineering, and project management expertise resident at NASA Centers. They also provide substantial opportunities for international partnerships. Medium and small missions provide opportunities to broaden our research portfolio, to engage universities and other research institutions in mission development, and to spawn innovation and competition. Suborbital programs, comprising sounding rockets, balloons, and aircraft provide complementary observations, opportunities for innovative instrument demonstration, and workforce development, as was highlighted recently by the NRC in its report *Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce* (NRC, 2010).

The pace of scientific progress is enhanced by rapid, open access to data from science missions. NASA requires that science data from its missions be made available as soon as possible after scientific validation. SMD invests substantially in active archive systems to enable public access to science data via the Internet and to preserve data that enables long-term data records to be established and improved in climate change, comparative planetology, and other key areas. An open data policy is especially important to progress in Earth science, and NASA's Earth science data policy is posted at http://science.nasa.gov/earth-science/earth-science-data-centers/data-and-information-policy.

The NASA mandate includes broad public communication. NASA carries out Education and Public Outreach (E/PO) programs that capture the imagination and enhance knowledge. As a Federal agency, NASA has a responsibility to communicate information about its programs and scientific discoveries to the public, and this responsibility is highlighted in NASA's founding legislation. As a research and development agency, NASA shares with the nation's educators the goal of enhancing the scientific literacy of the American public, as well as the training of its future workforce. SMD contributes to these goals in part through its E/PO programs by making it easier for scientists to get involved in E/PO and for students to gain access to NASA science. SMD's base program of education totals about $65 million annually and includes such innovative cooperative endeavors as the FIRST Robotics program and the Global Learning and Observations for a Better Environment (GLOBE) program. In addition, as a general rule,



JWST in the Clean Room

Six of the James Webb Space Telescope (JWST) primary mirror segments being prepared for cryogenic optical testing at the MSFC X-Ray Calibration Facility.

Image Credit: Ball Aerospace & Technologies Corp.

SMD policy requires programs invest at least 1% of mission project funds in E/PO.

Accountability, transparent processes, accessible results, and capture of lessons learned are essential features of this Federal science enterprise. The nation makes a substantial investment in this very complex endeavor. Thus, it is incumbent upon SMD to provide a commensurate return on investment, to be accessible to its stakeholders, and to continue to improve based on lessons learned from both successes and failures. NASA reports on its progress through various means, including annual performance reports to Congress, regular meetings of its advisory committees, and frequent posting on developments on its website. SMD's website, and especially its Service and Advice for Research and Analysis, provides a portal into its key business processes.

3.2 Strategies

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

Design programs that accomplish breakthrough science and applications within the available budget. In NASA, programs comprise a set of projects—featuring space missions—that together advance science in that program area. In Earth Science, space weather, and other areas, significant tangible societal benefits flow from this research. Accomplishing breakthrough science with innovative space missions requires effective management of a program portfolio, including:

- Measure mission success by accomplishment of top-level science requirements;
- Provide realistic budget envelopes and mission concept cost estimates as basic input to National Academy of Science committees formulating decadal surveys;
- Establish a budget for each new mission that matches a probable life-cycle cost defined by engineering studies and independent cost estimates;
- Obtain tactical-level community advice on portfolio adjustments via the NAC Science Subcommittees; and
- Use special peer review panels of senior scientists to determine the scientific value of continued operation of existing missions beyond their prime mission lifetimes;

Partner with other nations' space agencies to pursue common goals. Both longstanding and newly space-faring nations have scientific interests similar to ours. As we progress from, for example, fly-bys to orbiters to landers and rovers to sample return missions, the cost of doing more challenging missions stresses the budget capacity of any one nation. For example, NASA and ESA are moving to coordinate plans for Mars exploration and for selected other missions, such as the next flagship-class mission to the Jupiter system, and priority Astrophysics and Heliophysics missions that are identified by the NRC decadal survey in the U.S. and by ESA's Cosmic Vision process. For strategic missions, international collaboration is government-to-government based on an alignment of NASA and its partners' science priorities, capabilities, and resources. For competed missions, international collaboration is based on scientist-to-scientist collaboration in formulating proposed investigations to Announcements of Opportunity.

Mature technologies through focused efforts prior to committing to implement missions that need them. Advancing scientific understanding often requires new measurement techniques or increases in spacecraft performance which in turn require technology advances. This involves identifying technical risks and investing in new technologies before committing to proceed with mission implementation. It means anticipating and investing in science-driven and performance enhancing technologies that can then become available to proposers of new instruments and mission concepts. Therefore, technology development programs are essential for increasing the impact of scientific missions.

Setting up JUNO's Radiation Vault

Workers place the special radiation vault for NASA's Juno spacecraft onto the propulsion module. Juno's radiation vault has titanium walls to protect the spacecraft's electronic brain and heart from Jupiter's harsh radiation environment. The whole vault, with more than 20 electronic assemblies inside, weighs about 200 kilograms (500 pounds). This image was taken on May 19, 2010, in the high-bay cleanroom at Lockheed Martin Space Systems in Denver, during Juno's assembly process.

NASA's Jet Propulsion Laboratory, a division of the California Institute of Technology, Pasadena, manages the Juno mission for the principal investigator, Scott Bolton, of Southwest Research Institute, San Antonio. Lockheed Martin Space Systems is building the spacecraft. The Italian Space Agency, Rome, is contributing an infrared spectrometer instrument and a portion of the radio science experiment.

Image Credit: NASA/JPL-Caltech/LMSS

Share the story, the science, and the adventure of NASA missions and research to engage the public in scientific exploration and to improve science, technology, engineering, and mathematics (STEM) education nationwide. SMD invests in formal and informal education and outreach activities that engage scientific experts to reach learners of many backgrounds and throughout the education "pipeline." Avenues of engagement include:

- Direct student participation in NASA science missions;
- Tools that enable students to analyze science mission data;
- Citizen-scientist opportunities;
- Interactive Web presence;
- Teacher training and professional development;
- Award-winning educator guides and resources.

SMD implements its E/PO programs through:

- Competitively-selected Forums in each of SMD's four science areas;
- Supplemental E/PO grants to funded researchers;
- Student Fellowships;
- Focused, targeted outreach programs.

3.3 Challenges

This section discusses the challenges NASA currently faces in carrying out its Science Plan according to the Principles and Strategies outlined above.

Access to Space

SMD relies on commercial expendable launch vehicles (ELVs) acquired for SMD by the Space Operations Mission Directorate's Launch Services Program (LSP). In the medium class of ELVs, the pending retirement of the Delta II (after about 2011) leaves SMD without a certified vehicle in this class. Orbital Sciences' Taurus II and SpaceX's Falcon 9 are currently being developed to fill that void, and the LSP is working with the vendors on the steps toward certification. Until then, NASA is working with DoD to enable the use of Minotaur launch vehicles on a case-by-case basis. In the intermediate class of ELV the challenge is national capacity. Currently, launches of ELVs in this class require no less than 60 days of schedule room on either side of the launch date and 90 days when the payload carries radioisotope thermal generators (RTGs). The U.S. Air Force, NASA, and the ELV vendor are working to shorten the "turn around time" between launches. Nevertheless, as a matter of national policy, NASA science missions take last place in priority behind national security and commercial missions (with allowances made for NASA planetary missions with tight launch windows). In all classes of ELV's, constraining cost per vehicle is important; within a total mission life cycle cost target, lower launch costs mean more dollars for science.

Availability of Plutonium 238

Radioisotope Power Systems (RPS) provide electrical power for spacecraft and planetary probes that operate where the Sun is too far distant, not consistently observable, or too obscured to rely on solar energy for power or that operate in environments with stressing power needs; Pu-238 is the fuel that powers these RPS. U.S. production of Pu-238 ceased in the 1980's. The total amount of Pu-238 available to NASA, including the remaining domestic supply and supply purchased from Russia, is insufficient to support the planned flagship mission to Europa. Given that it would take the Department of Energy (DOE) 3 to 5 years to produce the first Pu-238 after restart of production, SMD is facing a gap, and is already making mission-limiting decisions based on the short supply of Pu-238. The NRC provided a useful analysis of this topic in its report *Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration* (NRC, 2009). The President's FY 2011 Budget Request includes $15 million each for NASA and DOE to enable DOE to establish a capability to restart domestic production of Pu-238. In response to this request, NASA and DOE have developed a plan to produce 1.5 to 2 kg of Pu-238 per year. NASA believes that this rate, together with the existing inventory, will be sufficient to meet mission requirements for the foreseeable future. NASA is also supporting DOE efforts to procure all remaining Russian Pu-238 to retire much of the risk to NASA missions of timely availability of new domestic supply. In the meantime, SMD is investing in the development of Stirling engines which are more than four times more efficient than current technology in converting heat energy from Pu-238 into electrical power for space missions. This technology will provide NASA with a new capability to make more efficient use of the scarce Pu-238 resource.

Unrealized Expectations

The last round of space science NRC decadal surveys were developed in a time of rising budgets. In the current era, budgets are flat, and purchasing power is declining. The Earth Science decadal survey, released in 2007, was the first to be released in the current budget environment, and the gap between its assessment of national needs and available resources is substantial. At the same time, the cost of implementing space missions is rising, widening the gap between science community expectations and resources. For the upcoming round of NRC decadal surveys, NASA has provided explicit guidance on projected budget resources to enable independent cost estimates of candidate mission concepts. This may help the NRC propose priorities implementable with the available budget.

Mission Cost Estimation and Management

High-profile science questions before us will require sample returns, operation of satellites and probes in hostile environments, larger aperture telescopes, and observations sustained over decades. These objectives require NASA to embrace the risk of conducting ever more challenging missions in even more challenging space environments. In addition to technical risk, cost and schedule risk are incurred through increased complexity and integration inherent in larger missions. Further, rising ELV prices and consolidation in the aerospace industry also tend to raise "the cost of doing business." NASA has taken several steps to more accurately project and constrain mission costs, including:

- Establish program life-cycle budget at the 70% confidence level;
- Obtain multiple, independently generated internal and external cost estimates;
- Review projects at multiple, formal Key Decision Points that function as gates to the next stage of development;
- As required by the 2005 NASA Authorization Act (P.L. 109–155), prepare reports to Congress on projects projected to exceed 15 percent cost growth or delay their launch date milestone by more than six months from their baselines, identifying corrective actions, their costs, and any alternatives;
- Require that cost estimates of mission concepts submitted by NASA Centers to NRC decadal survey committees be independently reviewed, and approved by the cognizant SMD Science Division Director.

Further, the NRC report *Controlling Cost Growth of NASA Earth and Space Science Missions* (NRC 2010) calls for a comprehensive and integrated strategy for cost and schedule control. NASA believes these steps will improve mission cost estimation and management. Over time we will collect the data to assess the realized versus expected improvements in mission cost management and budgeting. SMD conducts 'lessons learned' activities through its Science Office for Mission Assessments at the Langley Research Center. Inevitably, as implied by the 70% rule, there will be cost and schedule overruns on some missions, given the first-of-a-kind nature of most space research missions, but significantly fewer overall. One impact of the policy of budgeting at the 70% confidence level has been to reduce the number of new mission starts. When missions do overrun, SMD endeavors to confine the impacts to the program in which that mission resides. Where that is not possible, SMD seeks the advice of its NASA Advisory Council Science Subcommittees on options SMD develops for resolution.

Technology Development and Demonstration

The nation views NASA as a key source of advanced technology development both to enable innovative space missions and to benefit the economy and society more broadly. NASA developed a Technology Readiness Level (TRL) scale of technology maturity as a way to describe the steps of technology development and to aid in analyzing its technology investment portfolio. In tight budgetary times, the focus tends to be on technology developments needed to enable specific missions. The lower TRLs, where specific uses are not yet defined, and the mid to upper levels, where demonstrations of technologies in space can be expensive, tend to languish. For example, the New Millennium Program of in-space technology demonstration was effectively ended in 2009. However, with the President's FY 2011 Budget Request, NASA is renewing its emphasis on technology development and demonstration across the full length of the TRL scale. NASA has created a new Directorate-level organization to manage this new investment, which will augment the investments currently made by the Mission Directorates and meet broader agency goals. SMD will work with this new organization to leverage its investments, particularly in the lower and higher ends of the TRL scale. In addition, the FY 2011 budget request created a new line of robotic precursor exploration missions in ESMD that may involve technologies beneficial to both Directorates' future missions.

National Strategy for Earth Observation

The interim decadal survey report *Earth Science and Applications from Space* (NRC 2005) stated with alarm that the nation's system of environmental satellites was "at risk of collapse." Their final report in 2007 noted that in the intervening time, the situation has for several reasons worsened considerably: NASA's Earth science budget had declined since FY 2000; the National Polar-orbiting Operational Environmental Satellites System (NPOESS) co-funded by NOAA and DoD has been deemed by an independent review team to have a "low probability of success" as currently structured; and the Geostationary Environmental Operational Satellite (GOES-R) series has been descoped. Additionally, no stable funding and management paradigm is in place for the Landsat program, nor for the systematic transition of appropriate NASA-pioneered observations to operational systems. With the release of the President's FY 2011 Budget Request, the Administration has taken enormous steps to rectify this situation. The FY 2011 request adds a total of $2.4 billion for the period FY 2011–2015 to NASA's Earth Science budget, enabling the acceleration of NRC Decadal Survey missions and the addition of new missions to address continuity of selected key climate measurements. Further, the Administration has moved to restructure the operational polar environmental satellite program, giving DoD responsibility for "early morning orbit" satellites and NOAA/NASA responsibility for "afternoon orbit" satellites.

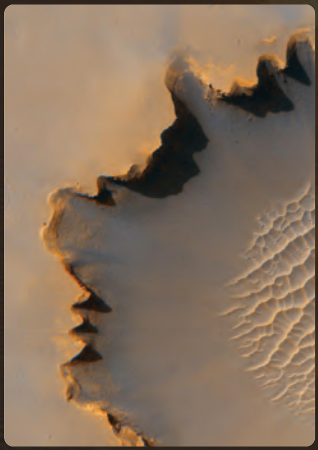
Impediments to International Collaboration on Space Missions

In 1999, Congress redefined civilian spacecraft as "defense articles" and transferred all aspects of their design, manufacturing, and operation from the Department of Commerce to the State Department's more restrictive International Traffic in Arms Regulations (ITAR). This change introduced a variety of serious legal and administrative complications into the conduct of international cooperative projects involving scientific spacecraft. By precluding the dissemination of information on the design, fabrication, assembly, and operation of NASA spacecraft and instruments to foreign colleagues and foreign students and researchers at U.S. universities, ITAR hampers the universities' collaborative environment, which depends upon the open exchange of information and ideas among students and faculty without regard to nationality. Currently, the ITAR requires that individual Technical Assistance Agreements (TAAs) be established between each U.S. and foreign entity working on a NASA program. The James Webb Space Telescope project, for example, currently has in place 140 individual TAAs approved by the State Department. Discussions ongoing in both the Executive and Legislative branches on potential future directions such as legal differentiation between scientific spacecraft and weapons, with a correspondingly differentiated regulatory treatment, could mitigate or eliminate these challenges.

Mars rover Curiosity with Newly Installed Wheels

Mars rover Curiosity, the centerpiece of NASA's Mars Science Laboratory mission, is coming together for extensive testing prior to its late 2011 launch. This image taken June 29, 2010, shows the rover with the mobility system—wheels and suspension—in place after installation on June 28 and 29. Spacecraft engineers and technicians are assembling and testing the rover in a large clean room at NASA's Jet Propulsion Laboratory, Pasadena, Calif. Curiosity's six-wheel mobility system, with a rocker-bogie suspension system, resembles the systems on earlier, smaller Mars rovers, but for Curiosity, the wheels will also serve as landing gear. Each wheel is half a meter (20 inches) in diameter.

Image Credit: NASA/JPL-Caltech



Chapter 4

Detailed Plans by Science Area

Based on national policy direction and recommendations from the nation's science community via NRC decadal surveys, each of the four SMD science divisions has developed plans for future missions and supporting research and technology. Each of the four major sections to follow identifies the top-level science questions to be pursued, the strategy to do so, and the current and planned future missions and research programs.

The grouping of SMD research into these four science areas is a useful management construct, but the science itself knows no boundaries. Indeed, important scientific processes exist in the regions of overlap among them. Therefore, between each of the science area sections in this chapter are text boxes highlighting research that involves more than one of the four science areas.

Chapter 4

4.1 Earth Science

In parallel with the past 50 years of the Space Age, world population has doubled, world grain supplies tripled, and total economic output grown sevenfold. From space we observe that expanding human activities now affect half the entire land surface of the Earth and are altering world atmospheric composition, oceans, and ice masses, as well. Recently, society has also observed how intergovernmental policies and international agreements can, as in the case of industrially produced chlorofluorocarbons, begin to reverse some of those trends. NASA pioneered Earth System Science and observations from space to lay the essential scientific foundation for sound decision-making by the nation to mitigate and adapt to global change.

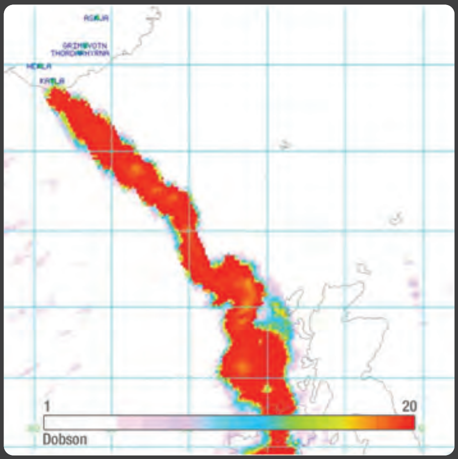
Strategy

Objectives and Goals

At NASA's request, the National Research Council conducted the first ever decadal survey for Earth Science, and released in January 2007 the report: "*Earth Science and Applications from Space—National Imperatives for the Next Decade and beyond*". In it, the NRC articulates the following vision for the future:

Understanding the complex, changing planet on which we live, how it supports life and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity. It is also one of the most important challenges for society as it seeks to achieve prosperity, health, and sustainability.

NASA's ability to observe global change on regional scales and conduct research on the causes and consequences of change positions it to help fulfill this vision. NASA's strategic goal: ***"Advance Earth System Science to meet the challenges of climate and environmental change"*** is expressed by the fundamental question, "How is the Earth changing and what are the



OMI SO2 DATA FROM ICELAND

Volcanic Cloud Data for Aviation Hazards

Iceland's Eyjafjallajökull Volcano burst into life on March 20, 2010. A 2,000-foot long fissure opened in the Fimmvörduháls Pass, accompanied by lava fountains and steam explosions. In mid-April, a huge plume of ash erupted and spread across the North Atlantic, shutting down air traffic in Europe causing airline business losses greater than $1 billion. NASA's Ozone Monitoring Instrument (OMI) aboard the Aura satellite was demonstrated to provide reliable and more accurate detection of volcanic ash clouds. Specifically sulfur dioxide (SO_2) is a reliable marker for fresh volcanic ash clouds under clear skies especially in the early days of a high-altitude eruption. NASA for the first time began providing near real time customized reports through NOAA to European advisory centers in April 2010, to assist the operational Volcanic Ash Advisory Centers (VAAC's) in London and Toulouse with the ongoing Iceland eruption. The Applied Sciences program turns research data and results into reliable products of societal benefit.

Image Credit: OMI SO2 data from Iceland sector on April 21, 2010 (1301Z).

consequences for life on Earth?" and its component questions:

- How is the global Earth system changing? *(Characterize)*
- What are the sources of change in the Earth system and their magnitudes and trends? *(Understand)*
- How will the Earth system change in the future? *(Predict)*
- How can Earth system science improve mitigation of and adaptation to global change? *(Apply)*

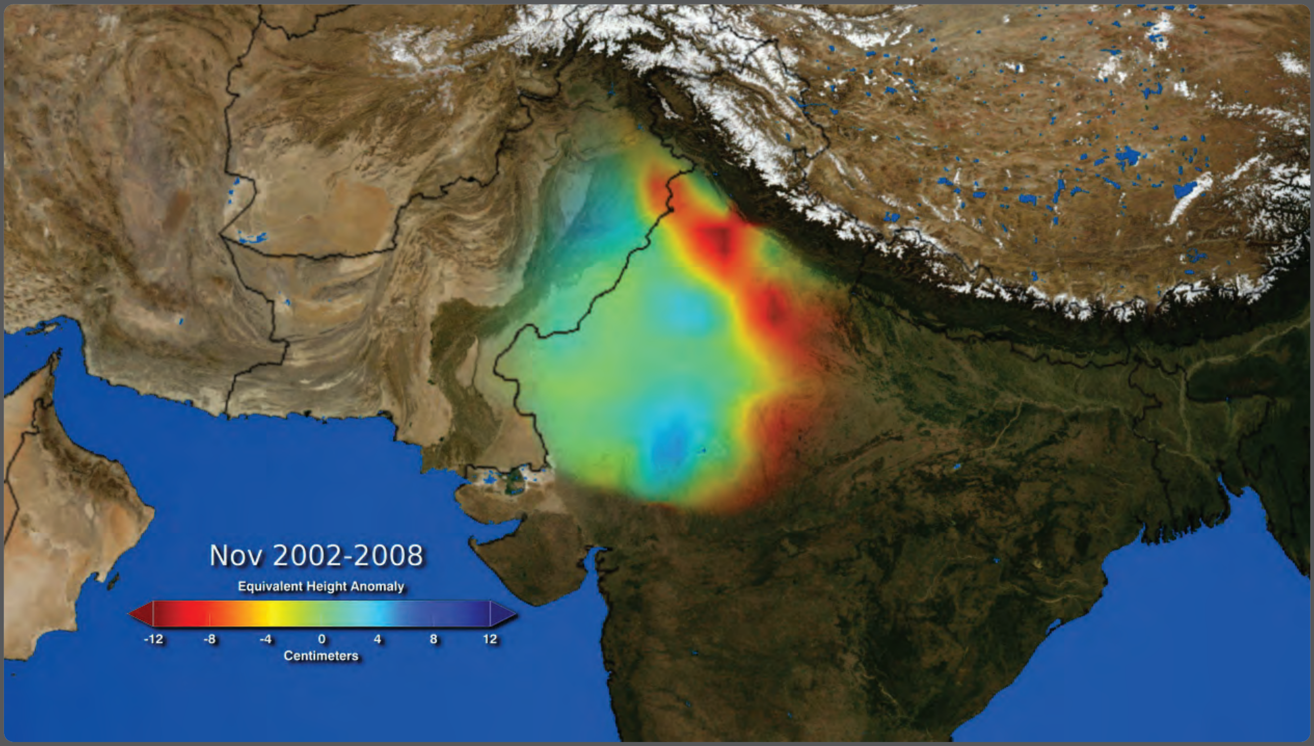
External Context

NASA is the US civilian space agency and in this role has key responsibilities in meeting the nation's needs for Earth observations from space. NASA provides the bulk of the global observations employed by the U.S. Global Change Research Program, and much

NASA Satellites Unlock Secret to Northern India's Vanishing Water

Beneath northern India's irrigated fields of wheat, rice, and barley, beneath its densely populated cities of Jaiphur and New Delhi, the groundwater has been disappearing. Halfway around the world, hydrologists, including Matt Rodell of NASA, have been monitoring it. Where is northern India's underground water supply going? According to Rodell and colleagues, it is being pumped and consumed by human activities—principally to irrigate cropland—faster than the aquifers can be replenished by natural processes. They based their conclusions—published in the August 20, 2009 issue of Nature—on observations from the NASA/DLR Gravity Recovery and Climate Experiment (GRACE). "If measures are not taken to ensure sustainable groundwater usage, consequences for the 114 million residents of the region may include a collapse of agricultural output and severe shortages of potable water," said Rodell, who is based at NASA's Goddard Space Flight Center in Greenbelt, Md.

