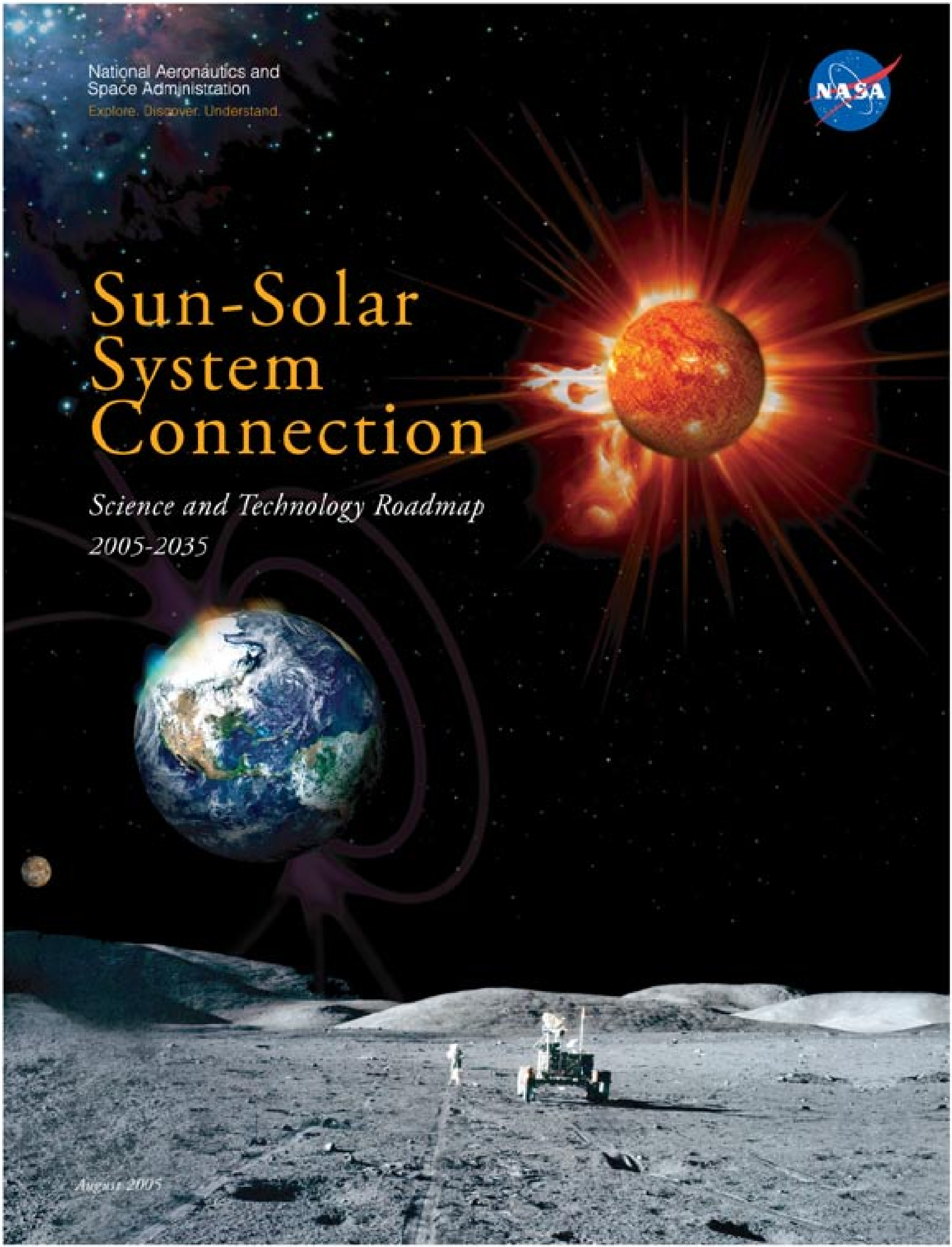
National Aeronautics and
Space Administration
Explore. Discover. Understand.

Sun-Solar System Connection

Science and Technology Roadmap

2005-2035



August 2005

NASA'S VISION

To improve life here,
To extend life to there,
To find life beyond.

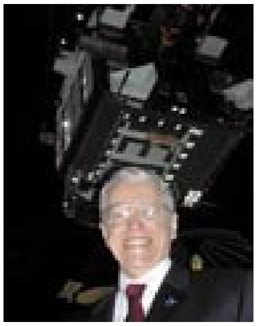
NASA'S MISSION

To understand and protect our home planet,
To explore the universe and search for life,
To inspire the next generation of explorers
... As only NASA can.

The SOHO and TRACE missions reveal intricate structures above the bright active regions strewn across the Sun's surface, which would otherwise appear as groups of dark sunspots in ordinary visible light. Colorized extreme-ultraviolet images have been melded to show that the magnetic field in the Sun's upper atmosphere confines gas at widely differing temperatures virtually side by side. Million-degree material has a bluish hue; features include faint coronal holes and large bright prominences above the edge of the Sun. The redder active regions and extended loops are two or more times as hot. The Solar Dynamics Observatory, to be launched in 2008, will image the entire Sun every few seconds in several temperatures and measure surface velocity and magnetic field. SDO data will dramatically advance our ability to determine the origins of these structures and understand how they change.

NASA STRATEGIC OBJECTIVE #15

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 human explorers, and demonstrate technologies that can improve future operational systems.



"Thought Generates Action" -

- C. Hobbs, Time Power, (1987)

It is a pleasure to accept the 2005 Sun-Solar System Connection Roadmap from the national science community.

It presents a strategic outlook for the nation and agency toward the development of new knowledge for exploration. It also reveals the progress made to date, our plans for the near future, and our opportunities for supporting the Agency's Vision, Mission, and Values.

