

Executive Summary

The exotic environment of space beyond Earth's protective atmospheric cocoon is highly variable and far from benign. It is the one part of the cosmos accessible to direct scientific investigation, our only hands-on astrophysical laboratory. Our technological society is increasingly susceptible to space weather disturbances in this curious region. A host of interconnected physical processes, strongly influenced by solar variability, affect the health and safety of travelers in space and the habitability of alien environments. Building on NASA's rich history of exploration of the Earth's neighborhood and distant planetary systems, we are poised to develop the quantitative knowledge needed to help assure the safety of the new generation of human and robotic explorers. The Sun-Solar System Connection Program has been completely reevaluated to address the needs of the Vision for Space Exploration.

[[[Figure Caption: NASA's Advanced Planning and Integration Office (APIO) developed the statement of NASA Strategic Objective #15 for the Sun-Solar System Connection division to support NASA's Guiding National Objectives (in *NASA's Direction for 2005 and Beyond*, NASA HQ, Feb., 2005)]]]

NASA's future research and exploration within its Sun-Solar System Connection program aims to "explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by explorers, and to demonstrate technologies that can improve future operational systems." We have unfolded this into the three broad science and exploration objectives listed below.

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

These will be accomplished by studying the Sun, the heliosphere, and planetary environments as elements of a single inter-connected system that contains dynamic space weather and evolves in response to solar, planetary and interstellar conditions. Focused research programs addressing specific space environmental hazards will help guide the design and operations of safe and productive missions. At the same time we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space. Such an understanding will represent not just a grand intellectual accomplishment for our times - it will also provide knowledge and predictive capabilities essential to future human and robotic exploration of space and will serve key societal objectives in important ways. Herein, we describe current plans for NASA's research programs in this area and the guiding principles we will follow in pursuit of forthcoming exploration challenges.

This scientific exploration will target the highly coupled system that stretches from the Sun's interior to planetary neighborhoods and the vast expanses of interplanetary space. We are

already transforming human understanding of this fascinating global system of systems, so closely connected that a single explosive event on the Sun can produce power outages on the Earth, degradation of solar panels on interplanetary spacecraft, fatal damage to instrumentation in Mars orbit, and auroral displays at Saturn – effects that span the entire solar system. By expanding and deepening that understanding, we will not only develop a predictive capability to address hazards to space travelers and to important technological assets closer to home, but we will learn how the fundamental space processes interact to affect the habitability of other distant environments, beyond our own solar system.

In keeping with our requirements driven approach, each objective has been associated with research focus areas and scientific investigations. Targeted outcomes for each decade have been identified for each objective and these have led to our recommendation for missions. Our goals will be achieved by utilizing three groups of strategic missions and the rapid-response Explorer Program, all supported by programs for research and analysis, technology development, and education and public outreach. Investigations supported by missions that can launch in the next ten years are described below. Subsequent mission candidates for each line are described in the report.

The **Solar-Terrestrial Probe** (STP) missions address fundamental science questions about the physics of space plasmas and the flow of mass and energy through the solar system. Three STP missions already begun can be launched in the next decade. Solar-B, a partnership mission led by Japan, will be launched in 2006 to observe how magnetic fields on the Sun's surface interact with the Sun's outer atmosphere, which extends millions of miles into space. The STEREO mission, also to be launched in 2006, will provide an unprecedented three-dimensional view of the magnetic field and particle flows throughout the inner heliosphere. Third, the Magnetospheric Multiscale Mission, to be launched in 2011, will explore the fundamental physical processes responsible for the transfer of energy from the solar wind to Earth's magnetosphere and the explosive release of energy during solar flares.

The **Living With a Star** (LWS) missions will enhance knowledge of the Earth-Sun system that directly affects life and society. The budget enables the launch of four synergistic missions by 2015. The Solar Dynamics Observatory, to be launched in 2008, will continuously observe the Sun's interior, surface, and atmosphere to determine the physical causes of solar variability. The Radiation Belt Storm Probes, to be launched in 2011, will determine how space plasmas are accelerated to hazardous energies, thereby enabling scientists to predict changes to planetary radiation environments and protect space explorers. The Ionospheric / Thermospheric Storm Probes, to be launched in 2015, will help scientists understand, to the point of acquiring a predictive capability, the effects of geomagnetic storms on the ionosphere / thermosphere—a region in the atmosphere located approximately 50 to 800 miles above Earth's surface. Last, the Inner Heliospheric Sentinels, also to be launched in 2015, will provide understanding on the propagation and evolution of eruptions and flares from the Sun to the planetary environments. Partnership is crucial to LWS and we recommend SSSC collaboration on ESA's Solar Orbiter mission in this time frame. The LWS Space Environment Testbeds provide an opportunity for technological partnerships with spacecraft designers.