Image Credit: NASA/Trent Schindler and Matt Rodell



of the observations and research that forms the basis of international scientific assessments of climate and other environmental change. NASA and the U.S. Geological Survey are long-time collaborators in the Landsat program, and that partnership is evolving in keeping with the maturity of land cover remote sensing. Similarly, NASA and NOAA are long-time collaborators in satellite systems for use in weather observation and forecasting. Today's civilian weather satellite system was built and launched by NASA under reimbursable arrangements with NOAA, and NOAA operates this system and manages the data for use in its operational forecasting role. In addition, NASA provides global ocean observations and research in partnership with NOAA, NSF, the U.S. Navy, and other agencies. NASA is a key participant in the interagency Climate Change Adaptation Task Force. NASA also has a longstanding Congressional mandate to monitor and periodically report on the state of the Earth's protective stratospheric ozone layer.

NASA, together with NOAA, USGS, NSF, and OSTP, provides 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. NASA maintains an expansive web of partnerships with foreign space agencies and international research organizations with common goals, which substantially leverages NASA's investment, ranging from data sharing agreements to joint development of satellite missions. Many of NASA's current and planned satellite missions include international partnerships and most of NASA's field campaigns are conducted internationally, involving close interactions with our partners.

The Earth Science Decadal Survey noted with alarm the decline of NASA's Earth Science budget since 2000 and found that the nation's system of environmental satellites was "at risk of collapse." In addition, the Obama Administration, recognizing the pressing challenge of climate change, observed the need to address continuity of key climate measurements in order to inform policy and action.

With the 2009 American Recovery and Reinvestment Act and the Fiscal Year (FY) 2010 budget, the Administration and Congress placed on a firm path for completion the Foundational Missions that NASA had under development at the time the Decadal Survey was published and which were among the Survey's first recommendations. With the President's FY2011 Budget Request, the Administration has moved to accelerate substantially NASA's fulfillment of other key Decadal Survey recommendations as well as address related Administration climate change priorities.

The requested budget for NASA Earth Science, totaling $10.2 billion from FY11–15, is consistent with the recommendations of the Decadal Survey, which called for rapid restoration of NASA's Earth Science Division budget to the 2000-era level of ~$2 billion annually (in FY06 dollars). This budget constitutes the largest increase of any of the Federal agencies contributing to the US Global Change Research Program (USGCRP). The activities enabled by the budget are consistent with the comprehensive vision for NASA's Earth Science endeavor set forth in the NRC's Decadal Survey, as well as with the Administration's focus on climate research and monitoring to advance science, expand applications, and address national information requirements for near-term policy development and future evaluations of policy efficacy.

With the President's FY2011 Budget Request the Administration announced a restructuring of the National Polar-orbiting Operational Satellite System (NPOESS) Program. NASA and NOAA will take primary responsibility for the satellites operating in the afternoon orbit. This program, named the "Joint Polar Satellite System" (JPSS), will be funded by NOAA, and NASA will serve as the acquisition agent to manage development and launch of satellites under a reimbursable arrangement like that utilized for today's civilian weather satellites. The DoD will take responsibility for satellites in the early morning orbit to complete the originally planned orbital configuration (the European Meteorological Satellite Organization—EUMETSAT—will continue to provide coverage in the mid-morning orbit). NOAA will be responsible for the ground system and data management for the JPSS. NASA is also collaborating with NOAA to acquire key climate measurements and transition them into the operational satellite system. A notable transition example is the NOAA/EUMETSAT Jason-3 mission that will provide continuity of sea surface height measurements initiated by NASA and the French Space Agency with the TOPEX/Poseidon, Jason-1, and OSTM/Jason-2 research satellites.

Implementation Approach

NASA's program is an end-to-end one that encompasses the development of observational techniques and the instrument technologies needed to implement them; laboratory testing and demonstrations from an appropriate set of surface-, balloon-, aircraft-, and space-based platforms; development and operation of satellite missions and production and dissemination of resulting data products; research to increase basic process knowledge; incorporation of results into complex computational models that can be used to more fully characterize the present state and predict the future evolution of the Earth system; and development of partnerships with other national and international organizations that can use the generated information in environmental forecasting and in policy, business, and management decisions. These activities are grouped into the Flight Program, Research Program, Applied Sciences Program, and Technology Program, described in the subsections below.

Flight Program

The Decadal Survey identified fifteen systematic missions for NASA, and a line of competed small missions, and also made recommendations on two foundational missions currently in development (LDCM, Global Precipitation Measurement). In addition, the FY11 Budget Request funds an Orbiting Carbon Observatory-2 (OCO-2) mission to replace OCO lost in a 2009 launch vehicle failure, and funds a line of climate continuity missions to assure data continuity for high-priority observations. NASA implements the current and recommended missions through two programs:

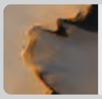
Earth Systematic Missions: To implement the missions listed in the decadal survey report, foundational missions, additional climate continuity missions, and address the highest priority science and societal benefit areas.

Earth System Science Pathfinder: To implement low to moderate-cost research and applications missions to foster revolutionary science and train future leaders of space-based Earth science and applications. This includes the new Venture class program recommended in the decadal survey, consisting of low cost, competed suborbital and orbital missions as well as instruments for Missions of Opportunity.

The status and plans for specific missions within these two programs follows.

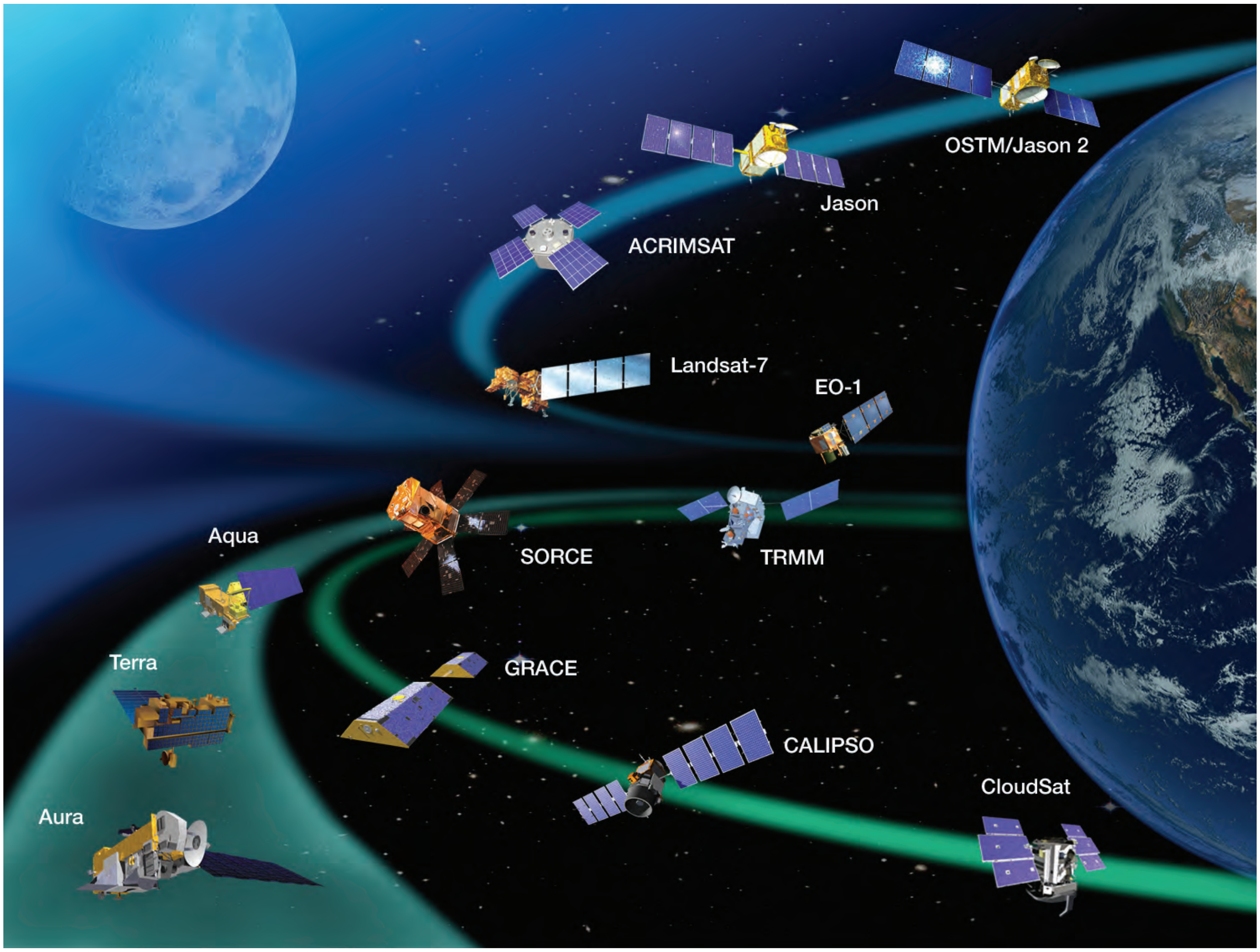
Operating missions

To address the challenges of recording simultaneous observations of all Earth components and interactions to generate new knowledge about the global integrated Earth system, NASA and its partners developed and launched the Earth Observing System and ancillary satellites. As shown below, 13 satellites comprise today's fleet of NASA Earth observing missions.



Chapter 4

Figure 4.1 Current Earth Science Missions in Operation



The scientific benefit of simultaneous Earth observation—the Earth System Science construct—is substantial. For example, NASA's Aqua, Aura, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and CloudSat satellites and France's Centre National d'Etudes Spatiales (CNES) Polarization and Anisotropy of Reflectances for Atmospheric Sciences (PARASOL) satellite, collectively known as the A-Train, are in specific orbits to record unprecedented atmospheric chemistry and composition observations over the same region within 15 minutes. The A-Train is the first Earth science space "super-observatory" and it will continue to expand with the incorporation of the Glory spacecraft, planned for launch in late 2010.

Missions in Development

Five foundational missions are in various stages of development, assembly and test, and constitute the bridge between the Earth Observing System and the decadal survey missions to follow. They will continue selected measurements made by EOS and will also observe new features of the global integrated Earth system. These five missions are described in Table 4.1a.

Table 4.1a Earth Science Foundational Missions (with planned launch years noted)

Glory—2010 Strategic mission; Initializes a systematic measurement/data continuity	Measure global aerosols and cloud liquid properties and total solar irradiance. Addresses high priority objective of the U.S. Global Change Research Program.
Aquarius—2011 Competed mission; Earth System Science Pathfinder	Global measurement of sea surface salinity from space; PI-led small Earth science mission. NASA partnership with Argentine space agency.
NPOESS Preparatory Project—2011 Strategic mission; Systematic measurement/data continuity	Continues several key climate measurements of the Earth Observing System and bridges to JPSS. Joint mission with the NPOESS partners (DOC and DoD); will fill an operational need for JPSS.
Landsat Data Continuity Mission—2012/13 Strategic mission; Systematic measurement/mandated data continuity	Continues long-term global land cover change data record. Includes thermal infrared sensor. Joint mission with USGS.
Global Precipitation Measurement—2013 Strategic mission—Initializes a systematic measurement	Extends precipitation measurements spatial coverage to global and temporal coverage to every 3 hours, via a core satellite and a constellation of smaller satellites. NASA partnership with JAXA.

The NPOESS Preparatory Project (NPP) will serve a dual role as a NASA research mission to continue key measurements from the Terra, Aqua, and Aura satellites, and as a data source to fill an operational role in the Joint Polar Satellite System. NPP now includes two NOAA-funded sensors de-manifested from NPOESS in 2006: the Ozone Mapping and Profiling Suite-Limb (OMPS-Limb) and the Clouds and the Earth's Radiant Energy Sensor (CERES).

Future Missions

The Decadal Survey priorities are now NASA's principal determinant of the priority of Earth science satellite missions beyond 2010 and, therefore, replace the list of potential Earth Science missions in the NASA Science Plan published in January 2007. The Decadal Survey recommended 14 missions for NASA to launch during 2010–2020 and one additional mission for NASA to implement jointly with NOAA. The NASA missions were grouped into three time frames or Tiers. Each Tier reflects scientific synergies among the missions in that Tier. The succession of Tiers correlates both to the level of technology readiness of the major components of missions in each Tier and the context of measurements to be made by international and interagency partners.

The Earth Science Decadal Survey recommended an integrated slate of missions. In the NRC's view, implementing some missions but not others would break the observing strategy they proposed, requiring a reassessment of the proposed plan. Further, the Survey recognized the importance of the synergies between the existing and planned research and operational missions—synergies that would be lost if the timeline for the decadal survey missions is greatly extended. Thus, NASA is pursing all four of the Tier 1 missions for launch in a four-year period. While implementing all three Tiers of missions in the time frame recommended by the NRC is not feasible with current resources, NASA is making technology investments and conducting other preparatory analyses for the Tier 2 and 3 missions.

Chapter 4

Table 4.1b Earth Science Decadal Survey Tier 1 Missions (with launch year noted)

Soil Moisture Active-Passive (SMAP)—2014	Soil moisture and freeze-thaw for weather and hydrological cycle processes.
Ice, Cloud and land Elevation Satellite (ICESat-II)—2015	Ice sheet height changes for climate change diagnosis and assessment of land carbon standing stock.
Climate Absolute Radiance and Refractivity Observatory (CLARREO)—2017 and 2020	The NASA portion of this mission employs interferometers to measure solar radiation reflected from and infrared radiation emitted by the Earth as a benchmark for climate.
Deformation, Ecosystem Structure, and Dynamics of Ice (DESDynI)—2017	Earth surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health.
Venture class missions—2017 for first satellite mission New class of innovative science mission recommended by the decadal survey.	Calls for proposals every other year, alternating between suborbital and orbital missions. In addition, instruments of opportunity will be solicited annually.

Table 4.1c Earth Science Climate Continuity Missions (with planned launch year noted)

Orbiting Carbon Observatory-2 (OCO-2)—2013 Earth System Science Pathfinder	Global atmospheric column CO_2 measurement from space to quantify CO_2 fluxes. Replacement for the competitively selected OCO mission lost in a launch vehicle failure.
Stratospheric Aerosol and Gas Experiment - III (SAGE III)—Available 2014	Global stratospheric aerosols measurements, and measurements of ozone, water vapor and trace gases, to understand their significant roles in atmospheric radiative and chemical processes and monitor climate change. Seeking a launch opportunity of this existing instrument for delivery to the International Space Station (and development of interface hardware).
Gravity Recovery and Climate Experiment Follow-on (GRACE FO)—2016	Continue high-resolution gravity field measurements, develop time variable gravity and mass re-distribution. Provide continuity between the existing GRACE and the more capable GRACE II mission recommended in the Decadal Survey.
Pre-Aerosol, Clouds, and Ocean Ecosystem (PACE)—2018	Provide continuity of aerosol, cloud, and ocean color measurements until availability of the more advanced Decadal Survey Tier 2 ACE mission.

NASA is currently developing the Tier 1 decadal survey missions and Venture class airborne instrument and mission with projected launch dates (advanced by the FY11 budget request) as shown in Table 4.1b.

The Climate Continuity Mission launch dates reflect advances based on the FY11 budget request, which also enables the development of missions to address continuity of selected key climate observations as shown in Table 4.1c.

The FY11 budget request enables acceleration of the Decadal Survey Tier 2 missions as well. The first two Tier 2 missions, Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) and Surface Water and Ocean Topography (SWOT) will be launched before the end of CY 2020, with the rest to be developed for launch at the rate of one each year. The order of development of the balance of the Tier 2 missions will be determined by scientific priority, national needs for climate continuity or other data, technology readiness, and partnership opportunity. Tier 2 and 3 missions of the Decadal Survey are listed in Appendix 3: Status of Missions Identified in Most Recent NRC Decadal Surveys.

Three new mission program elements were added to realize the full potential of the mission accelerations enabled by the FY11 budget request. These are:

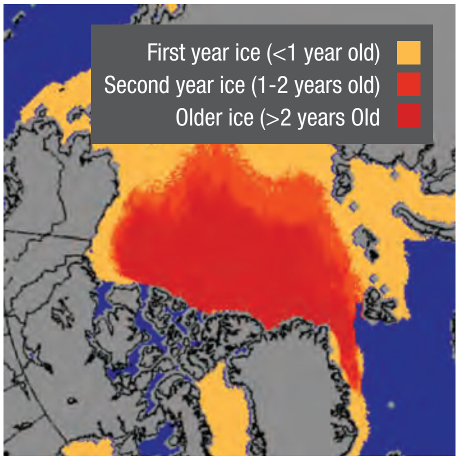
1) the development of a Dual Satellite System (DSS) for Evolved Expendable Launch Vehicles (EELV) to enable launch of two medium satellites on a single EELV;
2) the development of standardized instrument to spacecraft interfaces for future Venture Class missions; and
3) acceleration of upgrades to existing mission operations, data capture, and critical science data ground systems.

NASA's acquisition strategy and mission development methodology is designed to minimize cost, maximize efficiency, and enhance success through design, procurement, and testing of common components, subsystems or spacecraft designs that may be shared by two or more missions. This overall acquisition strategy will also involve dialogue and joint planning with other nations' space agencies on collaborative and coordinated programs to leverage each other's resources to meet common objectives.

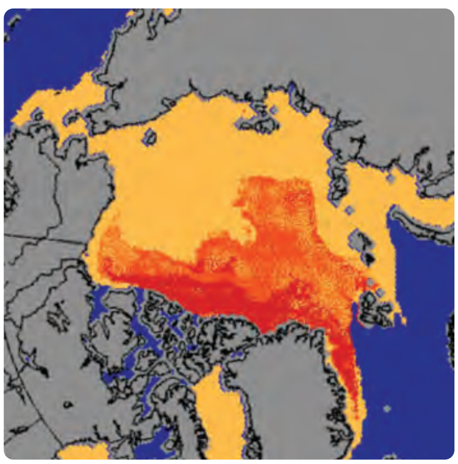
Data and Information Systems

NASA's principal Earth Science information system is the Earth Observing System Data and Information System (EOSDIS), which has been operational since August 1994. EOSDIS acquires, processes, archives, and distributes Earth Science data and information products created from satellite data, which arrive at the rate of more than four trillion bytes (4 terabytes) per day. Having successfully created this system, NASA is using advances in information technology to expand its capabilities while providing continuous service to the user community.user community. The successful completion of the Evolution of EOSDIS Elements (EEE) effort has increased efficiency and operability; increased data usability by the research, application, and modeling communities. EOSDIS is now; providing services and tools needed to enable use of NASA's Earth Science data in next-decadal models, research results, and decision support system benchmarking; and improving support for end users. The budget request for FY 2011 incorporates cost savings that result from this effort. A system plan for 2015 and beyond will guide further improvements and will take into account evolution needs for new missions being developed in response to the decadal survey Earth Science and Applications from Space (National Research Council). Very modest investments will enable the system to keep technologically current, and incorporate new research data and services.

Chapter 4



1981–2000 MEDIAN



2009

Satellites Show Arctic Literally on Thin Ice

The latest Arctic sea ice data from NASA and the National Snow and Ice Data Center show that the decade-long trend of shrinking sea ice cover is continuing. New evidence from satellite observations also shows that the ice cap is thinning as well.

Arctic sea ice works like an air conditioner for the global climate system. Ice naturally cools air and water masses, plays a key role in ocean circulation, and reflects solar radiation back into space. In recent years, Arctic sea ice has been declining at a surprising rate.

Image Credit: From NSIDC, courtesy Chuck Fowler and Jim Maslanik, University of Colorado

NASA Earth Science information is archived at eight Distributed Active Archive Centers (DAACs) located across the United States. The DAACs specialize by topic area, and make their data available to researchers around the world. For more information, please see http://eos.nasa.gov/eosdis. Research opportunities related to EOSDIS are available through the Advanced Collaborative Connections for Earth System Science (ACCESS) at http://access-projects.gsfc.nasa.gov and Making Earth System data records for Use in Research Environments (MEaSUREs) at http://measures-projects.gsfc.nasa.gov programs. Participants in these programs are solicited through the Research Opportunities in Space and Earth Sciences (ROSES), the NASA Research Announcement soliciting basic and applied research proposals.

Research Program

Earth science research aims to acquire deeper scientific understanding of the components of the Earth system, their interactions, and the consequences of changes in the Earth system for life. These interactions occur on a continuum of spatial and temporal scales ranging from short-term weather to long-term climate and motions of the solid Earth, and from local and regional to global. These involve multiple, complex, and coupled processes that affect climate, air quality, water resources, biodiversity, and other features that allow our Earth to sustain life and society. The challenge is to predict changes that will occur in the next decade to century, both naturally and in response to human activities. To do so requires a comprehensive scientific understanding of the entire Earth system, how its component parts and their interactions have evolved, how they function, and how they may be expected to further evolve on all time scales.

The Research Program sponsors research to advance toward goals in each of the six Science Focus Areas and their component disciplinary programs. The most recent comprehensive description of the research goals of NASA's Earth Science Research Program is in the *2003 Earth Science Enterprise Strategy* at http://science.nasa.gov/about-us/science-strategy. The most up-to-date description of the Earth Science Research Program Science Focus Areas may be found at http://science.nasa.gov/earth-science/focus-areas. Research aims at advances in:

- **Atmospheric Composition:** understanding and improving predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition;
- **Weather:** enabling improved predictive capability for weather and extreme weather events;

- **Carbon Cycle & Ecosystems:** quantifying, understanding and predicting changes in Earth's ecosystems and biogeochemical cycles, including the global carbon cycle, land cover, and biodiversity;
- **Water & Energy Cycle:** quantifying the key reservoirs and fluxes in the global water cycle and assessing water cycle change and water quality;
- **Climate Variability & Change:** understanding the roles of ocean, atmosphere, land, and ice in the climate system and improving predictive capability for future evolution; and
- **Earth Surface & Interior:** characterizing the dynamics of the Earth surface and interior and form the scientific basis for the assessment and mitigation of natural hazards and response to rare and extreme events.

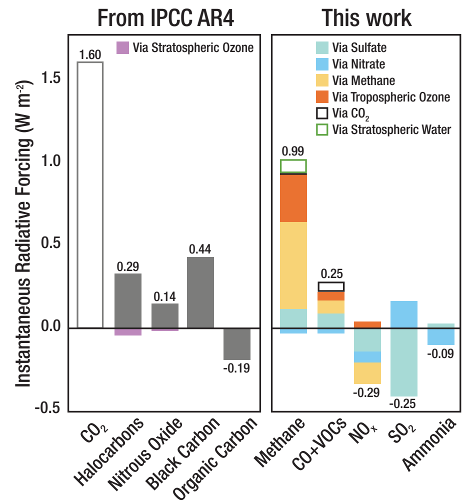
Using the observations from the Flight Program, the Research Program both advances the interdisciplinary field of Earth System Science and provides much of the scientific basis for major periodic assessments of climate change. These include the World Meteorological Organization's triennial ozone assessment, the Assessment Reports of the Intergovernmental Panel on Climate Change, and U.S. national assessments of climate change impacts. The FY2011 budget request enables a greater NASA contribution to the 2013 U.S. National Assessment to be prepared by the U.S. Global Change Research Program.

The Earth Science Research Program is designed to leverage NASA's unique capabilities in the context of related research carried out by other Federal agencies, especially that conducted as part of organized interagency activities (including those coordinated through the Committee on Environment and Natural Resources under the National Science and Technology Council), such as the U.S. Global Change Research Program, the U.S. Group on Earth Observations, the National Oceanographic Partnership Program, the Earth Scope Program, and NASA-National Oceanic and Atmospheric Administration (NOAA) and NASA-USGS efforts to support the transition from research to operations.

The following programmatic elements are of sufficient breadth that they contribute to a broad range of activities within the Earth Science Research Program. They involve the development of some kind of capability, whose sustained availability is considered to be important for the Earth Science Research Program's future.

Airborne and Suborbital Science

The Earth Science Research Program's airborne science program provides access to aircraft and balloon-based platforms that can be used for *in situ*



RIISER-LARSEN ICE SHELF

Breakthrough in Methane and Carbon Monoxide Role in Climate Forcing

A team of NASA researchers at the Goddard Institute for Space Studies found that two greenhouse gases—methane and carbon monoxide—have significantly more powerful impacts on global warming than previously thought. In a paper published in October 2009, the team conducted one of the first modeling experiments designed to rigorously quantify the impact of greenhouse gas-aerosol interactions on climate and air quality. The study found methane's global warming impact has been underestimated, and the combined impacts of emissions that cause both warming and air pollution have as much effect on warming as carbon dioxide does. This improved knowledge of the warming effect of these greenhouse gases will help policymakers devise more efficient strategies to mitigate climate change.

Image Credit: NASA/Goddard

Chapter 4

observation of the atmosphere and remote sensing of the Earth's surface. Airborne and balloon-based platforms may be used to test new measurement approaches, collect detailed *in situ* and remote-sensing observations that are needed to better document and test models of Earth system processes, and provide calibration/validation information for satellites. Airborne and balloon-based platforms contribute to training the next generation of scientists since they enable students to be engaged in all aspects of science, from sensor development, through utilization, to completing analysis of data obtained. The program has been fostering the development of our future workforce with the hands-on involvement of graduate students and young scientists/engineers in all aspects of ongoing Earth science investigations.

Aircraft have proven to be of particular value in Earth system science research for investigation of specific processes. They provide the capability to obtain high-resolution temporal and spatial measurements of complex local processes, which can be coupled to global satellite observations for a better understanding of the Earth system. NASA makes use of several existing aircraft through an annual Call Letter process, most notably the NASA-owned DC-8, WB-57F, ER-2, P-3B, and Global Hawk as well as several independently owned aircraft, including those operated by other Federal agencies. By working with the NASA Aeronautics Research Mission Directorate, SMD hopes to pioneer new types of airborne missions that capitalize on NASA's unique expertise in platforms, sensors, and aeronautical operations.

High-End Computing, Networking, and Storage

High-end computing, networking, and storage are critical enabling capabilities for Earth system science. Satellite observations must be converted into scientific data products through retrieval and/or data assimilation processes. Long-term data sets must be synthesized together and become a physically consistent climate-research quality data set through reanalysis. These data products, in turn, provide initial and boundary conditions, validation and verification references, and internal and external constraints to the models that describe the behavior of the Earth system. None of the above will be possible without advanced techniques in high-end computing, networking, and storage.

SMD recognizes the need for such an enabling capability and maintains the high-end computing, networking, and storage within its programs. Computing resources are provided through various program elements. Proposers to solicitations may request computing resources. NASA also supports computational science research and development, including software designed to exploit an advanced computing architecture to facilitate improvement of Earth system modeling and data assimilation.

Education

The Earth Science Research Program recognizes its essential role in NASA's mission to inspire the scientists and engineers of tomorrow. The Earth system science concept pioneered by NASA is changing not only how science research is conducted, but also the way Earth and space science education is taught at elementary through postgraduate levels, as well as the way space exploration is presented to the public by the media and informal learning communities.

In addition to the education and outreach opportunities that are embedded in and competitively selected as part of the Earth Science flight and research programs, other program announcements are issued periodically to focus on continued workforce enrichment. The Earth Science component of the NASA Earth and Space Science Fellowship (NESSF) program supports the training of graduate students in Earth system science and/or remote sensing. The New Investigator Program in Earth Science, which is directed toward scientists and/or engineers within five years of their receipt of a terminal degree, issues a solicitation every two years.

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 use and benefit to society. The overarching purpose of the Applied Sciences Program is to discover and demonstrate innovative uses and practical benefits of NASA Earth science research, technology, and observations.

The Applied Sciences Program primarily works through partnerships with organizations that have established connections to users and decision makers. The Program supports applied science research and applications projects to promote innovation in the use of NASA Earth science, transition of applied knowledge to public and private organizations, and integration of Earth science in organizations' decision making and services, helping to improve the quality of life and strengthen the economy.

The Program is organized thematically to support integration of Earth science in specific decision-making activities: Agriculture, Air Quality, Climate, Ecological Forecasting, Public Health, Natural Disasters, Water Resources, and Weather. The Program also manages specific activities to build skills and capabilities in the US and developing countries to access and apply NASA Earth science, currently including DEVELOP, SERVIR (with USAID), the Gulf of Mexico Initiative, and related training modules.

The Applied Sciences Program has three primary goals articulating priority directions.

- **Enhance Applications Research:** Identify and track evolving societal needs, assess trends in technology and decision-support tools, conduct applied research to generate innovative applications, and support projects that demonstrate uses of NASA Earth science.
- **Increase Collaborations:** Pursue and focus on partnerships to share costs and risks, promote partner collaborations to extend the Program's reach and impact, and pursue projects that reflect the multidisciplinary nature of Earth science applications, including scientific, technological, social, behavioral, and economic aspects.
- **Accelerate Applications:** Enable identification of applications early in a mission's lifecycle, integrate user needs into future mission planning, enable applied sciences involvement in mission science teams, and facilitate communication between applications communities and Earth science research and flight mission communities.

In the coming years, the Program will continue to promote and support applications projects. Scores of projects will reach maturity and deliver results in the near-term, and the Program plans to increasingly demonstrate the uses, articulate benefits, and promote transitions for sustained use by the partners. The Program will also expand applied research activities crossing several applications themes. The Program will augment SERVIR, including increased capabilities of the U.S. office to serve as a test-bed facility for domestic and international applications. The Program also plans greater attention to climate-related issues and applications across all parts of the program.

With a significant portion of NASA Earth science satellites currently in extended mission phase, the Applied Sciences Program may face a challenge of interesting new partners in investing resources and integrating observations from aging satellites in their decision-making activities. The Program will place increasing emphasis on involving partners and applications specialists in mission planning and science teams to identify potential applications sooner and to sustain their interest.

The Applied Sciences Program serves as a bridge between the data and knowledge generated by NASA Earth Science and the information and decision making needs of public and private organizations. To this end, the Applied Sciences Program seeks to increase the benefits to society of the nation's investments in NASA Earth Science.

Earth Science Technology Program

This program of competed technology research and development projects advances Earth observing instrumentation, mission components, and advanced information systems to make future missions feasible and affordable. The program is based on a science-driven strategy that employs open peer-reviewed solicitations to produce the best appropriate technologies. The primary science requirements are derived from the NRC Decadal Survey. In general, the second and third Tier Earth science decadal survey missions present increasing technological challenges. A number of the instruments will contain active components such as radars and/or lasers. Other missions will require larger collection optics and antennas to meet requirements. Therefore, NASA has focused its Earth Science Technology Program on advancing technologies needed for the Tier 2 and 3 missions.

The program consists of three 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.

As a final element of the program, aircraft and where possible even space flight validations are performed. The Earth Science Technology Program continues to provide technology developments focused on critical Earth Science measurements with a release every third year (including FY10) of an Instrument Incubator Program solicitation targeted to specific Decadal Survey needs.

The FY11 President's budget request will provide a 10% increase in the technology program to fund new competitively-selected technology developments related to climate measurements, and collaborations with the broader climate community to acquire comparative flight data and validate key components of new technologies. In addition, the Earth Science Technology Program will coordinate with the NASA Office of the Chief Technologist to leverage the investments made by the new Agency technology program defined in the FY11 budget.

Solar Systems as Solar Atmospheres

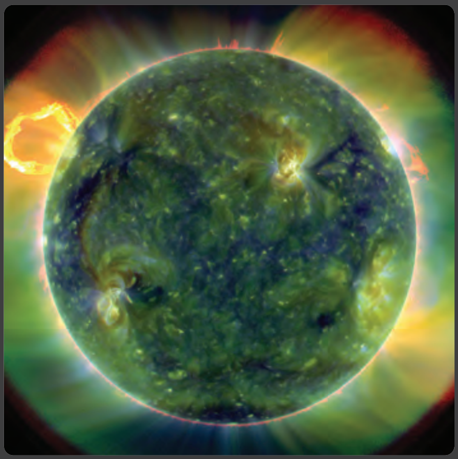
The Sun, our solar system, the universe, and our own Earth's extended space environment consist primarily of plasma, the electrically conducting mixes of positively and negatively charged particles that account for an estimated 99% of the visible universe. Plasmas are more complex than solids, liquids, and gases because the motions of electrons and ions produce both electric and magnetic fields. The electric fields accelerate particles, sometimes to very high energies, and the magnetic fields guide their motions. This results in a rich set of interacting physical processes, including exchanges with the neutral gas in planetary atmospheres.

Although physicists know the laws governing the interaction of electrically charged particles, the collective behavior of the plasma state leads to complex and often surprising phenomena. The same processes can occur in many locations, and with vastly different magnitudes of energy, size, and time. For example, planetary systems form in disks of gas and dust around young stars. Stellar UV emission, winds, and energetic particles alter this process, both in the internal structure of the disk and its interaction with its parent star. The role of magnetic fields in the formation process has not been fully integrated with other parts of the process.

Another example unites three explosive space events—giant magnetar flares, solar flares, and the space weather storms of our own magnetosphere. At their heart is a process known as magnetic reconnection, which taps the energy stored in a magnetic field and converts it to heat and kinetic energy in the form of charged particle acceleration and large-scale flows of matter. Reconnection occurs universally in plasmas. Besides its role in the three examples above, magnetic reconnection has been invoked in theoretical models of a variety of astrophysical phenomena, including star-accretion disk interaction, pulsar wind acceleration, the heating of stellar coronas and the acceleration of stellar winds, and the acceleration of ultra-high-energy cosmic ray in active galactic nuclei jets.

SMD seeks to understand the processes of magnetic reconnection, particle acceleration and transport, ion-neutral interactions, and the creation and variability of magnetic dynamos. As a foundation for each SMD science area's long-term research program, SMD is developing a comprehensive scientific understanding of the fundamental physical processes that control our space environment and that influence our Earth's atmosphere.

Chapter 4



SDO'S FIRST IMAGE

NASA's New Eye on the Sun Delivers Stunning First Images

NASA's recently launched Solar Dynamics Observatory, or SDO, is returning early images that confirm an unprecedented new capability for scientists to better understand our sun's dynamic processes. These solar activities affect everything on Earth.

Some of the images from the spacecraft show never-before-seen detail of material streaming outward and away from sunspots. Others show extreme close-ups of activity on the sun's surface. The spacecraft also has made the first high-resolution measurements of solar flares in a broad range of extreme ultraviolet wavelengths.

"These initial images show a dynamic sun that I had never seen in more than 40 years of solar research," said Richard Fisher, director of the Heliophysics Division at NASA Headquarters in Washington. "SDO will change our understanding of the sun and its processes, which affect our lives and society. This mission will have a huge impact on science, similar to the impact of the Hubble Space Telescope on modern astrophysics."

Image Credit: NASA/SDO/AIA

4.2 Heliophysics

Strategy

At the center of our solar system is a magnetic variable star, our Sun, that drives the space environment of the planets, including the Earth, and sculpts the flows of interplanetary space itself. At the dawn of the space age, the earliest experiments discovered this link between the Sun and the Earth: Explorer 1 (1958—radiation belts), Mariner 2 (1962—solar wind) and Skylab (1973—coronal mass ejections and coronal holes as the source of solar wind). This led to the understanding that stars interact with the universe not just through gravity and photon radiation but also through electromagnetic fields and particles.

Our planet is immersed in a seemingly invisible yet exotic and inherently hostile environment. Above the protective cocoon of Earth's atmosphere is a plasma soup composed of electrified and magnetized matter entwined with penetrating radiation and energetic particles. Our Sun's energy output, which varies on time scales from milliseconds to billions of years, forms an immense structure of complex magnetic fields. Inflated by the solar wind, this colossal bubble of magnetism, known as the heliosphere, stretches far beyond the orbit of Pluto. This extended atmosphere of the Sun drives some of the greatest changes in our local space environment—affecting our magnetosphere, ionosphere, atmosphere, and potentially our climate.

Heliophysics is the study of these interactions throughout the region of space influenced by the Sun. It seeks to understand these influences throughout the solar system but, in particular, the connection to the Earth and the Earth's extended space environment. The science of Heliophysics provides cultural and intellectual research benefits and the application of new research results also provide economic benefit for modern society.

It is a bold enterprise to strive to understand the vast and seemingly invisible connections that govern the environment within our solar system. But with new understanding in this area it is possible to forecast the highly variable conditions that affect our planet and through which human and robotic space explorers must travel. An effective plan requires viewing the Sun, heliosphere, and planetary environments as elements of a single interconnected system—one that contains dynamic space weather and space climatology, and that evolves in response to solar, planetary, and interstellar conditions.

NASA's role is to answer fundamental questions about this system's behavior:

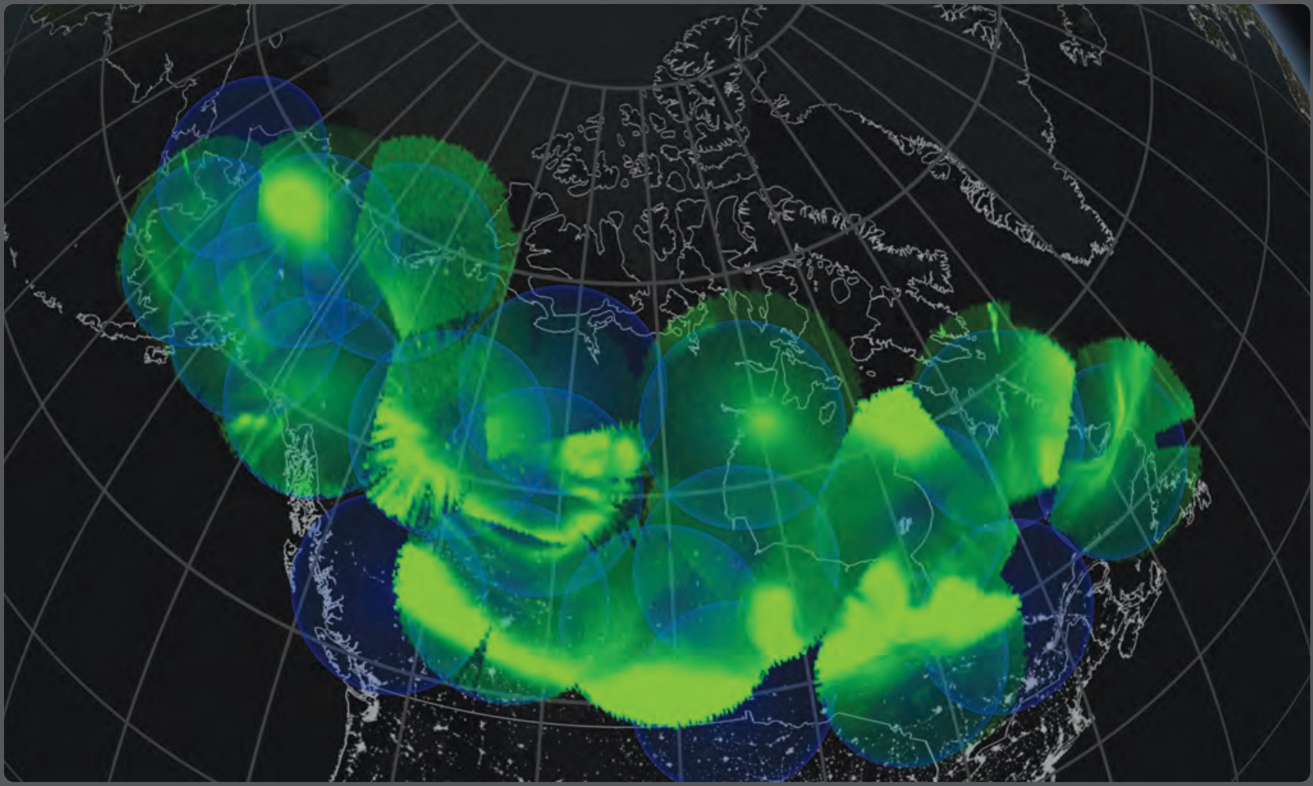
- What causes the Sun to vary?
- How do the Earth and the heliosphere respond?
- What are the impacts on humanity?

We know that the Sun, the solar system, and the region of the galaxy just outside the solar system present us with a complex, interacting set of physical

Lighting up the Night

Researchers using a fleet of five NASA satellites discovered in 2008 that explosions of magnetic energy occurring a third of the way to the moon power substorms that cause sudden brightenings and rapid movements of the aurora borealis, or Northern Lights. The cause is magnetic reconnection, a common process that occurs throughout the universe when stressed magnetic field lines suddenly snap to a new shape, like a rubber band that has been stretched too far. These substorms often accompany intense space storms that can cause power outages and disrupt radio communications and global positioning system signals. Scientists are studying the beginning of substorms using a network of 20 ground observatories located throughout Canada and Alaska and five THEMIS, or Time History of Events and Macroscale Interactions during Substorms, satellites.

Image Credit: NASA/THEMIS, GSFC SVS



processes. But it is also the part of the cosmos accessible to *in situ* scientific investigation; it is a hands-on astrophysical laboratory. The NRC decadal survey in this area, *From the Earth to the Sun: A Decadal Survey for Solar and Space Physics*, (NRC, 2003), articulated the scientific challenges for this field of study and recommended a slate of missions to meet them, to culminate in the achievement of a predictive capability to aid human endeavors on Earth and in space.

Based on this NRC decadal survey and U.S. goals in space, NASA's strategic goal, **Understand the Sun and its interactions with the Earth and the solar system**, has been parsed into three Heliophysics science objectives to guide the selection of investigations and other programmatic decisions:

- **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 interacting with planetary magnetic fields and atmospheres; and,
- **Safeguard the Journey of Exploration:** Maximize the safety and productivity of human and robotic explorers by enabling the capability to predict the extreme and dynamic conditions in space.

The Heliophysics Division at NASA has made a strategic commitment to "systems science" in approaching these scientific objectives—to seek understanding of the processes and interconnections at work across the traditional scientific disciplines involved. The heliospheric system is highly complex over large and small spatial scales and a variety of temporal scales. The same basic physics can be at work at the Sun, at the near-Earth space environment, and at the edge of the heliosphere. This means that different components of the system are intertwined, making the study of isolated parts inefficient and, at times, unsuitable. Processes observed in one part of the system can be used to correlate to and understand observations made elsewhere. This interdependence requires a renewed consilience of flight and research programs to integrate observations, theory, and modeling as well as direct future technology and workforce development activities.

Program Implementation

The Heliophysics science program consists of two strategic programs/mission lines: the Solar Terrestrial Probes and Living with a Star; one Principal Investigator-led competed line (the Explorers); and a set of Research programs including the Heliophysics System Observatory. All play a part in the development of scientific understanding of the heliophysics system. Partnerships with other national and international agencies and within NASA provide additional opportunities to meet shared science goals.