Flagship and Partnership missions address highly challenging and important goals, but are not part of the baseline funded program. **Flagship** missions cannot be afforded without additional resources.. The Solar Probe mission will explore the frontier at the inner edge of our solar system; the mission is ready to fly and is our highest priority for new resources. Much later flagships are an interstellar probe and a stellar imager. **Partnerships** must leverage

opportunities available in other programs. The Pluto/Kuiper mission already includes space plasma instrumentation to examine solar wind interactions out to the most remote bodies in our solar system. The Solar Sail Demo mission will enable future missions of much higher delta-V capability. A Jupiter Polar Orbiter mission will enable us to compare the solar wind interaction for a rapidly rotating magnetosphere with that of Earth. The Aeronomy and Dynamics at Mars (ADAM) mission, a potential Mars Scout, will provide information about the Martian atmosphere in support of human and robotic exploration of Mars.

The **Explorer Program** provides a vital and effective means of achieving urgent strategic goals in a timely way. Explorers are highly responsive to new knowledge, new technology, and updated scientific priorities by supporting smaller missions that are conceived and executed in a relatively short development cycle, based on open solicitation of concepts from the entire community. The program also enables participation in missions-of-opportunity provided by other national or international agencies. Three Explorers currently in development are relevant to this Roadmap. AIM will determine why polar mesospheric clouds form and why they vary and will determine the mesospheric response to solar energy deposition and coupling among atmospheric regions. The five-spacecraft THEMIS mission will elucidate the mechanisms of transport and explosive release of solar wind energy within the magnetosphere and is a technology precursor to future ‘constellation’ missions. The recently selected IBEX mission will image the edge of our solar system to examine galactic cosmic rays and particle acceleration at the heliopause.

The currently operating spacecraft missions supporting Sun – Solar System Connections research collectively constitute a Great Observatory that can address the fundamental challenge for SSSC science. The **SSSC Great Observatory** provides the simultaneous measurements in multiple locations needed to resolve temporal and spatial changes and to understand the interactions of complex systems of regimes. As we progress in the exploration of space, this essential capability must evolve to support ever more comprehensive understanding and predictive capabilities. In the years ahead, portions of this spacecraft fleet will be configured into “smart” constellations - sets of strategically-located satellites that can work together to provide timely data for on-demand assimilation to enable scientific research, national policymaking, economic growth, hazard mitigation, and the exploration of other planets in this solar system and beyond.

Several smaller but no less crucial program elements support the implementation of the SSSC program. **Low cost access to space** using ever more capable rockets and balloons provides unique science, community development, and technology and instrument development. The interplay among **observation, simulation, modeling, and theory** is essential for the vitality of our space science program. A model or simulation often provides specific predictions to spur the course of future observation. Unexplained observations have led to the development of new theories and the creation of entirely new models. We must continue supporting fundamental theory, modeling, data assimilation, and simulation programs, the development of space weather modeling frameworks, and the transition to applications-based codes necessary for space weather operational predictions. The burgeoning maturity of current, comprehensive theoretical modeling systems, spanning many regions and times scales, provides the essential underpinnings for NASA’s effort to integrate and synthesize knowledge of the complete system of systems.

As an essential element of its plan to meet these challenging requirements, NASA will invite active participation by **international and national partners** to support the exploration and research program

Education and public outreach have become an integral part of SSSC activities. Building on this foundation, we recommend that E/PO activities stemming from the science achievements or milestones be developed to support the following five messages:

- *NASA keeps me informed about what's going on with the Sun*
- *The Solar System is an Astrophysical Laboratory for NASA*
- *NASA science helps us protect our society from hazardous space weather*
- *NASA science helps us understand climate change*
- *NASA science helps keep space explorers safe and supports exploration activities*

SSSC embraces the development, infusion, and study of **new technology**, both for its stimulating effect on science and because of the key role that understanding and predicting the space environment presents for the safety of other NASA missions and of our global infrastructure that is increasingly space-based. Continuing progress requires technological development in a number of key areas.

- *Developing compact, low-cost spacecraft and launch systems;*
- *Achieving high V propulsion (solar sails);*
- *Designing, building, testing, and validating the next generation of SSSC instrumentation;*
- *Returning and assimilating large data sets from throughout the solar system;*
- *Analysis, data synthesis, modeling, and visualization of plasma and neutral space environments throughout the solar system.*

This proposed SSSC program has been derived directly from NASA's new priorities. It is both reassuring and puzzling that the new plan is largely consistent with previous recommendations. The long-term goals and the near-term budget have shifted since the solar and space physics strategy was presented in the National Research Council's 2002 decadal report, *The Sun to the Earth – and Beyond*. However, as noted in the 2004 NRC update, *Solar and Space Physics and Its Role in Space Exploration*, “the basic priorities of the decadal strategy are still valid for the simple reason that the fundamental principles used in constructing the strategy were the need for a balanced program of basic and applied research that endeavors to recognize the solar-planetary environment for the complex system that it is. We do not know enough today to perform the predictive task required of us by the exploration initiative, and only by pursuing fundamental knowledge and employing a system-level approach can we hope to succeed.”

[[[Caption for Exec. Summary Graphic:

This figure illustrates the flow of requirements from an overarching strategic goal to principal science objectives, through implementation, to anticipated achievements and impacts relative to the goal and objectives.]]]