Solar Terrestrial Probes provide understanding of the fundamental processes inherent in all astrophysical systems and how they affect the nature of our Earth's home in space. The goal is to understand the processes that determine the mass, momentum, and energy flow in the solar system from the Sun to planetary bodies, including Earth, to the interstellar boundary. The three currently operating STP missions are the Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED) mission, the Solar TErrestrial RElations Observatory (STEREO), and the JAXA/NASA Hinode. TIMED provides a fundamental climate data record for upper atmosphere circulation models. STEREO provides the only 3-dimensional views of coronal mass ejections, a major driver of space weather phenomena. Hinode is validating theoretical models of solar coronal heating. The results have been significant not only because they help us to understand energy conversion at the Sun, but also because we now better understand the source and impacts of the energy absorbed by the Earth's magnetosphere, ionosphere, and upper atmosphere.

The next mission in the STP program is the Magnetospheric Multiscale (MMS) mission, a four-spacecraft constellation designed to use Earth's magnetosphere as a laboratory to study the microphysics of magnetic reconnection, a fundamental process that converts magnetic energy into heat and the kinetic energy of charged particles. In addition to solving the mystery of the reconnection process, MMS will also investigate how the energy conversion that occurs accelerates particles to high energies and what role plasma turbulence plays in reconnection events. The mission is in development for launch in 2015.

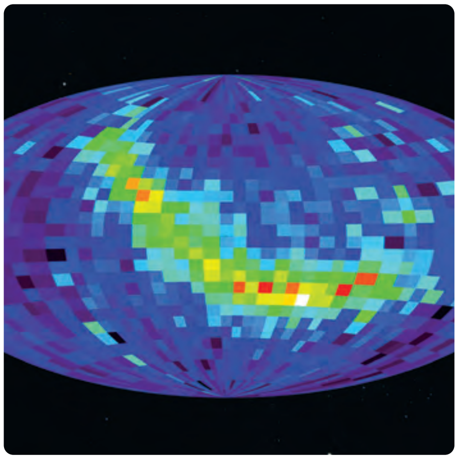
Living With a Star emphasizes the science necessary to understand those aspects of the Sun and space environment that most directly affect life and society. LWS missions target the linkages across the interconnected system with an ultimate goal of enabling a predictive understanding. The first LWS mission is the Solar Dynamics Observatory (SDO), which was launched early in 2010. This mission observes how the Sun's magnetic field is generated and structured and stored magnetic energy is converted and released into the heliosphere in the form of solar wind, energetic particles, and variations in the solar irradiance. The second LWS mission will be the Radiation Belt Storm Probes (RBSP). The twin RBSP spacecraft will determine how charged particles in space near the Earth are accelerated to hazardous energies that affect satellites, astronaut safety, and high-altitude aircraft. Concurrently with RBSP, the Balloon Array for Radiation-belt Relativistic Electron Losses (BARREL) will measure the high-energy particle precipitation from the radiation belts into our Earth's atmosphere. RBSP will launch in 2012.

Following RBSP are the Solar Probe Plus mission and Solar Orbiter Collaboration. Solar Probe is mankind's first mission to a star and will travel into one of the last unexplored regions of our solar system, the Sun's corona. Solar Orbiter is a Sun-observing satellite under study as a collaborative mission with the European Space Agency. Solar Orbiter will be the first satellite to provide close-up views of the Sun's polar regions, which are very difficult to see from Earth.

An LWS Science component provides two services to the missions planned. First, the program supports Targeted Research and Technology (TR&T) investigations in a few key areas, especially those crossing boundaries between scientific disciplines and research techniques. Second, LWS supports the comprehensive models required for development of a forecast capability. These Strategic Capability models are made available (e.g. via the Community Coordinated Modeling Center) for use by the scientific community and for evaluation for potential transition to operational use.

The Space Environment Testbeds (SET) Project is an element of the LWS Program that characterizes the space environment and its impact on hardware performance in space. The goal is to improve engineering approaches to mitigating solar weather effects on spacecraft design and operations. The SET-1 instrumentation is set for a 2012 launch on a technology spacecraft sponsored by the U.S. Air Force.

The Explorer program complements the two strategic mission programs described above by providing smaller competitively selected PI-led missions. The program provides frequent flight opportunities for investigations focused on new scientific questions revealed by the larger strategic missions. Priorities are based on an open competition of concepts solicited from the scientific community. The most recently launched Heliophysics Explorers are AIM, THEMIS, and IBEX. AIM,



IBEX Map of the Solar System Boundry

NASA's Interstellar Boundary Explorer, or IBEX, spacecraft allowed scientists to construct the first comprehensive sky map of our solar system and its location in the Milky Way galaxy. The sky map was produced with data that two detectors on the spacecraft collected during six months of observations. The detectors measured and counted particles scientists refer to as energetic neutral atoms. The new map revealed the region that separates the nearest reaches of our galaxy from our heliosphere—the protective bubble that shields and protects our solar system from most of the dangerous cosmic radiation traveling through space. This new map will change the way researchers view and study the interaction between our galaxy and sun.

Image Credit: NASA/IBEX

the Aeronomy of Ice in the Mesosphere mission, is providing major advances in understanding polar mesospheric clouds (PMCs), the highest clouds in the Earth's atmosphere. In addition, AIM has made the first global measurements of meteoric smoke particles in Earth's upper atmosphere. THEMIS, the Time History of Events and Macroscale Interactions during Substorms mission, has been investigating the 'double layer' mechanism that accelerates particles in the Earth's magnetotail. This same mechanism accounts for the strong, long-lived particle acceleration in the Earth's aurora. The latest Heliophysics Explorer mission to launch is IBEX, the Interstellar Boundary Explorer, which observes the heliospheric boundary from high Earth orbit. The most recently selected Heliophysics Explorer is IRIS, the Interface Region Imaging Spectrograph, which will explore the flow of energy and plasma at the foundation of the Sun's atmosphere. IRIS will launch in 2012. A new competition for Explorer missions will open late in 2010.

Heliophysics Research: A hierarchy of supporting research programs provides two services to meet SMD's Heliophysics science goals. First the program provides a solid scientific basis for the conceptualization of future missions. Second, the supported investigations provide the method by which integration of the science of the many flight missions is ultimately realized. This research program is an end-to-end one that starts with the formulation of theories of the phenomena proposed for future mission study and the design of experimental studies to test those theories. The program supports the development of observational techniques and the instrument technologies needed to implement them. Proof of concept experiments are conducted in the laboratory or from an appropriate set of balloon-, sounding rocket- and/or space-based platforms. A broad range of investigations proposed by the Heliophysics science community is supported to increase scientific knowledge across the discipline. Another set of investigations is supported to increase the scientific output of missions currently in flight. The results are incorporated into computational models used to more fully characterize the present state and future evolution of the Heliophysics system. Other national and international agencies use the generated knowledge in their space weather forecasting and in policy and resource management.

- The *Heliophysics Theory Program* is the foundation. Supported investigations integrate the advancements of previous work and evolve the scientific theories and concepts to be pursued by future missions. The program supports larger PI-proposed team efforts that require a critical mass of expertise in order to make significant progress in understanding complex physical processes with broad importance.

- The *Supporting Research and Technology Program* is an ever-evolving suite of individual PI-led investigations that cover the complete range of science disciplines and techniques essential to achieve Heliophysics research objectives. The program has three elements: analysis and interpretation of space data, development of new instrument concepts, and laboratory measurements of relevant atomic and plasma parameters.

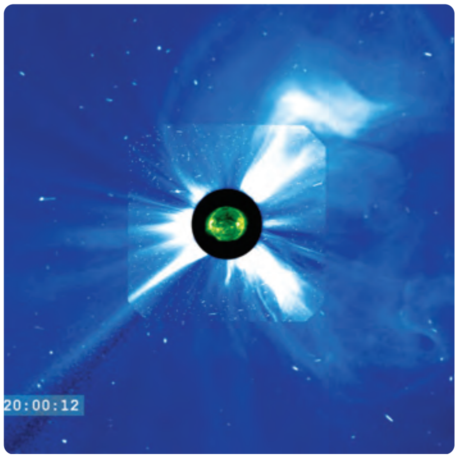
- *Supporting Research investigations* serves as the advanced planning arm of Heliophysics research. Results of investigations guide the direction and content of future science missions. Individual tasks employ a variety of techniques (e.g., theory, numerical simulation, and modeling), analysis and interpretation of space data, development of new measurement concepts, and laboratory measurements of relevant atomic and plasma parameters.

- *Instrument and Technology Development* supports the development of instrument concepts that show promise for use on future Heliophysics missions.

- *The Low-Cost Access to Space* (LCAS) program, which includes balloon and sounding rocket investigations, supports science investigations that may be completed through suborbital flight, as well as proof-testing new technologies that may ultimately find application in free-flying Heliophysics space missions.

- The *Heliophysics System Observatory (HSO):* Each Heliophysics flight mission has a specific, often tightly focused scientific goal. In addition, the missions taken together form an extended sensor web of spacecraft that are utilized to understand the dynamics of the solar system as an integrated whole. Experience has demonstrated that combinations of heretofore-uncoordinated observations enable larger, solar-system-scale investigations. This distributed observatory has flexibility and capabilities that evolve with each new mission launched. Knowledge, data, and new interpretive models facilitate the path toward new scientific understanding. In addition to its science value, the system observatory forms the backbone of NASA's ability to enable an operational capability for predicting space weather, a priority of the National Space Policy.

- The *Guest Investigator Program* is focused on maximizing the scientific return of the missions of the HSO. The focus of the selected



NASA's STEREO Spacecraft Show Three-dimensional Anatomy of a Solar Storm

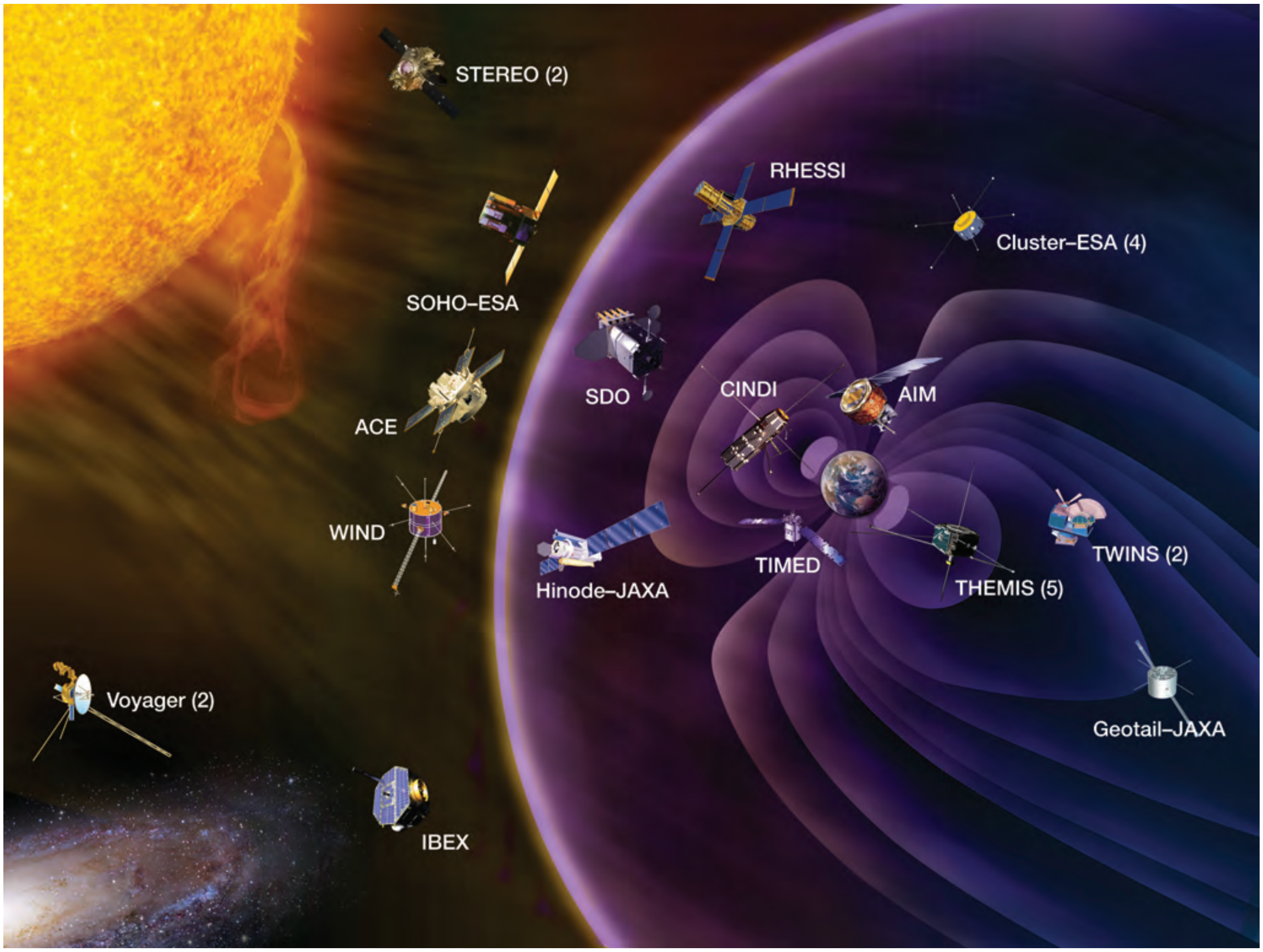
NASA's twin Solar Terrestrial Relations Observatory, or STEREO, spacecraft have provided scientists with their first view of the speed, trajectory, and three-dimensional shape of powerful explosions from the sun known as coronal mass ejections, or CMEs. This new capability will dramatically enhance scientists' ability to predict if and how these solar storms could affect Earth. When directed toward our planet, these ejections can be breathtakingly beautiful and yet potentially cause damaging effects worldwide. The brightly colored phenomena known as auroras—more commonly called Northern or Southern Lights—are examples of Earth's upper atmosphere harmlessly being disturbed by a CME. Satellite communications, navigation systems, and electrical power to our homes can all be disrupted by magnetic storms triggered by solar activity.

Launched in October 2006, STEREO's nearly identical observatories can make simultaneous observations of these ejections of plasma and magnetic energy that originate from the sun's outer atmosphere, or corona. The spacecraft are stationed at different vantage points. One leads Earth in its orbit around the sun, while the other trails the planet.

Image Credit: NASA/STEREO

Chapter 4

Figure 4.2 Current Heliophysics Science Missions in Operation



research continuously evolves to ensure that the most important questions identified by the biannual Senior Review are addressed.

Perhaps most important, international partnerships have augmented the capabilities of most Heliophysics science missions. The technical teamwork between the U.S. and other space agencies permit investigations that could not be achieved separately. Examples of international partnerships with high value to the heliophysics program include SOHO, GEOTAIL, CLUSTER, and Hinode. Solar Orbiter is a new ESA mission for which NASA will provide Heliophysics instrumentation and launch.

In addition to its science program, the Heliophysics Division routinely partners with other agencies to fulfill the space weather research or operational objectives of the nation. Examples include the real-time space weather data supplied by the ACE, STEREO, and SDO missions; the Coupled Ion-Neutral Dynamics Investigation (CINDI) instrument supplied to the Air Force C/NOFS satellite, and the Two Wide-angle Imaging Neutral Atom Spectrometers (TWINS-A & B) provided for two National Reconnaissance satellites. In turn, the National Reconnaissance Office (NRO) has provided the Proton Spectrometer Belt Research (PSBR) instrument to NASA's RBSP spacecraft.

Current Missions

As noted above, NASA operates its constellation of Heliophysics missions as a System Observatory, utilizing the entire fleet of solar, heliospheric, geospace, and planetary spacecraft as a sensor web to discover the larger scale and/or coupled processes at work throughout the space environment. Heliophysics is unique in that the relevant decadal survey often emphasizes missions that employ fleets of satellites to provide multi-point diagnostics. By combining the measurements from all deployed space assets, some of these decadal survey goals can be met earlier in time. Heliophysical system science is enabled across the vast spatial scales of our solar system, such as the solar wind in free space and its interaction with the magnetic fields of the planets, as well as with the interstellar medium. Figure 4.2 shows the currently operating and near term HSO.

American science has never been so well prepared for the onset of the next solar cycle. Even with the sparse set of observations deployed thus far we are beginning to assemble system-wide models. The current era is a "golden age" for Heliophysics. The twin STEREO spacecraft were launched in 2006. Japan's Hinode satellite was also launched in 2006 with three U.S. instruments onboard. AIM and THEMIS were launched in 2007. The CINDI instrument was launched on the USAF's C/NOFS in the spring of 2008. IBEX was launched in 2008. SDO was launched in 2010. These spacecraft join an existing constellation of 15 other U.S. and international spacecraft that monitor the Sun, Geospace, and the space environment between the Sun and the Earth, such as the Cluster and Wind spacecraft and the two Voyager spacecraft that are exploring the farther reaches of the heliosphere. The

Table 4.2a Heliophysics Missions in Development or Formulation (with launch year noted)

Radiation Belt Storm Probes (RBSP)—2012 Strategic Mission; Living with a Star	Understand how radiation environments hazardous to satellites and humans form and change; this mission is one half of the #2 priority mid-scale mission in the 2003 decadal survey.
Magnetospheric Multiscale (MMS)—2015 Strategic Mission; Solar Terrestrial Probes	Understand the microphysics of three fundamental plasma processes: magnetic reconnection, energetic particle acceleration, and turbulence; this mission is the #1 priority mid-scale mission in the 2003 decadal survey.
Interface Region Imaging Spectrograph (IRIS)—2012 Competed mission; Small Explorer	Small Explorer mission to study the solar chromosphere to understand energy transport into the solar wind.
Solar Orbiter—2017 Strategic Collaboration with ESA; Living with a Star	Partnership with ESA to measure properties and dynamics of solar wind; this mission is the #4 priority small-scale mission in the 2003 decadal survey.
Solar Probe Plus—2018 Strategic Mission; Living with a Star	Probe the processes controlling heating of the solar corona; this mission is the highest-priority large-scale mission in the 2003 decadal survey.

Heliophysics Division also operates instrumentation on foreign space missions, such as the Solar and Heliospheric Observatory (SOHO).

Heliophysics augments its program with Missions of Opportunity deployed on other agency's satellites, as done with TWINS and CINDI with DoD. Heliophysics also utilizes the considerable synergies 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 fulfills the third priority mid-scale mission recommendation in the Heliophysics decadal survey. In addition, some planned space radiation research topics can be addressed with the LRO Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument and the MSL Radiation Assessment Detector (RAD) instruments.

Missions in Formulation and Development

The Heliophysics missions now in development or formulation for launch over the next decade address some of the highest priorities in the Heliophysics decadal survey. As one example, to meet a longstanding NRC recommendation, SMD recently challenged the scientific community to develop a more affordable, nonnuclear powered version of the Solar Probe mission. The science community has met the challenge, and thus Solar Probe Plus was included as a new initiative in the FY 2009 budget. The missions now in development or formulation are shown in Table 4.2a.

Future Missions

In advance of the next NRC decadal survey in this area, SMD's Heliophysics Division chartered a group of community scientists under the auspices of the Heliophysics Subcommittee of the NASA Advisory Council to prepare a strategic roadmap for the next two decades. This strategic roadmap employs a new approach to address two issues inherent in the previous decadal survey. First, by adopting a commitment to a series of competed cost-capped missions, several missions will be deployed over the range of locations needed to address the integrated system science research strategy recommended by the 2003 Decadal Survey. Second, by emphasizing the scientific objective for each mission, pre-formulation phases will be devoted to developing enabling technologies, stable requirement trees, and to the development of a variety of implementation strategies to better manage costs within the prescribed cost-caps. Definition of the final mission design will be in response to competitive cost-capped solicitations. This paradigm shift to focus on science strategy during the planning phases, rather than tactical implementation, is intended to enable the flexibility needed to respond to new scientific advances, changes in the cost of doing business, the availability of new launch options, and the potential for partnership opportunities.

The new roadmap establishes a queue of science targets for the two Heliophysics strategic mission lines, as shown in Table 4.2b. These science targets address the most urgent and compelling science issues in Heliophysics and provide several new opportunities for discovery.

The Explorer Program has a well-known history of high science return for a relatively small investment. This program is essential to providing the mix of large, medium, and small missions known to be required for a robust scientific flight program. NASA will continue the Explorer program with periodic solicitations, with the timing and mission size determined by available resources. Strategic planning recommendations indicate that a Heliophysics Explorer should be launched once every two years in order to address new scientific inquiries and space weather initiatives that will emerge during the conduct of the strategic program.

Table 4.2b Heliophysics Future Missions (with notional launch year from 2009 Heliophysics Roadmap)

Origins of Near Earth Plasma—2018 Solar Terrestrial Probe	Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.
Climate Impacts of Space Radiation—2020 Living With a Star	Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on ozone.
Solar Energetic Particle Acceleration and Transport—2021 Solar Terrestrial Probe	Understand how and where solar eruptions accelerate energetic particles that reach the Earth.
Dynamic Geospace Coupling—2023 Living With a Star	Understand how magnetospheric dynamics provides energy into the coupled ionospheric-magnetospheric system.
Ion-Neutral Coupling in the Atmosphere—2025 Solar Terrestrial Probe	Understand how neutral winds control ionospheric variability.
Heliospheric Magnetics—2026 Living With a Star	Understand the flow and dynamics of transient magnetic structures from the solar interior to Earth.

The next NRC decadal survey for Heliophysics is underway. It should be completed in early 2012.

Applications of Heliophysics Science

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities become more obvious and more worrisome. A report issued in December 2008 by the NRC addressed the impacts of space weather events on human technologies. The report, *Severe Space Weather Events—Understanding Societal and Economic Impacts*, estimates that the economic cost of a severe geomagnetic storm could reach $1–$2 trillion during the first year, with a recovery period of 4–10 years. These long recovery times would result from damage to large power transformers and other hard-to-replace facilities.

Modern society depends on a variety of technologies susceptible to the extremes of space weather. Strong electrical currents driven along the Earth's surface during auroral events disrupt electric power grids and contribute to the corrosion of oil and gas pipelines. Changes in the ionosphere during geomagnetic storms interfere with high-frequency radio communications and Global Positioning System (GPS) navigation. During polar cap absorption events caused by solar protons, radio communications can be compromised for commercial airliners on transpolar crossing routes. Exposure of spacecraft to energetic particles during solar energetic particle events and radiation belt enhancements cause temporary operational anomalies, damage critical electronics, degrade solar arrays, and blind optical systems such as imagers and star trackers.

Human and robotic explorers across the solar system are also affected by solar activity. Research has shown, in a worst-case scenario, astronauts exposed to solar particle radiation can reach their permissible exposure limits within hours of the onset of an event. Surface-to-orbit and surface-to-surface communications are sensitive to space weather storms in the ionospheres, thermospheres, and mesospheres of planetary bodies. Aerobraking utilizes the thermosphere and mesosphere of a body and depends on knowledge of upper atmosphere neutral density. Dust grain adhesion on astronaut suits and instrumentation is a plasma physics problem that is not well understood or resolved.

Currently, protection of humans in space is an operational activity within the Space Operations Mission Directorate, which supports the International Space Station and Space Shuttle flights. Collaborations between Heliophysics supported scientists and those preparing for human and robotic exploration are fostered through interdisciplinary research programs and the common use of NASA research assets in space. The Heliophysics Division also collaborates with the Space Radiation Analysis Group at NASA's Johnson Space Center, which is responsible for ensuring that the radiation exposure of astronauts remains below established safety limits.

Beyond NASA, interagency coordination in space weather activities has been formalized through the Committee on Space Weather, which is hosted by the Office of the Federal Coordinator for Meteorology. This multiagency organization is co-chaired by representatives from NASA, NOAA, DoD, and NSF and functions as a steering group responsible for tracking the progress of the National Space Weather program. External constituencies requesting and making use of new knowledge and data from NASA's efforts in Heliophysics include the FAA, DoD, and NOAA.

Partnerships are NASA's preferred method for satisfying the national need for space weather knowledge and observations. Presently, this is accomplished with the existing fleet of NOAA satellites and some NASA scientific satellites. Space weather "beacons" on NASA spacecraft provide real-time science data to space weather forecasters. Examples include ACE measurements of interplanetary conditions from L1, CME alerts from SOHO, and STEREO beacon images of the far side of the Sun. NASA will continue to cooperate with other agencies to enable new knowledge in this area and to measure conditions in space critical to both operational and scientific research.

To facilitate and enable this cooperation, the Science Mission Directorate makes its Heliophysics research data sets and models continuously available to industry, academia, and other civil and military space weather interests via existing Internet sites. These include the Combined Community Modeling Center and the Integrated Space Weather Analysis System associated with GSFC. Also provided are publicly available sites for citizen science and space situational awareness through various cell phone and e-tablet applications.

The Science of Exploration

In addition to advancing NASA's scientific goals, SMD missions and research also generate data and knowledge important to the advance of NASA's human exploration goals. Since Explorer I discovered the Van Allen radiation belts while orbiting the Earth, robotic missions have tested the waters for human exploration as either the product or byproduct of their scientific investigations. The International Space Station embodies the knowledge gained over decades enabling safe and productive operations in low Earth orbit. As NASA and partners prepare for exploration beyond LEO, the question to be answered next is "what are the hazards and resources in the solar system environment that will affect the extension of human presence in space?"

NASA's Exploration Systems Mission Directorate (ESMD) is initiating a new program of Exploration Precursor Robotic Missions to fulfill the Agency's objective to "conduct robotic missions to scout destinations, find resources, and lower risk for future human exploration." Led by ESMD, NASA will send precursor robotic missions to candidate destinations for human exploration such as the Moon, Mars and its moons, Lagrange points, and nearby asteroids to scout targets for future human activities and identify hazards and resources that will determine the future course of expanding human civilization into space. This represents significant opportunities for ESMD-SMD cooperative partnerships, similar to the highly successful and currently operating Lunar Reconnaissance Orbiter (LRO). Projects will make critical observations, test approaches and operations concepts, and identify specific target destinations directly beneficial to future human space activities. Instruments, destinations, and missions will be prioritized based on their utility to future human activities, but as has been shown by LRO, significant science can also be conducted during such missions.

Portions of SMD's Planetary Science and Heliophysics research portfolios also contribute to answering this question, and thus SMD's relevant activities are managed and budgeted in those two areas. In Planetary Science, the directly relevant programs are the Lunar Quest and Mars Exploration programs. In addition, depending on the future direction of human exploration, the portion of the Research and Analysis program addressing Near-Earth Objects will also be relevant. Future solicitations in the Discovery and New Frontiers programs may include scientific missions to probe destinations also of interest for future human exploration.

Regardless of destination, elements of the Heliophysics program provide scientific understanding essential to the protection of human and robotic explorers. The Living with a Star and Solar-Terrestrial Probes programs explore the solar phenomena and their interactions with planetary environments that produce what is known as 'space weather.' Solar radiation and solar coronal mass ejections pose hazards to human health and to the functionality of equipment and robotic missions. SMD provides the scientific measurements and understanding that enables space weather prediction, NOAA performs space weather forecasting using NASA research assets, and the NASA Office of the Chief Engineer leads the effort to identify and meet human exploration needs for space weather information.

SMD and ESMD are coordinating their respective mission and research plans to share mission results and identify areas for collaboration.

Chapter 4

4.3 Planetary Science

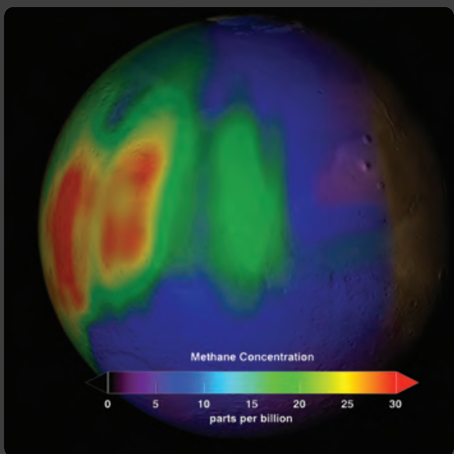
Strategy

Planetary science is a grand human enterprise that seeks to understand the history of our solar system and the distribution of life. 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).

NASA is at the leading edge of a journey of scientific discovery that will yield a profound new understanding of our solar system. Robotic exploration is the current approach to planetary science and is the necessary precursor to the expansion of humanity beyond Earth. Ground-based observations supplement our space-based assets. In the future, humans will go to and explore the Moon, asteroids, Mars, and ultimately other bodies.

NASA's goal in Planetary Science is to "Ascertain the content, origin, and evolution of the solar system, and the potential for life elsewhere." Underlying this goal are the themes of comparative planetology and habitability—the capacity of an environment (which pertain to an entire planet) to harbor life in the past, present, or future. We pursue this goal by seeking answers to fundamental science questions that guide NASA's solar system exploration:

- What is the inventory of solar system objects and what processes are active in and among them?
- How did the Sun's family of planets, satellites, and minor bodies originate and evolve?
- What are the characteristics of the solar system that lead to habitable environments?
- How and where could life begin and evolve in the solar system?
- What are characteristics of small bodies and planetary environments that pose hazards and/or provide resources?



METHANE ON MARS

Methane on Mars Suggests "It's Alive!"

The Mars methane mystery continues with a team of NASA and university scientists using Earth-based telescopes to detect methane and its rapid global variation in the atmosphere of Mars. The presence of methane indicates the planet is either biologically or geologically active, or both, while its rapid disappearance challenges our understanding of the chemical sinks for this possibly biogenic trace gas. The team found methane in the Martian atmosphere by carefully observing the planet during several Mars years with NASA's Infrared Telescope Facility and the W.M. Keck telescope, both located at Mauna Kea in Hawaii. The team detected three spectral features called absorption lines that together are a definitive signature of methane. If microscopic Martian life is producing the methane, it likely resides far below the surface, where it is warm enough for liquid water to exist. It is possible a geologic process produced the Martian methane, either now or eons ago. On Earth, the geochemical conversion of certain iron oxide minerals into a group of more oxidized minerals creates methane. On Mars, this process could occur using water, carbon dioxide and the planet's internal heat.

Image Credit: NASA

NASA's Planetary Science program pursues a strategy of surveying the planetary bodies of interest and targeting for repeated visits those likely to enable greatest progress toward answering the above science questions. For selected planetary bodies, successive visits progress from fly-by missions, to orbiters, to landers and entry probes, to rovers, to sample return missions. With the launch of the New Horizons mission to Pluto and the Kuiper Belt, the launch of Dawn to the asteroids Ceres and Vesta, and the flight of MESSENGER to explore Mercury's previously unseen hemisphere, and robotic exploration of the Martian surface, NASA is making significant progress on its reconnaissance of the major bodies in the solar system. Missions currently in development and those planned for the future continue the next steps.

In planning for the future, the Planetary Science Division lays out programs with three major classes of destinations in view:

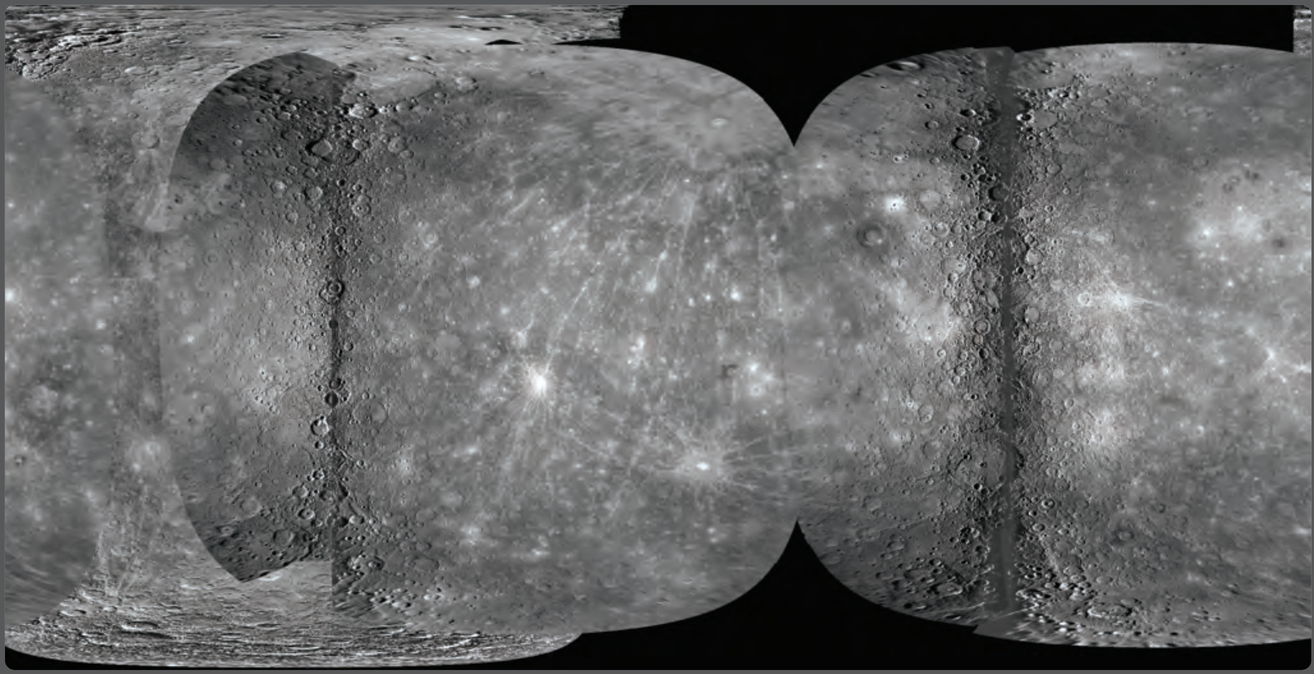
- **Inner planets:** Earth's Moon, Mars and its satellites, Venus, and Mercury

MESSENGER Team Releases First Global Map of Mercury

NASA's MESSENGER mission team and cartographic experts from the U. S. Geological Survey have created a critical tool for planning the first orbital observations of the planet Mercury—a global mosaic of the planet that will help scientists pinpoint craters, faults, and other features for observation. The map was created from images taken during the MESSENGER spacecraft's three flybys of the planet and those of Mariner 10 in the 1970s.

The MESSENGER spacecraft completed its third and final flyby of Mercury on September 29, 2009 concluding its initial reconnaissance of the innermost planet. The MESSENGER team has been busily preparing for the yearlong orbital phase of the mission, beginning in March 2011, and the near-global mosaic of Mercury from MESSENGER and Mariner 10 images is key to those plans.

Image Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington/U. S. Geological Survey/Arizona State University



- **Outer planets:** Jupiter and its moons, especially Europa; Saturn and its moons, especially Titan and Enceladus; Uranus and its satellites; Neptune and its moon Triton; Pluto and its satellites, and Kuiper Belt Objects
- **Small bodies:** Comets, asteroids, and planetary rings.

The major flight and research program elements of the Planetary Division are:

Discovery Program: a series of PI-led medium-size innovative planetary missions solicited from the community as complete scientific investigations through an open, competitive Announcement of Opportunity. The Dawn (asteroids) and MESSENGER (Mercury) missions are examples of Discovery missions launched in recent years.

New Frontiers Program: a series of PI-led large planetary missions solicited from the community as complete scientific investigations through an open, competitive Announcement of Opportunity. In New Frontiers solicitations, the set of candidate mission concepts/science targets from which Principal Investigator may propose is specified based on the recommendations of the NRC's decadal survey. New Horizons (Pluto) and Juno (Jupiter) are New Frontiers missions.

Lunar Quest Program: The prospect of a human space exploration program operating beyond low Earth orbit has fostered a renaissance in lunar science, as a potential return of humans to the Moon both requires and enables greater scientific understanding of Earth's natural satellite. The NRC's report *The Scientific Context for Exploration of the Moon* (NRC, 2007) provided a "mini-decadal survey" for a focused lunar science program. This program includes flight missions (first, the Lunar Atmosphere and Dust Environment Explorer mission), sponsored research, and the NASA Lunar Science Institute. Responsibility for operation of the Lunar Reconnaissance Orbiter (LRO) moves from ESMD to SMD in September 2010 following completion of its one-year exploration mission for ESMD.

Mars Exploration Program: SMD continues it strategy of launching successive missions to Mars (roughly every 26 months) to evolve a scientifically integrated architecture of orbiters, landers and rovers. The goal to "follow the water" helped frame an exploration program developed to determine the possible past, present, and future habitability of the Red Planet. The recent successes of the Spirit and Opportunity rovers, the Mars Reconnaissance Orbiter, and the Phoenix Polar Lander have led to the new goal of "seeking signs of life" and are paving the way for the next quantum leap in Mars exploration: the Mars Science Laboratory scheduled for launch in the Fall of 2011. The eventual collection and return of samples from Mars remains the long-term goal of the scientific community. SMD is jointly planning its Mars Exploration Program beyond 2013 with ESA to combine capabilities to achieve common goals.

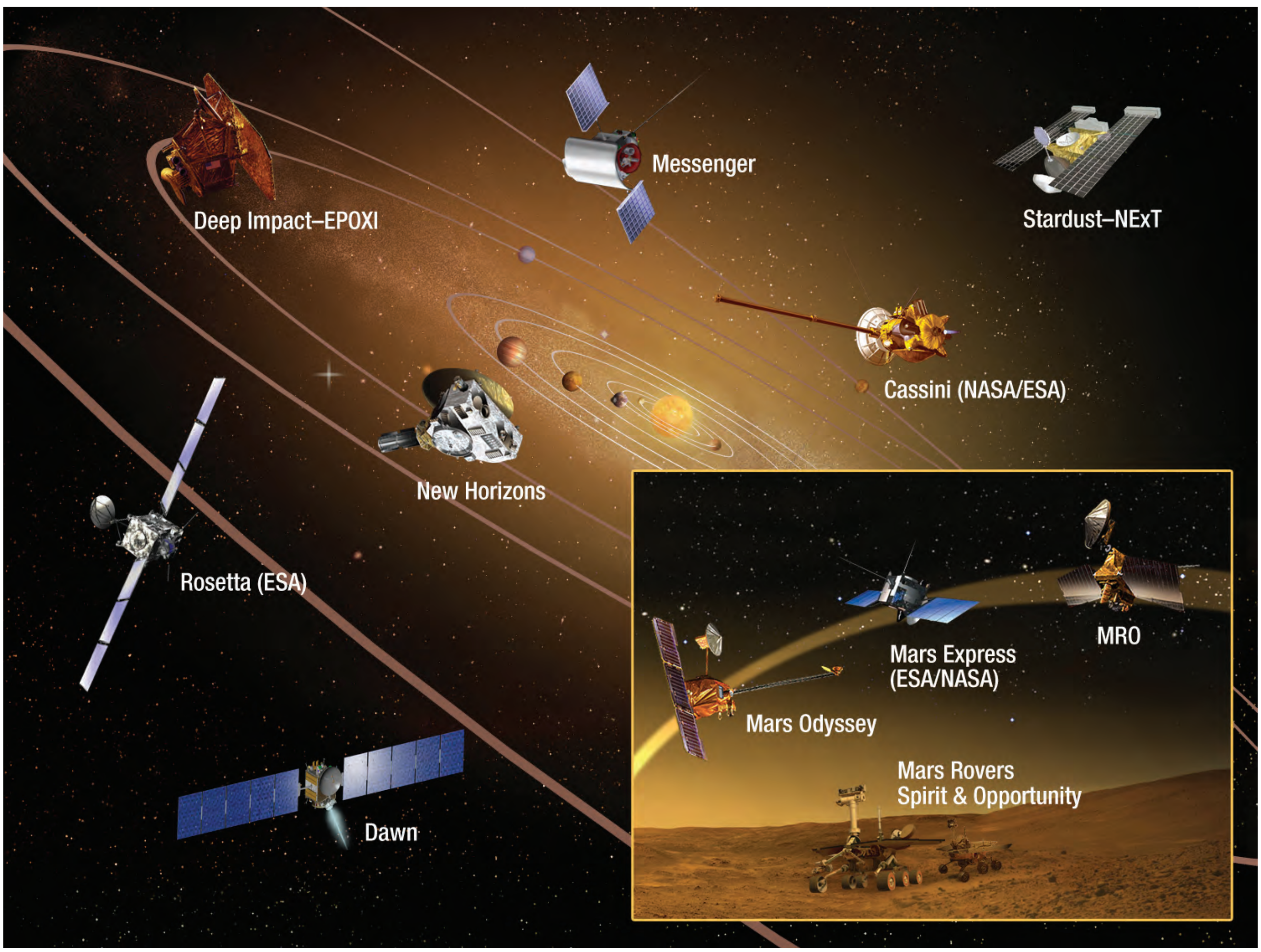
Outer Planets: The Galileo and Cassini missions to Jupiter and Saturn, respectively, have greatly deepened our understanding of these giant planets and their intriguing moons. But they have also raised new questions. Cassini has begun its final major extended mission phase—the Solstice campaign—that will continue to 2017. It is time to undertake the next flagship-class mission to the outer planets. NASA and ESA have decided jointly that the Jupiter system will be the destination of the next Outer Planets Flagship, with coordinated missions to Europa (NASA) and Ganymede (ESA) already proposed. ESA's participation awaits the outcome of their Cosmic Visions process which sets their future mission priorities. In the U.S. the NRC's ongoing Planetary Science decadal survey will prioritize the Europa Jupiter System Mission project.

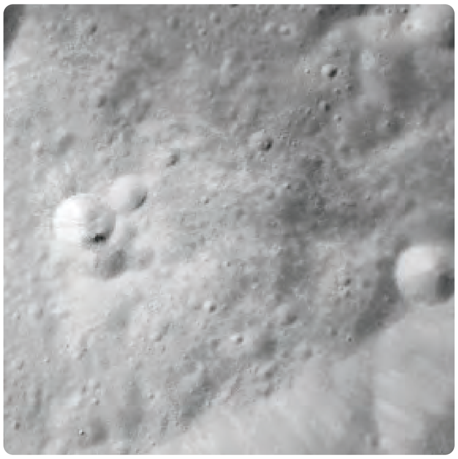
Planetary Science Research: Discoveries and concepts in the Research program are the genesis of scientific priorities, new mission concepts, and science instruments and provides the crucial context within which mission data are interpreted. This research spans ground-based telescope observations, theoretical work, laboratory studies, field work, and the continuing analysis and modeling of data and returned samples from past missions. In addition, this program includes NASA's Near Earth Object (NEO) Observation program.

Within the Planetary Science Research program, unique mission support capabilities are provided to enable and facilitate this research. Facilities and programs supporting planetary science research and missions include:

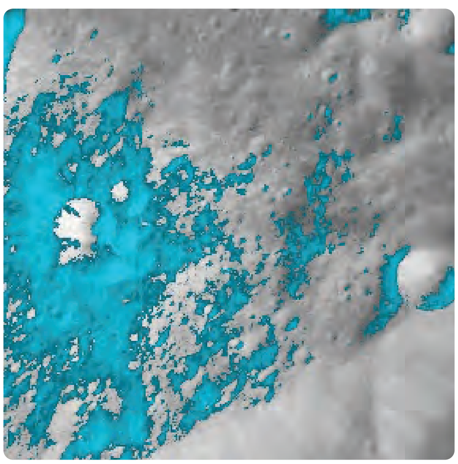
- Sample return curation facilities to store, disseminate, and support the analysis of samples returned from other planetary bodies;
- The Planetary Data System (PDS) to archive and disseminate data from all missions;
- Minor Planet Center to catalog all asteroids, comets, Kuiper Belt objects and other small bodies and all known NEOs in our solar system;

Figure 4.3 Current Planetary Science Missions in Operation





INFRARED REFLECTANCE



WATER ABSORPTION

Water on the Moon? NASA Finds the Answer

NASA scientists discovered water molecules in the polar regions of the moon using instruments aboard three separate spacecraft. The amounts are greater than predicted but still relatively small. Data from the Lunar Crater Observation and Sensing Satellite also confirmed water in the debris clouds from its lunar impact in October 2009. Hydroxyl, a molecule consisting of one oxygen atom and one hydrogen atom, also was found in the lunar soil. NASA's Moon Mineralogy Mapper on India's Chandrayaan spacecraft reported the observations. Data from instruments aboard NASA's Cassini and EPOXI spacecraft helped confirm the water finding.

Image Credits: ISRO/NASA/JPL-Caltech/USGS/Brown Univ.

- Virtual institutes to enable broad collaboration on key scientific foci—the NASA Astrobiology Institute and the NASA Lunar Science Institute;
- Planetary Protection research to protect solar system bodies from contamination from Earth and Earth from contamination from possible biological samples from elsewhere;
- Nationally-unique facilities on Earth that complement robotic space explorers, including the Infrared Telescope Facility and time on the Keck telescope (both in Hawaii), the Goldstone Solar System Radar, and SMD's evolving partnership with NSF in the operation of the Arecibo planetary radar.

Technology: Future missions will require new technologies in power generation, propulsion, navigation, aerocapture, instrumentation, miniaturization, radiation hardening and sample acquisition, handling and return. The Technology program in Planetary Science conducts research and development in all these areas and will benefit from new developments funded by the Agency's Office of the Chief Technologist. Current projects include ion thrusters for in-space propulsion and Advanced Stirling Radioisotope Generators that will use scarce Plutonium-238 more efficiently to generate electrical power where solar power is impossible.

Currently Operating Missions

Current missions include Cassini, now preparing to begin its extended mission in the Saturnian system, the Discovery missions Dawn and MESSENGER, and the New Horizons mission in the New Frontiers program. Additionally, two active missions are orbiting Mars—Mars Odyssey and Mars Reconnaissance Orbiter. On the martian surface, Opportunity continues to rove, while Spirit is currently immobile and may serve as an *in situ* surface scientific observing mission.

In July 2007, NASA announced that two spacecraft that had completed their prime missions, Deep Impact and Stardust, would now be tasked with new missions as Discovery Program Missions of Opportunity. Deep Impact is now EPOXI, to carry out the Deep Impact Extended Investigation to fly by comet Hartley 2 in late 2010, as well as a cruise experiment called the Extrasolar Planet Observation and Characterization (EPOCH). Stardust is now the New Exploration of Temple 1 (NExT), on course to a flyby of that comet in early 2011.

NASA also participates in the payloads and scientific investigations of the current ESA Mars Express orbiter, as well as the ESA Venus Express orbiter, the ESA Rosetta comet rendezvous mission, the JAXA Venus Climate Orbiter, and the JAXA Hayabusa NEO asteroid mission.

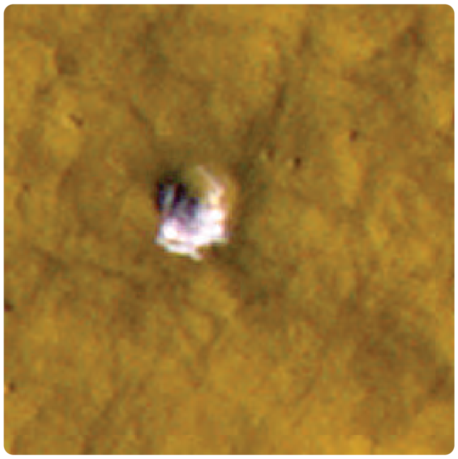
Missions in Development

The NRC decadal survey report *New Frontiers in the Solar System* (NRC, 2003) for Planetary Science called upon NASA to launch Discovery missions at the rate of one every 18 months, New Frontiers missions at the rate of one every three years, and a Flagship mission once per decade. Fiscal realities have slowed this pace to approximately once every three years for Discovery and once every five years for New Frontiers. The Mars Science Laboratory is the next planetary flagship, scheduled for launch in 2011. Pending the next decadal survey, NASA's plan is to proceed next with the Outer Planets Flagship planned for launch in the early 2020's should funding be made available, and then Mars Sample Return in the ensuing years. The planetary missions in Table 4.3a are currently in development.

Future Missions

The Discovery Announcement of Opportunity issued in 2010 is expected to result in selection of up to three Discovery mission proposals for a 9-month Phase-A study. Following evaluation of Phase-A reports, NASA expects to approve one Discovery mission to proceed into Phase B and subsequent mission phases. Launch Readiness Date (LRD) is to occur no later than December 31, 2017. The proposed missions may target any body in the Solar System, including Mars and Earth's Moon, but excluding the Earth and Sun.

The 2003 decadal survey identified five candidate destinations and associated scientific goals for New Frontiers missions, and two of the five are launched or in development (New Horizons and Juno, respectively). Before proceeding with the next solicitation for New Frontiers missions, NASA asked the NRC to update their list of remaining candidates in light of recent scientific discoveries. The NRC report identified 5 additional high priority targets for New Frontiers. The list from the resulting NRC report *Opening New Frontiers in Space: Choices for the next New Frontiers Announcement of Opportunity* (NRC, 2008) was incorporated in the New Frontiers AO released in April 2009. From the proposals submitted, SMD selected three for Phase A concept studies: the Surface and Atmospheric Geochemical Explorer (SAGE) mission to Venus; the Origins Spectral Interpretation, Resource Identification and Security Regolith Explorer



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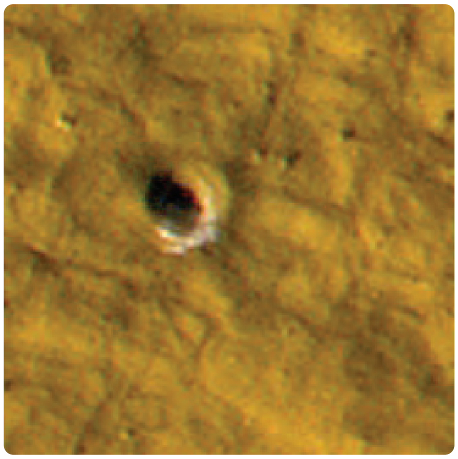


JANUARY 14, 2009

Underground Ice on Mars Exposed by Impact Cratering

The High Resolution Imaging Science Experiment camera on NASA's Mars Reconnaissance Orbiter took these images of a fresh, 6-meter-wide crater on Mars on Oct. 18, 2008, and on Jan. 14, 2009. Each image is 35 meters across. This crater's depth is estimated to be 1.33 meters. The impact exposed water ice from below the surface. It is the bright material visible in this pair of images. The change in appearance from the earlier image to the later one resulted from some of the ice sublimating away during the Martian northern-hemisphere summer, leaving behind dust that had been intermixed with the ice.

Image Credit: NASA

Chapter 4

Table 4.3a Planetary Science Missions in Development (with launch year noted)

Mars Science Laboratory—2011 Strategic mission; Mars Exploration Program	Roving analytical laboratory to address questions of habitability. High-priority medium class mission in 2003 decadal survey; developed as a flagship-class mission.
Juno—2011 Competed mission; New Frontiers 2	Jovian gravity, composition, and magnetic fields. High-priority medium class mission in 2003 decadal survey; also high priority in Heliophysics decadal survey.
Gravity Recovery and Interior Laboratory (GRAIL)—2011 Competed mission; Discovery 2006 selection	Generate detailed gravity field maps of the Moon, in the same way as GRACE does now for the Earth, in order to probe the Moon's interior structure.
Lunar Atmosphere and Dust Environment Explorer (LADEE)—2012 Strategic mission; Lunar Quest Program	Small mission to study the tenuous atmosphere of the Moon and the dust lofted into the atmosphere.
Mars Atmosphere and Volatile EvolutioN (MAVEN)—2013 Competed mission; Mars Exploration Program	Make definitive scientific measurements of present-day atmospheric loss that will offer clues about the history about the Martian atmosphere. High priority science objective of the 2003 decadal survey.

Table 4.3b Future Planetary Science Missions (with planned launch year noted)

ExoMars Trace Gas Orbiter—2016 Strategic Mission	ESA-led joint mission with NASA; Mars orbiter to follow up on recent methane discovery; entry, descent, landing system (EDLS) tech demo; and telecom package. NASA providing launch, science instruments, and telecom package.
Discovery-12—2015/17 Competed mission	Opportunity for a medium planetary mission; solicitation in 2010.
New Frontiers 3—2018 Competed mission	Three candidates selected for concept studies; asteroid sample return, lunar south pole/Aiken Basin sample return, and Venus atmosphere and surface probe. SMD will select one in 2011 for development.
Mars 2018—2018 Strategic mission	NASA-led joint mission with ESA. NASA to provide launch, EDLS, rover; ESA to provide a rover/driller. NASA rover to cache samples.
Europa Jupiter System Mission—early 2020s Strategic mission	Flagship mission to explore two icy moons of Jupiter. Pursuing as a joint Jupiter System Mission with ESA. NASA spacecraft destination is Europa; ESA's spacecraft destination is Ganymede.
Mars Sample Return—mid 2020s Strategic mission	Flagship mission to return the samples collected by the Mars 2018 mission. Joint NASA-ESA campaign of three shared mission elements and their respective launches.

(called Osiris-Rex) asteroid sample return mission; and MoonRise—a sample return mission to the Moon's South Pole-Aiken Basin. Based on the results of the concepts studies, SMD will select one to proceed to development.

SMD's goal is to have one Planetary Science flagship mission in development at any given time. The current flagship mission in development is the Mars Science Laboratory, and the next is likely to be the Europa-Jupiter System mission, depending on the recommendations of the 2011 NRC decadal survey for Planetary Science.

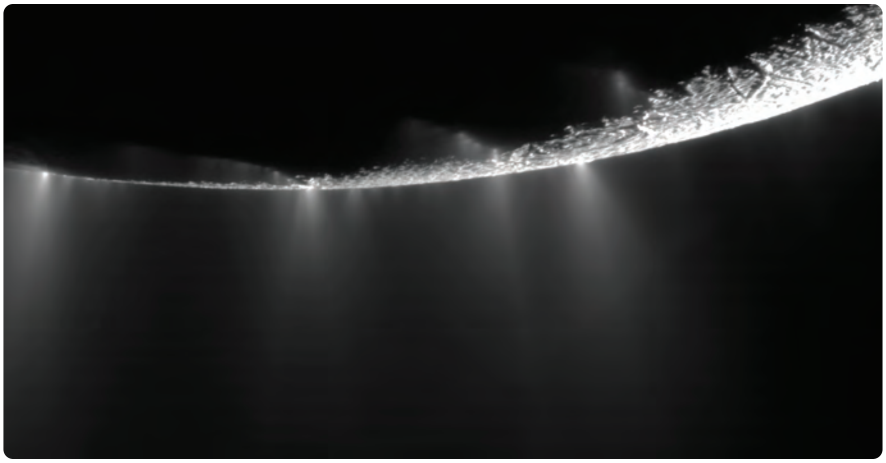
NASA and ESA are jointly planning future Mars missions. NASA has solicited for science instruments to fly on the ESA-led ExoMars Trace Gas Orbiter mission in 2016 that will also carry ESA's entry, descent, and landing system technology demonstrator. The NASA-led Mars 2018 mission will include a NASA-provided rover and ESA's ExoMars rover. These will provide essential science and technical advances for a Mars sample return campaign that could be completed in the 2020s. Other future planetary missions being planned are described in Table 4.3b.

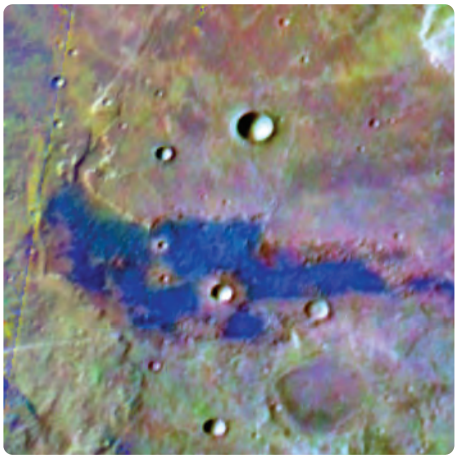
Cassini Finds Plethora of Plumes, Hotspots at Enceladus

Newly released images from the November 2009 swoop over Saturn's icy moon Enceladus by NASA's Cassini spacecraft reveal a forest of new jets spraying from prominent fractures crossing the south polar region and yield the most detailed temperature map to date of one fracture.

The new images from the imaging science subsystem and the composite infrared spectrometer teams also include the best 3-D image ever obtained of a "tiger stripe," a fissure that sprays icy particles, water vapor and organic compounds. There are also views of regions not well-mapped previously on Enceladus, including a southern area with crudely circular tectonic patterns.

Image Credit: NASA/JPL/SSI





CHLORIDE SALT DEPOSITS

Signs of Past Surface Water on Mars

Remote sensing data from the Mars Reconnaissance and Odyssey Orbiters reveal a diverse set of minerals, produced by water activity, in thousands of local areas distributed across broad sections of Mars. These range from chloride deposits in small basins to exposures of clay-like materials in areas as small as a football field at the base of cliffs and mesas, in central peaks of craters, and in the great rift valleys extending across the planet. Together with discoveries from the Mars Express orbiter, these mineral detections indicate that aqueous mineral formation and alteration by water was extensive, diverse, and changing with time, sometimes episodically. The resulting diversity of environmental conditions (e.g., some acidic, some not) increases the potential that evidence of ancient life could be preserved even today at or near the surface of Mars. Meanwhile, radar profilers on Mars Reconnaissance Orbiter and Mars Express have detected subsurface ice layers in mid-latitudes and multiple layers within the polar ice caps, indicating geologically recent climate change, with ice redistributed between high and low latitudes; such redistribution likely depends on cyclic changes over a few million years of the tilt of the planet's rotation axis and eccentricity of its orbit.

Image Credit: NASA/JPL-Caltech/Arizona State University/ University of Hawaii

Mathide, Gaspra, Ida Comparison

These are views of three of the asteroids that have been imaged at close range by spacecraft. The image of Mathilde (left) was taken by the NEAR spacecraft on June 27, 1997. Images of the asteroids Gaspra (middle) and Ida (right) were taken by the Galileo spacecraft in 1991 and 1993, respectively. All three objects are presented at the same scale. The visible part of Mathilde is 59 km wide x 47 km high (37 x 29 miles). Mathilde has more large craters than the other two asteroids. The relative brightness has been made similar for easy viewing; Mathilde is actually much darker than either Ida or Gaspra.

Image Credit: NASA/JPL

A new NRC decadal survey for Planetary Science is underway, and will be completed in the spring of 2011. The new Planetary Science decadal survey will provide integrated science and mission priorities for the entire solar system, including Mars and Earth's Moon, but excluding the Earth and the Sun (which have their own decadal surveys). This next decadal survey will provide to NASA the science community's priorities, and a basis for adjustment to the table of future missions (Table 4.3b).

Near Earth Objects Observation

The Near Earth Object Observations (NEOO) program objective is to detect and track at least 90 percent of the Near Earth Objects, asteroids, and comets that come within 1.3 Astronomical Units of the Sun, and to find those at least 140 meters in size which have any potential to collide with Earth and do significant damage at the surface. In the course of this effort many objects which present viable targets for future exploration will be found and initially characterized. A significant increase in effort is planned for this program, in accordance with the findings and recommendations of the recent National Research Council study on the NEO hazard, issued January 2010. While NEOO Program continues to fund the existing network of 1-meter class ground-based telescopes and supporting data processing and analysis infrastructure at the Minor Planet Center and JPL, it will seek to improve the current capability with upgrades and modifications to existing and planned ground and space-based observatory missions. The NEOO Program will:

- Extend the collection, archive and analysis of small body data collected by NASA's WISE mission and support increased follow-up and analysis of this data,
- Enable collection of NEO detection and characterization data by the USAF's Panoramic Survey Telescope and Rapid Reporting System (Pan-STARRS) and investigate the use of other USAF space surveillance assets for this mission,
- Support the continued operation of planetary radar capabilities at the NSF's Arecibo and NASA's Goldstone facilities,
- Begin the investigation of both ground and space-based concepts for dedicated capacity to detect, track and characterize Potentially Hazardous Objects (PHOs) down to sizes 140 meters and below, and
- Determine the parameters necessary to understand the characteristics of PHO's important for determination of possible mitigation actions against a detected impact threat.

More information on NASA's NEO observation program is available at http://neo.jpl.nasa.gov.

Planetary Protection

Planetary protection involves preventing biological contamination of other planetary bodies and the Earth, including both one-way and round-trip missions. 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 also is a component in the U.S. adherence to the 1967 United Nations Outer Space Treaty, which requires that states party 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 to avoid "adverse changes in the environment of Earth resulting from the introduction of extraterrestrial matter." NASA's Planetary Protection Officer has Agency-wide responsibilities in this arena and is hosted in SMD, along with the research program that advances the science needed to perform this function.

For NASA, planetary protection requirements are imposed according to mission operations at the target body, informed by recommendations from the National Academies of Science on strategic issues and advice from the NAC Science Committee's Planetary Science Subcommittee for implementation issues. The Planetary Protection Officer is charged with certifying prior to launch or return of missions to other planetary bodies that planetary protection measures have been taken, mission requirements met, and international obligations fulfilled.

Image credit: Serabyn, Mawet & Burruss 2010, Nature 464, 1018

Planetary protection research enables these functions by advancing the state of the art in:

- Characterizing the limits of life in laboratory simulations of planetary environments or in appropriate Earth analogs;
- Modeling of planetary environmental conditions and transport processes that could permit mobilization of spacecraft-associated contaminants to locations in which Earth organisms might thrive;
- Development or adaptation of modern molecular analytical methods to rapidly detect, classify and/or enumerate the widest possible spectrum of Earth microbes carried by spacecraft; and
- Developing new or improved methods, technologies, and procedures for spacecraft sterilization that are compatible with spacecraft materials and assemblies.

Chapter 4

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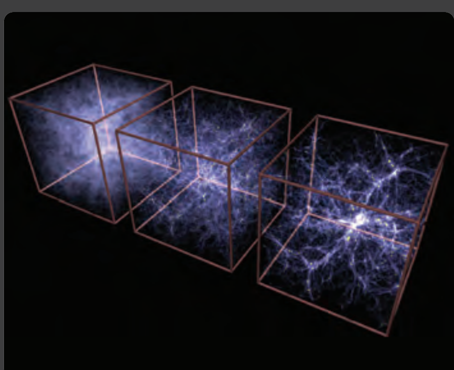


EVOLUTION OF THE UNIVERSE

Missions within the Physics of the Cosmos Program have provided stunning information on the nature of matter, energy, and even spacetime itself. The Chandra X-ray Observatory, along with optical telescopes, has made direct detections of halos of dark matter in galaxy clusters, some of which suggest novel properties for dark matter particle candidates (2007). Chandra has also provided the tightest limits on the properties of the mysterious dark energy that is causing the growth of the Universe to accelerate (2008). And perhaps most profoundly, the Fermi Gamma-ray Space Telescope has placed stringent limits on the graininess of spacetime (2009).

Top Image credit: X-ray: NASA/CXC/UVic./A. Mahdavi et al. Optical/lensing: CFHT/UVic./H. Hoekstra et al.. Bottom Image Credit: X-ray (NASA/CXC/SAO/A.Vikhlinin et al.); Optical (SDSS); Illustration (MPE/V.Springel)

4.4 Astrophysics

Strategy

The science goals of Astrophysics are breath taking: we seek to understand the universe and our place in it. 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. This is the broad sweep of science articulated in the NRC decadal survey *Astronomy and Astrophysics in the New Millennium* (NRC, 2001) and its complementary report *Connecting Quarks with the Cosmos* (NRC, 2003). The decadal survey identifies national scientific goals in this arena and identifies priority missions for both NASA and the National Science Foundation, which has the lead for ground-based astronomy.

NASA's goal in Astrophysics is to "Discover how the universe works, explore how the universe began and developed into its present form, and search for Earth-like planets." Three broad scientific questions emanate from this goal:

- **How do matter, energy, space, and time behave under the extraordinarily diverse conditions of the cosmos?**
- **How did the universe originate and evolve to produce the galaxies, stars, and planets we see today?**
- **What are the characteristics of planetary systems orbiting other stars, and do they harbor life?**

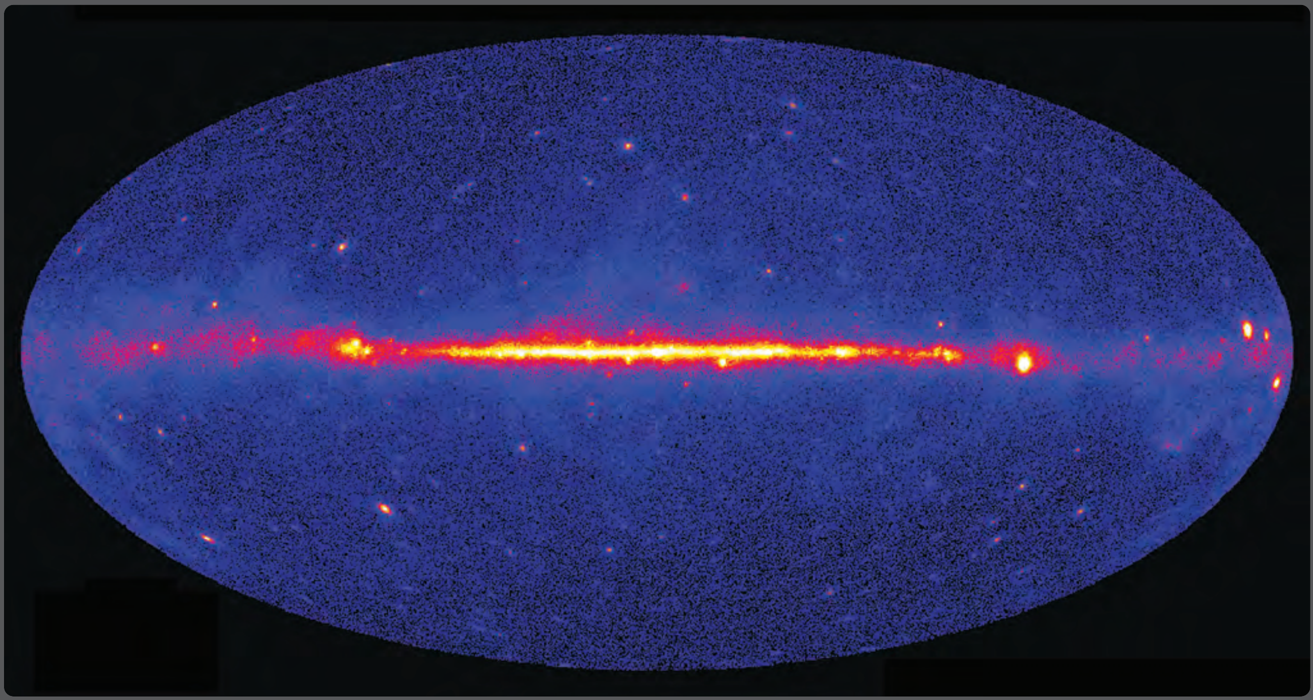
Astrophysics comprises three focused and two cross-cutting programs. These focused programs provide an intellectual framework for advancing science and conducting strategic planning. They are:

Physics of the Cosmos—"How does the Universe work?" The Physics of the Cosmos Program (which incorporates the former Beyond Einstein Program) contains missions that can explore the most extreme physical conditions of the universe, from black holes to dark energy. They will study the building blocks of our own existence at the most basic level: the matter, energy, space, and time that create the living Universe. The Physics of the Cosmos Program, whose scope includes cosmology, high-energy astrophysics, and fundamental physics is in part an implementation of the *Connecting Quarks with the Cosmos* (NRC, 2003) and *A 21st Century Frontier for Discovery: The Physics of the Universe—A Strategic Plan for Federal Research at the Intersection of Physics and Astronomy* (NSTC, 2004) reports. The most recently launched NASA-led mission in this program is the Fermi Gamma-ray Space Telescope, the top-ranked medium scale mission from the 2001 NRC decadal survey for astronomy and astrophysics. The Chandra X-ray Observatory, the third of NASA's Great Observatories, is the program's flagship mission. The 2010 Decadal Survey will prioritize future mission candidates in this program, which include a dark energy mission (such as the Joint Dark Energy Mission, JDEM) and two joint NASA/ESA missions, the Laser Interferometer Space Antenna (LISA) and the International X-ray Observatory (IXO).

Cosmic Origins—"How did we get here?" This program comprises projects that enable the study of how stars and galaxies came into being, how they evolve, and ultimately how they end their lives. The Hubble Space Telescope, Spitzer Space Telescope, and the Stratospheric Observatory For Infrared Astronomy

FERMI VIEWS THE GAMMA-RAY SKY

Image Credit: NASA/DOE/Fermi LAT Collaboration



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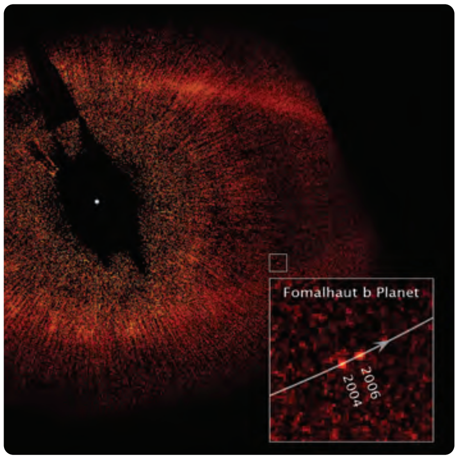


Hubble Spots an Exoplanet

The ExoPlanet Exploration Program's ultimate goal is to detect Earth-like planets, perhaps to discover evidence for the existence of life elsewhere. The recently launched Kepler satellite has already discovered five new planets, with the promise of many more in the near future (2010). The Spitzer Space Telescope achieved a major coup with its world's first measurement of the infrared spectrum emitted by the atmosphere of a Jupiter-like exoplanet (2007), while Hubble's observations of this same planet detected the presence of atmospheric methane and carbon dioxide (2008). And with Hubble we have directly seen a planet as it orbits its star, Fomalhaut, within a dense protoplanetary disk (2008).

Image Credit: NASA, ESA, P. Kalas, J. Graham, E. Chiang, E. Kite (University of California, Berkeley), M. Clampin (NASA Goddard Space Flight Center), M. Fitzgerald (Lawrence Livermore National Laboratory), and K. Stapelfeldt and J. Krist (NASA Jet Propulsion Laboratory)

(SOFIA) all address central questions of the Cosmic Origins Program. NASA's next flagship observatory, the James Webb Space Telescope (JWST) is the major new component of this program. JWST was named the highest priority major initiative in the 2001 National Academy of Science's decadal survey for astronomy and astrophysics.

Exoplanet Exploration—"Are we alone?" The emphasis of the Exoplanet Exploration Program (formerly the Navigator Program) is to advance our understanding of planets and planetary systems around other stars ("extrasolar planets" or simply "exoplanets"), The past ~15 years have seen an explosive growth in the identification of exoplanets—some 400 have been discovered in the solar neighborhood. The ultimate goal of the Exoplanet Exploration program is to extend this exploration to the detection of habitable, Earth-like planets around other stars, to determine how common such planets are, and to search for indicators that they might harbor life. To this end, the program supports the design, development, and operation of instruments and missions that are capable of discerning the vanishingly small signatures of exoplanets and analyzing their characteristics. The Kepler mission, launched in March 2009, is NASA's first dedicated Exoplanet Exploration mission. Kepler will spend the next several years searching for planets around 140,000 stars in a region near the constellation Cygnus, and will ultimately provide a measure of the frequency of Earth-like planets in our galaxy. Awaiting prioritization by the NRC's Decadal Survey are a number of exoplanet detection and characterization mission concepts. One such concept is the astrometric Space Interferometry Mission-Lite (SIM-Lite), which would detect exoplanets around nearby stars, including measuring their masses and orbits. SIM-Lite would also address a range of topics in astrophysics, such as the cosmic distance scale and the distribution and nature of dark matter. The program invests in other mission concept definition and technology development as well, such as advanced coronagraphic and interferometric measurement techniques that would measure exoplanet spectra directly.

Explorer Program—Smaller, PI-led Astrophysics missions are selected under the Explorer program, which is managed by the Heliophysics Division. Explorers provide opportunities for innovative science and fill the scientific gaps between the larger missions. For example, the Wide-field Infrared Survey Explorer (WISE), launched in December 2009, has surveyed the entire sky in the near-to-mid infrared, to find the brightest, most distant infrared galaxies and the faintest stars in the solar neighborhood. Similarly, the Nuclear Spectroscopic Telescope Array (NuSTAR), to be launched in 2012, will conduct a census of black holes for the Physics of the Cosmos program and study the birth of elements for the Cosmic Origins program. The Gravity and Extreme Magnetism (GEMS) mission, selected in 2009 for a launch in 2014, will use an X-ray telescope to explore the shape of space that has been distorted by a spinning black hole's gravity and probe the structure and effects of the formidable magnetic field around magnetars, dead stars with magnetic fields trillions of times stronger than Earth's.

Astrophysics Research—Sponsored research programs prepare for the next generation of missions, through both theoretical research and applied technology investigations. They also exploit data from current missions and use suborbital science investigations to advance NASA science goals. Suborbital missions, an integral part of the R&A program, include sounding rocket and balloon campaigns which provide ancillary measurements, demonstrate measurement technologies, and train future mission PIs and students. Suborbital astrophysics missions are receiving increased emphasis in NASA. A newly initiated Strategic Astrophysics Technology program is aimed at

Figure 4.4 Current Astrophysics Science Missions in Operation

Table 4.4 Astrophysics Missions in Development or Formulation

Stratospheric Observatory for Infrared Astronomy (SOFIA)—2010 Early Science Capability Strategic Mission	Aircraft-based observations of stellar and planet-forming environments. Endorsed as a "Moderate" program in the 1991 decadal survey; reaffirmed in the 2001 decadal survey.
Nuclear Spectroscopic Telescope Array (NuSTAR)—2012 Competed mission—Small Explorer	First focusing high energy X-ray mission; search for black holes and study extreme active galaxies. The 2001 decadal survey "endorses the continuation of a vigorous Explorer Program" in Astrophysics.
James Webb Space Telescope (JWST)—2014 Strategic mission	Infrared successor to Hubble to image first light after the Big Bang and the first galaxies to form in the early universe. Top-ranked space-based "Major Initiative" in the 2001 decadal survey.
Gravity and Extreme Magnetism SMEX (GEMS)—2014 Competed mission—Small Explorer	Small Explorer mission to detect and measure the polarization of the X-rays emitted by some of the most energetic and enigmatic objects in the cosmos.

bringing promising technologies closer to readiness for flight, with separate opportunities in each of the three program areas.

Current Missions

Current missions include three of the Great Observatories originally planned in the 1980's and launched over the past 20 years. The suite of currently working Great Observatories includes the Hubble Space Telescope (HST), the Spitzer Space Telescope (SST), and the Chandra X-ray Observatory (CXO). Additionally, the Fermi Gamma-ray Space Telescope and Kepler medium-sized missions explore the high-energy end of the spectrum and search for earthlike planets respectively. Innovative Explorer missions, such as WISE, the Wilkinson Microwave Anisotropy Probe (WMAP), Swift Gamma-ray Explorer, Rossi X-ray Timing Explorer (RXTE), and the Galaxy Evolution Explorer (GALEX) complement these strategic missions. Together, these missions view the universe across the entire electromagnetic spectrum and account for much of humanity's accumulated knowledge of the heavens. Many of these missions have achieved their prime science goals, but continue to produce spectacular results in their extended operations. NASA-funded investigators also participate in observations and data analysis and develop instruments for the astrophysics missions of our international partners, including ESA's Integral, XMM, Herschel and Planck missions, and JAXA's Suzaku.

Missions in Development

The next five to seven years will be dominated by two missions with especially broad scientific utility: SOFIA and JWST. Completing these missions, plus NuSTAR, GEMS, and an instrument for JAXA's Astro-H, operating the newly launched and extended operations missions, and increasing the funding for research and analyses programs will consume most of the Astrophysics Division resources.

Future Missions

A number of potential astrophysics space missions are in the conceptual development phase or have started technology development and studies; these include

SIM Lite, JDEM (in partnership with the Department of Energy), LISA (in partnership with the ESA) and IXO (in partnership with ESA and JAXA). Beyond JWST, however, SMD's plans for future strategic missions in Astrophysics will be based on the results of the NRC's new decadal survey, released in August 2010. SMD will combine the decadal survey recommendations with budget envelope, partnership opportunities, and other programmatic information to craft a plan for future missions and related research activities. In preparation for the decadal survey, SMD solicited proposals for strategic mission concept studies in 2007. SMD selected and funded nineteen teams for concept generation. In addition, SMD continues to fund supporting research and technology activities necessary to implement the resulting plan.

Hubble Opens New Eyes on the Universe

Proof that NASA's Hubble Space Telescope is better than ever came in September 2009 when astronomers released stunning new images from four of Hubble's six operating science instruments. Spacewalking astronauts brought the orbiting observatory to a new apex of scientific performance during a visit by shuttle Atlantis in May 2009. Astronauts installed two new instruments, the Wide Field Camera 3 and Cosmic Origins Spectrograph, and repaired the Advanced Camera for Surveys and Space Telescope Imaging Spectrograph circuit boards.

Image Credit: NASA, ESA, and the Hubble SM4 ERO Team

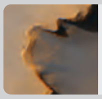
BUTTERFLY NEBULA

ARTIST'S EXTRASOLAR PLANET

Hubble Finds First Organic Molecule on an Exoplanet

NASA's Hubble Space Telescope (HST) has made the first detection ever of an organic molecule in the atmosphere of a Jupiter-sized planet orbiting another star. This breakthrough is an important step in eventually identifying signs of life on a planet outside our solar system. The molecule found by Hubble is methane, which under the right circumstances can play a key role in prebiotic chemistry—the chemical reactions considered necessary to form life as we know it. This discovery proves that Hubble and upcoming space missions, such as NASA's James Webb Space Telescope, can detect organic molecules on planets around other stars by using spectroscopy, which splits light into its components to reveal the "fingerprints" of various chemicals.

Image Credit: NASA, ESA, and G. Bacon (STScI)



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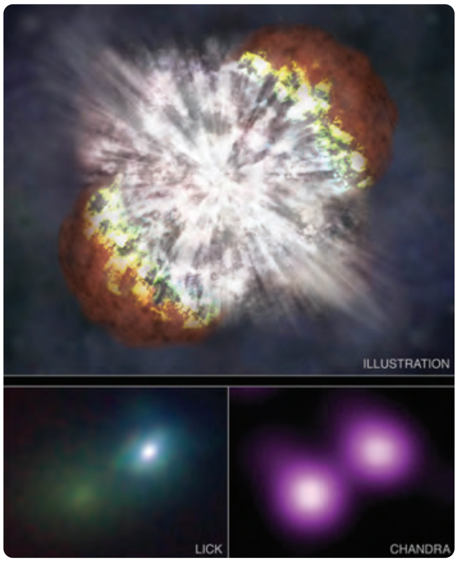
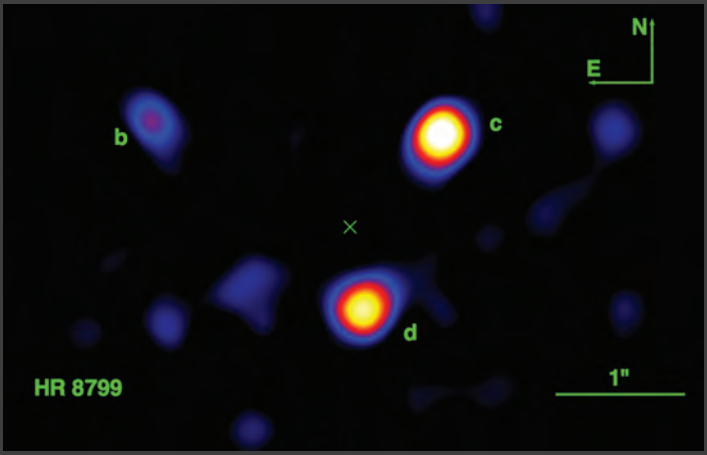


Star Power: CHANDRA Sees Brightest Supernova Ever

The brightest stellar explosion ever recorded was seen by NASA's Chandra X-ray Observatory and ground-based optical telescopes. The discovery indicates that violent explosions of extremely massive stars were relatively common in the early universe, and a similar explosion in our own galaxy could be imminent. This new supernova may offer a rare glimpse of how the first stars died. It is unprecedented to find such a massive star and witness its death. The discovery of the supernova provided evidence that the deaths of such massive stars are fundamentally different from theoretical predictions.

Image credit: Illustration: NASA/CXC/M.Weiss; X-ray: NASA/CXC/UC Berkeley/N.Smith et al.; IR: Lick/UC Berkeley/J. Bloom & C.Hansen

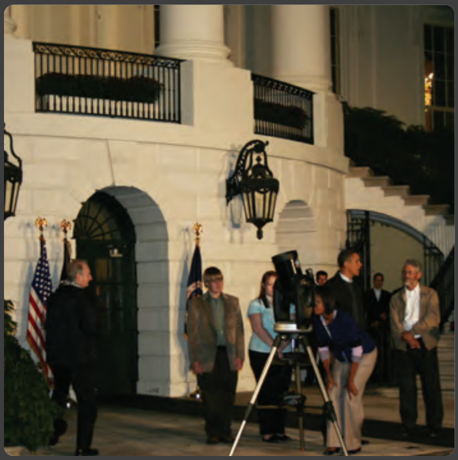
Origins of Solar Systems



SMD's Origins of Solar Systems research program sponsors research to advance scientific understanding of the formation and early evolution of planetary systems, including our own, and to provide the fundamental research and analysis necessary to detect and characterize other planetary systems. This research involves analytical and numerical modeling, laboratory research, and observational studies in star formation and the relationship to planetary formation, solar nebula processes, accumulation and dynamical evolution, analysis of primitive materials, and characterization of other planetary systems.

The Origins of Planetary Systems program requires interdisciplinary efforts to answer key scientific questions. These include studies of nebular chemistry and dynamics to understand the composition of primitive volatile-rich solar system bodies and collaborations between observational astronomers and modelers to study the initial collapse of a proto-stellar cloud to form a nebula.

Shown In the image above three exoplanets around the star HR 8799 have recently been discovered by means of differential imaging with large telescopes. Imaging faint planets at smaller angles calls for reducing the starlight and associated photon and speckle noise before detection, while efficiently transmitting nearby planet light. The stellar position is marked with a large cross, and the central 300 milliarcseconds radius region is blanked out.



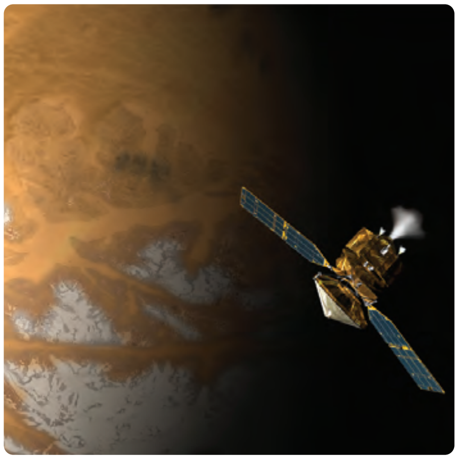
Local middle school students learned about the solar system and the vast universe beyond during an Astronomy Night event on the White House South Lawn on Oct. 7, 2009. The White House hosted 150 local students to star gaze and conduct hands-on experiments with astronomers from across the country. President Obama spoke about the importance of science, engineering and math education and his support for astronomy's capacity to promote a greater awareness of our place in the universe, expand human knowledge and inspire the next generation of explorers. The White House event was part of the International Year of Astronomy, a global celebration of its contributions to society and culture. More than 135 countries hosted events and activities to mark the 400th anniversary of Galileo's first astronomical observations with a telescope.

Chapter 5

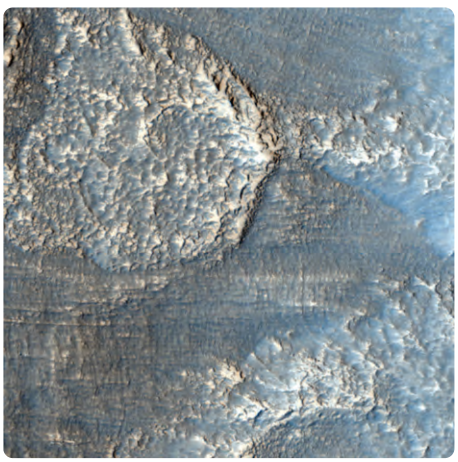
Engaging the Next Generation

SMD's education program implements the Agency's education goal and guidance in the areas of Earth and space science. SMD plays an essential role in NASA's Strategic Education Framework to "inspire, engage, educate, and employ" (Figure 5.1). 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 and Public Outreach Program sponsors both formal and informal educational opportunities that promote STEM literacy through the dissemination and application of unique NASA resources.

Chapter 5



MRO SPACECRAFT



HiRISE IMAGE

This is an artist's concept of the Mars Reconnaissance Orbiter (MRO) during its critical Mars Orbit Insertion process. In order to be captured into orbit around Mars, the spacecraft conducted a 25-minute rocket burn when it was just shy of reaching the planet.

Courtesy NASA/JPL-Caltech

Imaged by the HiRISE instrument aboard MRO through the HiWISH public suggestion program, this observation is located in the Deuteronilus Mensae region along the highland/lowland dichotomy boundary in the Northern hemisphere of Mars.

Credit: NASA/JPL/University of Arizona

The NASA Science Mission Directorate's vision for Education and Public Outreach is:

To share the story, the science, and the adventure of NASA's scientific explorations of our home planet, the solar system, and the universe beyond, through stimulating and informative activities and experiences created by experts, delivered effectively and efficiently to learners of many backgrounds via proven conduits, thus providing a direct return on the public's investment in NASA's scientific research.

NASA's science content is unique among Federal agencies. It provides an inspirational spark to seek out and engage in the exciting education and outreach opportunities that NASA offers to learn about new science discoveries and to acquire new skills in science, engineering, technology, and mathematics.

E/PO Implementation Approach

SMD's E/PO projects share the results of our missions and research to audiences through a portfolio of investments (E/PO projects) in Higher Education, Elementary and Secondary Education, Informal Education, and Outreach. These E/PO projects aim to attract and retain students in STEM disciplines by energizing science teaching and learning. In addition, E/PO projects promote inclusiveness and provide opportunities for minorities, students with disabilities, minority universities, and other target groups to compete for and participate in science missions, research, and education programs. The combined emphasis on precollege/preworkforce 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 its programs primarily through two means. One method is to embed E/PO projects in its flight programs or missions. SMD policy calls for each mission to allocate at least 1% of the mission budget for education and public outreach activities. E/PO plans are developed during the early mission phases and subjected to thorough review and approval processes. It is treated as though it were a mission subsystem. The other method is to support E/PO projects through awards for solicited or unsolicited proposals, or as elements of a major research-enabling program (e.g., suborbital science, science instrumentation, data and information systems, etc.). SMD offers multiple proposal opportunities for education and outreach efforts as part of the annual competitive solicitations. Science mission researchers and other personnel are particularly encouraged to become active participants in education and outreach activities. Education materials and products from SMD projects are peer reviewed and approved by educators and scientists prior to distribution. SMD works closely with the Office of Education to ensure that projects address agency objectives and end–user needs.

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 precollege level and to increasing the scientific literacy of the general public. The Directorate achieves this leverage in precollege 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 through the NASA Museum Alliance for 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. Mechanisms are in place to solicit and evaluate expert feedback on the quality and impact of all E/PO projects.

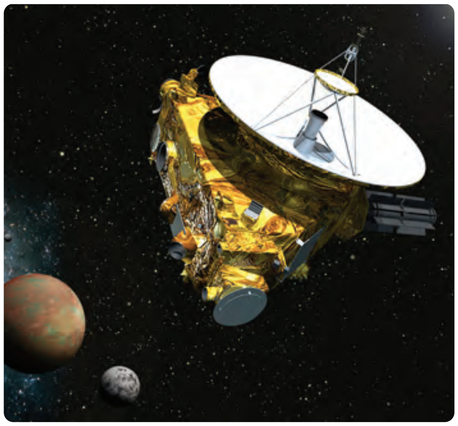
Management of the SMD E/PO portfolio is the responsibility of the SMD E/PO Lead and Division E/PO Leads in each of the four Science Divisions. Each Division has a Science Education and Public Outreach Forum (SEPOF) that collaborates with NASA and external science and education and outreach communities in E/PO to assist SMD in increasing the overall coherence of the E/PO program leading to more effective, sustainable, and efficient utilization of SMD science discoveries and learning experiences.

FAMILY SCIENCE NIGHT

SDO EPO LAUNCH ACTIVITIES

NASA's Solar Dynamics Observatory inspires students of all ages. At one of NASA Goddard Space Flight Center's monthly Family Science Nights (upper photo), middle school students and their parents learned how SDO's view of the Sun and solar storm formation will improve our understanding of space weather. Over 80 teachers participated in the SDO teachers' workshop at NASA's Kennedy Space Center (lower photo) in the days prior to SDO launch. The event at KSC was just one of over 200 education and public outreach events occasioned by the SDO launch and hosted around the nation and around the globe by teachers, librarians, and museums.

Chapter 5



Student Dust Collector on New Horizons

The New Horizon mission to Pluto and the Kuiper Belt carries a Student Dust Collector designed and built by students at the University of Colorado. SMD's Announcements of Opportunity for new missions include a funded provision for Principal Investigators to propose student collaborations in their missions.

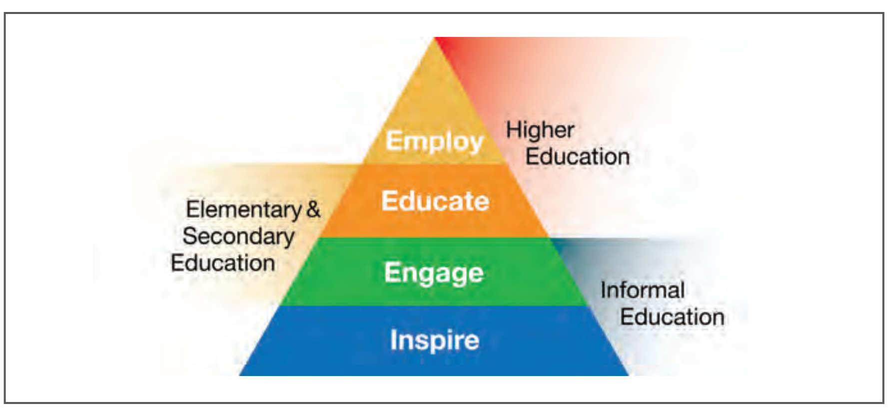
Credit: Johns Hopkins University Applied Physics Laboratory/ Southwest Research Institute (JHUAPL/SwRI)

- The Earth Science Forum is led by the Institute for Global Environmental Strategies;
- The Heliophysics Forum is led by the Space Science Laboratory of the University of California, Berkeley;
- The Planetary Science Forum is led by the Lunar and Planetary Institute;
- The Astrophysics Forum is led by the Space Telescope Science Institute.

Workforce Development Approach

SMD aids in workforce development through student support at the undergraduate, graduate, and postdoctoral 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 postdoctoral 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) ensure the continued training and nurturing of a highly qualified workforce to help NASA continue the scientific exploration of Earth and space. SMD also supports the Presidential Early Career Awards for Scientists and Engineers led by the Office of Science and Technology Policy.

Figure 5.1 NASA's Strategic Education Framework



Appendices

Appendix 1 Goals, Questions, and Research Objectives

Science Goals	Science Questions	Science Area Objectives[1]
Earth Science: Advance Earth System Science to meet the challenges of climate and environmental change.	• How is the global Earth system changing? (Characterize) • What are the sources of change in the Earth system and their magnitudes and trends? (Understand) • How will the Earth system change in the future? (Predict) • How can Earth system science improve mitigation of and adaptation to global change? (Apply)	1. Understand and improve predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition 2. Quantify the changing distributions of extreme weather events and enable improved weather prediction 3. Quantify and predict changes in global land cover, biological productivity, ecosystems, and the carbon cycle 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 roles of oceans, atmosphere, and ice in the climate system and improve predictive capability for future evolution 6. Characterize and understand Earth surface changes and variability of Earth's gravitational and magnetic fields 7. Enable the broad use of Earth system science observations and results in mitigating and adapting to a changing environment
Heliophysics: Understand the Sun and its interactions with the Earth and the solar system.	• What causes the Sun to vary? • How do the Earth and Heliosphere 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 interacting with planetary magnetic fields and atmospheres 3. Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space
Planetary Science: Ascertain the content, origin, and history of the solar system, and the potential for life elsewhere.	• What is the inventory of solar system objects and what processes are active in and among them? • How did the Sun's family of planets, satellites, and minor bodies originate and evolve? • What are the characteristics of the solar system that lead to habitable environments? • How and where could life begin and evolve in the solar system? • What are the characteristics of small bodies and planetary environments that pose hazards or provide resources?	1. Inventory solar system objects and identify the processes active in and among them 2. Understand how the Sun's family of planets, satellites, and minor bodies originated and evolved 3. Understand the processes that determine the history and future of habitability of environments on Mars and other solar system bodies 4. Understand the origin and evolution of Earth life and the biosphere to determine if there is or ever has been life elsewhere in the universe 5. Identify and characterize small bodies and the properties of planetary environments that pose a threat to terrestrial life or exploration or provide potentially exploitable resources
Astrophysics: Discover how the universe works, explore how the universe began and evolved, and search for Earth-like planets.	• How do matter, energy, space and time behave under the extraordinarily diverse conditions of the cosmos? • How did the universe originate and evolve to produce the galaxies, stars, and planets we see today? • What are the characteristics of planetary systems orbiting other stars, and do they harbor life?	1. Understand the origin and destiny of the universe, and the nature of black holes, dark energy, dark matter, and gravity 2. Understand the many phenomena and processes associated with galaxy, stellar, and planetary system formation and evolution from the earliest epochs to today 3. Generate a census of extra-solar planets and measure their properties

Appendix 2 Program/Mission Lines

Mission Lines	Mission Class	Objectives and Features	Example Missions
Earth Systematic Missions	Strategic missions of all sizes	Make new global measurements to address unanswered questions and reduce remaining uncertainties; maintain continuity of key measurements awaiting transition to operational systems managed by other agencies.	NPP, LDCM, OSTM, Decadal Survey missions
Earth System Science Pathfinder (ESSP)	Competed, PI-led small missions	Address focused Earth science objectives and provide opportunities for new science investigations. Includes the Venture class of suborbital campaigns, small satellites, and instruments of opportunity.	Aquarius, EV-2
Discovery	Competed, PI-led medium missions	Regular, lower cost, highly focused planetary science investigations of any solar system bodies other than the Earth and Sun.	Dawn, MESSENGER, GRAIL
New Frontiers	Competed, PI-led large missions	Focused scientific investigations designed to enhance our understanding of the solar system; competitively selected from among a specified list of candidate missions/science targets.	Juno, New Horizons
Mars Exploration	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, EMTGO
Lunar Quest	Strategic small missions	Explore the Moon, the lunar environment, and conduct key human precursor experiments with small missions and missions of opportunity.	LADEE, LRO
Solar Terrestrial Probes (STP)	Strategic medium and large missions	Strategic sequence of missions to provide understanding of the fundamental plasma processes inherent in all astrophysical systems.	TIMED, SOLAR-B, STEREO, MMS
Living With a Star (LWS)	Strategic medium and large missions	Strategic missions targeted toward those aspects of the Sun and space environment that most directly affect life and society.	SDO, RBSP, Solar Orbiter, Solar Probe Plus
Explorers	Competed, PI-led small or medium missions	Provide flight opportunities for focused scientific investigations from space with the Heliophysics and Astrophysics science areas. (Shared between Heliophysics and Astrophysics)	WISE, IBEX
Cosmic Origins	Strategic large and flagship missions	Provide the means to search out the farthest reaches and earliest moments of the universe	JWST, GLAST, SOFIA, HST
Physics of the Cosmos	Strategic medium and large missions	Complete Einstein's legacy and lead to understanding the underlying physics of the very phenomena predicted by his theories	IXO, LISA, JDEM
Exoplanet Exploration	Strategic medium and 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	Kepler
Missions of Opportunity	Small strategic or competed missions	Focused spaceflight investigations on missions led by international or other partners that offer high scientific or technical value for a modest cost to NASA	Strofio, Suzaku, TWINS, Astro-H

Appendix 3 Status of Missions Identified in Most Recent NRC Decadal Surveys

Survey	Class	Mission Concept	Status
Astrophysics: Astronomy and Astrophysics in the New Millennium (NRC, 2001)	Major Initiatives	Next Generation Space Telescope	James Webb Space Telescope now in development for 2014 launch
		Constellation-X Observatory	Candidate for prioritization in Astro 2010 as IXO
		Terrestrial Planet Finder (TPF)	Candidate for prioritization in Astro 2010
		Single Aperture Far Infrared (SAFIR) Observatory	Candidate for prioritization in Astro 2010
	Moderate Initiatives	Gamma-ray Large Area Space Telescope (GLAST)	Launched in June 2009
		Laser Interferometer Space Antenna (LISA)	Candidate for prioritization in Astro 2010
		Solar Dynamics Observatory (SDO)	Launched in February 2010
		Energetic X-ray Imaging Survey Telescope (EXIST)	Candidate for prioritization in Astro 2010
		Advanced Radio Interferometry between Space and Earth (ARISE)	Candidate for prioritization in Astro 2010
	Small programs	Endorsed continuation of vigorous Discovery and Explorer programs	Kepler Discovery missions launched in March 2009; Discovery now solely a Planetary Science program. Explorer program active at a reduced flight rate; WISE (launched 2009) and NuSTAR (2012) in development, GEMS (2014) selected.
	Reaffirmations from previous decadal survey	Stratospheric Observatory for Infrared Astronomy (SOFIA)	In development; early science flights in fall 2010;
		Space Interferometry Mission (SIM)	SIM-lite a candidate for prioritization in Astro 2010
		Hubble Space Telescope Fourth Servicing Mission	Completed in May 2009
	From Quarks to the Cosmos (NRC, 2003)	“wide field telescope in space…to fully probe the nature of dark energy”	Joint Dark Energy Mission a candidate for prioritization in Astro 2010
		“measure the polarization of the cosmic microwave background”	Inflation probe a candidate for prioritization in Astro 2010

Survey	Class	Mission Concept	Status
Planetary Science: New Frontiers in the Solar System (NRC, 2003)	Large missions	Europa Geophysical Explorer	Europa Jupiter System Mission chosen in 2009 to be implemented along with ESA's Ganymede Jupiter System Mission; early 2020's subject to decadal survey, ESA's process, and new start funding
	Medium missions (Candidates identified by NRC report Opening New Frontiers in Space: Choices for the Next New Frontiers AO (2008); all solicited thru New Frontiers AOs)	Kuiper Belt-Pluto Explorer	New Horizons mission launched in 2006; 2015 arrival at Pluto
		South Pole-Aitken Basin Sample Return	New Frontiers 3 mission candidate
		Jupiter Polar Orbiter with Probes	Juno mission (2011) in development
		Venus In-situ Explorer	New Frontiers 3 mission candidate
		Comet Surface Sample Return	Future New Frontiers mission candidate
		Network Science	Future New Frontiers mission candidate
		Trojan/Centaur Reconnaissance	Future New Frontiers mission candidate
		Asteroid Rover/Sample Return	New Frontiers 3 mission candidate
		Io Observer	Future New Frontiers mission candidate
		Ganymede Observer	See above for large missions
	Small missions	Discovery missions at a rate of one mission every 18 months	MESSENGER, Dawn (2007), Kepler (2009), Deep Impact/EPOXI, Stardust/NExT; ASPERA-3 on ESA's Mars Express, M3 on India's Chandrayaan; GRAIL (2011); next solicitation in 2010
		Cassini extended mission	Cassini Solstice mission underway; ends in 2017
	Large Mars missions	Mars Sample Return	Remains the goal of the Mars Exploration Program for 2020-2022 timeframe but will require additional funds or substantial foreign contributions
	Medium Mars missions	Mars Science Laboratory	MSL (2011) in development as a flagship mission
		Mars Long-lived Lander Network	Candidate for Mars 2018 or New Frontiers opportunity
	Small Mars missions	Mars Scout line	Phoenix Polar Lander completed mission in 2008; MAVEN (2013) selected in 2008. Future missions to be solicited via Discovery.
		Mars Upper Atmosphere Orbiter	MAVEN (2013) selected in 2008; Mars 2016 in definition with ESA will include trace gas observations

Appendix 3 Continued

Survey	Class	Mission Concept	Status
Heliophysics: The Sun to the Earth and Beyond (NRC, 2003)	Large missions	Solar Probe	Solar Probe-Plus (2018) in pre-formulation, with a science AO issued in December 2009
	Medium missions	Magnetospheric Multiscale	MMS (2014) in development
		Geospace Network	Partially met by RBSP (2012) in development
		Jupiter Polar Mission	Juno (2011) in development
		Multispacecraft Heliospheric Mission	Candidate for prioritization in 2012 decadal survey
		Geospace Electrodynamic Connections	Candidate for prioritization in 2012 decadal survey
		Suborbital Program	Restored to health in FY2009
		Magnetospheric Constellation	Candidate for prioritization in 2012 decadal survey
		Solar Wind Sentinels	Candidate for prioritization in 2012 decadal survey
		Stereo Multispheric Imager	Partially met by TWINS (2008)
	Small missions	Solar Orbiter (U.S. instrument contributions to ESA mission)	Four instruments selected by NASA in 2009
		Endorsed Explorer-class missions	Explorer program active at a reduced flight rate; IBEX launched in 2008; IRIS (2012) selected in 2009
		Endorsed University-Class Explorers	Incorporated into Explorer Missions of Opportunity as small complete missions
	Endorsed approved missions	Solar Dynamics Observatory	Launched in February 2010

Survey	Class	Mission Concept	Status
Earth Science: Earth Science and Applications from Space (NRC, 2007)	Foundation missions	Landsat Data Continuity Mission	LDCM (2012) in development
		Global Precipitation Measurement	GPM (2013) in development
	Tier 1	Soil Moisture Active-Passive	SMAP (2015) in formulation
		Ice, Cloud and land Elevation Satellite - II	ICESat-II (2016) in pre-formulation
		Climate Absolute Radiance and Refrac-tivity Observatory	CLARREO engineering studies underway prior to development for a 2017 launch
		Deformation, Ecosystem Structure and Dynamics of Ice	DESDynI engineering studies underway prior to development for a 2017 launch
		Venture class line of small, innovative missions	1st Venture class solicitation issued in 2009; planned for release every 2nd year thereafter, alternating between airborne and space missions. 1st space mission solicitation in FY2012 for a FY2017 launch. Venture program will include an annual instrument of opportunity solicitation begin-ning in FY2011.
	Tier 2	Hyperspectral Infrared Imager (HyspIRI)	The FY11 budget request funds the development of two Tier 2 missions (ASCENDS, SWOT) for launch by the end of 2020, and the acceleration the others to development and launch at a rate of approxi-mately one per year beginning in 2021.
		Active Sensing of CO_2 Emissions Over Nights, Days, and Seasons (ASCENDS)	
		SWOT	
		Geostationary Coastal and Air Pollution Events (GEO-CAPE)	
		Aerosol-Clouds-Ecosystems (ACE)	
	Tier 3	Lidar Surface Topography (LIST)	Technology development underway
		Precipitation and All-weather Temperature and Humidity (PATH)	Technology development underway
		Gravity Recovery and Climate Experiment (GRACE-II)	Technology development underway
		Snow and Cold Land Processes (SCLP)	Technology development underway
		Global Atmospheric Composition Mission (GACM)	Technology development underway
		Three-Dimensional Tropospheric Winds (3D-Winds) (demo)	Technology development underway

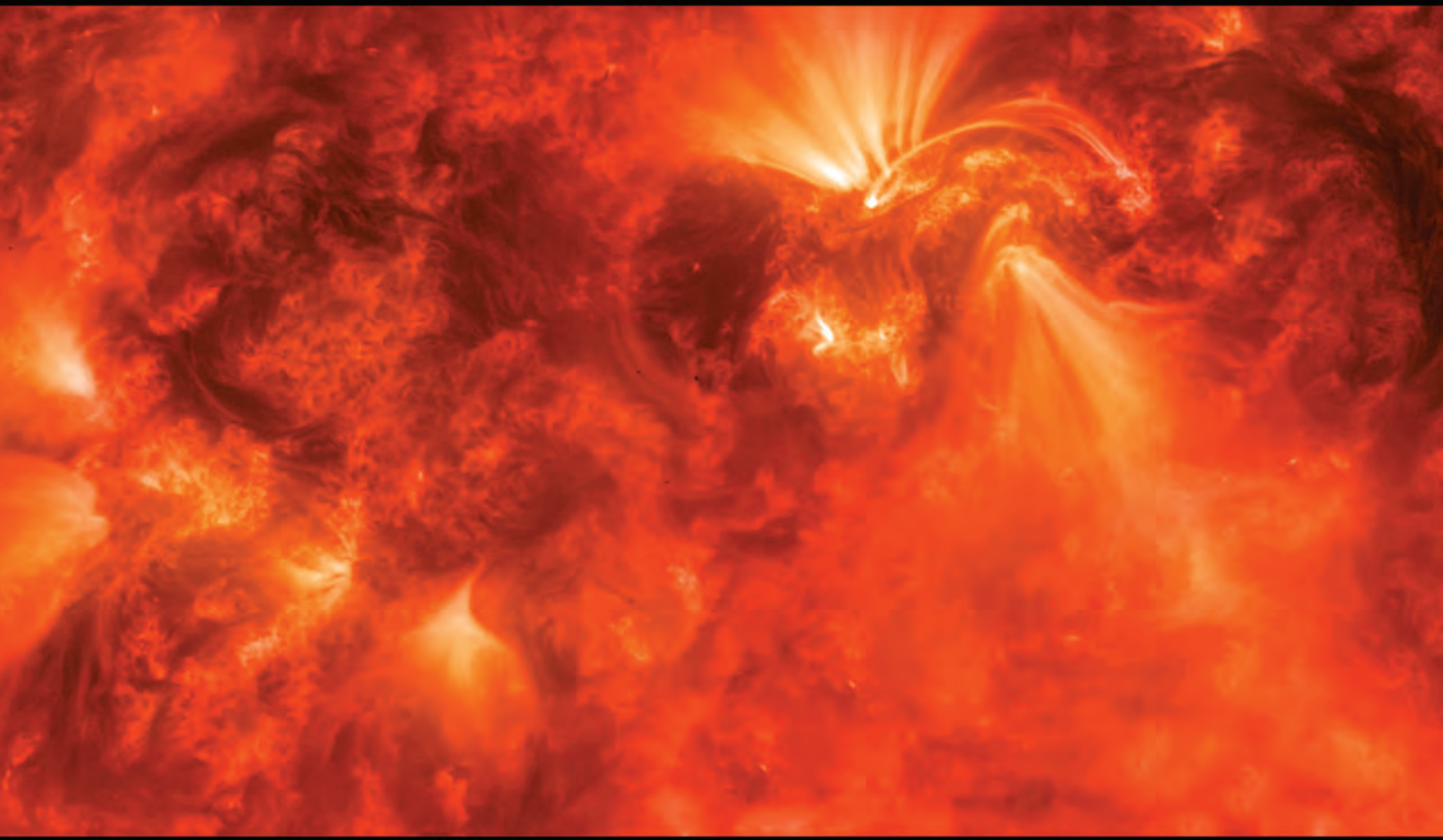
Appendix 4 Acronyms and Abbreviations

Abbreviations and Acronyms	Definition
AIM	Aeronomy of Ice in the Mesosphere
AO	Announcement of Opportunity
APS	Advanced Polarimeter Sensor
ASCENDS	Active Sensing of CO_2 over Nights, Days and Seasons
BARREL	Balloon Array for Radiation-belt Relativistic Electron Losses
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CERES	Cloud and the Earth's Radiant Energy System
CINDI	Coupled Ion-Neutral Dynamics Investigations
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CME	Coronal Mass Ejection
CNES	French Space Agency (Centre National d'Etudes spatiale)
CO_2	Carbon dioxide
CONTOUR	Comet Nucleus Tour
Con-X	Constellation-X
COSPAR	Committee on Space Research of the International Council of Scientific Unions
DESDynI	Deformation, Ecosystem Structure, and Dynamics of Ice
DoD	Department of Defense
DoE	Department of Energy
DLR	German Aerospace Center (Deutsches Zentrum fur Luft- und Rahmfahrt)
DSN	Deep Space Network
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
EMTGO	ExoMars Trace Gas Orbiter
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)
ESSP	Earth System Science Pathfinder
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FY	Fiscal Year
GALEX	Galaxy Evolution Explorer
GEMS	Gravity and Extreme Magnetism SMEX
GEO	Geostationary orbit
GEOSS	Global Earth Observation System of Systems
GLOBE	Global Learning and Observations for a Better Environment
GN	Ground Network
GPM	Global Precipitation Measurement
IDS	Interdisciplinary Science

Abbreviations and Acronyms	Definition
GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
HST	Hubble Space Telescope
IBEX	Interstellar Boundary Explorer
ICEsat-II	Ice, Clouds and land Elevation Satellite-II
IIP	Instrument Incubator Program
IPCC	Intergovernmental Panel on Climate Change
IRIS	Interface Region Imaging Spectrograph
IXO	International X-ray Observation
JAXA	Japanese Space Agency (Japan Aerospace Exploration Agency)
JDEM	Joint Dark Energy Mission
JPSS	Join Polar Satellite System
JWST	James Webb Space Telescope
L1	Lagrange point 1
LADEE	Lunar Atmosphere and Dust Environment Explorer
LASER	Lunar Advanced Science and Exploration Research
LDCM	Landsat Data Continuity Mission
LEO	Low Earth Orbit
LISA	Laser Interferometer Space Antenna
LRO	Lunar Reconnaissance Orbiter
LSP	Launch Services Program
LWS	Living With a Star
MAVEN	Mars Atmosphere and Volatile Evolution
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging
MMS	Magnetospheric Multiscale
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NEAR	Near Earth Asteroid Rendezvous
NEO	Near Earth Object
NEOO	Near Earth Objects Observation
NESSF	NASA Earth and Space Science Fellowship
NExT	New Exploration of Tempel-1
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
NuSTAR	Nuclear Spectroscopic Telescope Array

Appendix 4 Continued

Abbreviations and Acronyms	Definition
OCO	Orbiting Carbon Observatory
OMPS	Ozone Mapper and Profiler Suite
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
PACE	Pre-Aerosol, Clouds, and Ecosystems
PDS	Planetary Data System
PI	Principal Investigator
R&A	Research & Analysis
RBSP	Radiation Belt Storm Probes
ROSES	Research Opportunities in the Space and Earth Sciences
RPS	Radioisotope Power System
RTG	Radioisotope Thermal Generator
SAR	Synthetic Aperture Radar
SARA	Service and Advice for Research and Analyses
SDO	Solar Dynamics Observatory
SIM	Space Interferometry Mission
SMAP	Soil Moisture Active/Passive
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
STEM	Science, Technology, Engineering and Mathematics
STEREO	Solar Terrestrial Relations Observatory
STP	Solar Terrestrial Probes
SWOT	Surface Water and Ocean Topography
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TSIS	Total Solar Irradiance Sensor
USAF	United States Air Force
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey
WISE	Wide-field Infrared Survey Explorer
WMAP	Wilkinson Microwave Anisotropy Probe



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