Space physics has made rapid and spectacular advances over the past few years. Utilization of combinations of missions, each one with its own complement of instruments operating at a specific location, has been vital to the emergence of a new view of the Sun-Solar System as a connected system. There will be further dramatic advances as observational techniques, new missions, and a new understanding of how microphysical processes influence broad-scale dynamics emerge in the not-to–distant future. Computational and theoretical achievements presently facilitate the development of more sophisticated, and realistic models of the connected system, and achievements in this area foreshadow demonstration of the benefits of the research products as they are integrated into the conduct of both civil and governmental affairs. Each discovery impels us to ask new questions or regard old ones in new ways. How and why does the Sun vary? How do planetary systems respond? What are the impacts to humanity?

This roadmap outlines development of a common groundwork of explanation that crosses all the space physics branches of learning. It is anticipated that this will lead to a unification of long-separated fields of inquiry; thereby enabling the emergence of new and significant scientific insights. I believe that we are on the cusp of a flowing together of knowledge that will merge various disciplines of space physics research, and the results of this process will have not only cultural and intellectual value but also will be vital to the optimization of economic and political activities of the 21 st Century.

Finally, a new opportunity has presented itself since the generation of the previous roadmap, the possibility of participating in the nation's program of the exploration of space, both by human and robotic means. Development tools and data for the generation of end-to-end space hazard predictions of conditions throughout the solar system is an obvious contirbution to future flight operations and flight safety. Achievement of this level understanding will enrich human spirit and enable a new generation of explorers, scientists, and engineers.

This change forms a backdrop for the community's most ambitious roadmap plan to date for the conduct of a Sun-Solar System Connection scientific research program. The program described includes forefront research and technology development as well as the development and operation of the most complex flight missions conceived. The flight program is a balanced portfolio of small missions and larger spacecraft with the goal of obtaining the best science at the lowest cost that can meet our standards for mission success. Many of the recommended science priorities can be realized within the next 25 years. However, this roadmap recognizes that within the resources anticipated to be available, not all of these science objectives can be undertaken immediately. Constructing this roadmap has clearly entailed making choices, some of which have been difficult.

Previous investigation of our solar system has offered a menu of surprises and secrets.

We expect exposure to both as knowledge continues to expand concerning the history and future of our universe and of humankind's place within it. It is a privilege to associate with the people who have contributed their time and energy to the construction of this document.

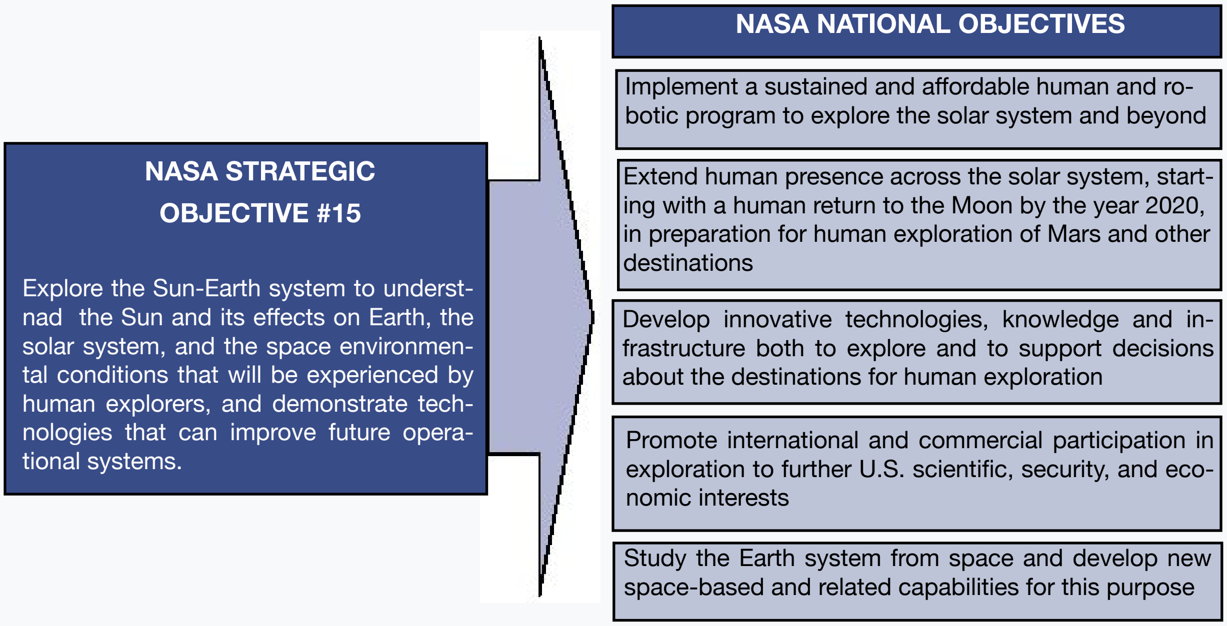
I am confident that the passage of time will validate the wisdom and choices of the committee and their consultants. To those involved with the generation of this plan, my warmest gratitude and my admiration for a comprehensive and articulate statement. I invite you the reader, to join this fascinating future journey of discovery.

The Sun-Solar System Connection

Science and Technology Roadmap

Table of Contents

APPENDICES:



NASA STRATEGIC OBJECTIVE #15

Explore the Sun-Earth system to understnad the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational systems.

NASA NATIONAL OBJECTIVES

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations
- Develop innovative technologies, knowledge and infrastructure both to explore and to support decisions about the destinations for human exploration
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests
- Study the Earth system from space and develop new space-based and related capabilities for this purpose

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)

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.

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 the Journey of Exploration:*** Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space

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 now 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 top-down 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 pursuing 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.

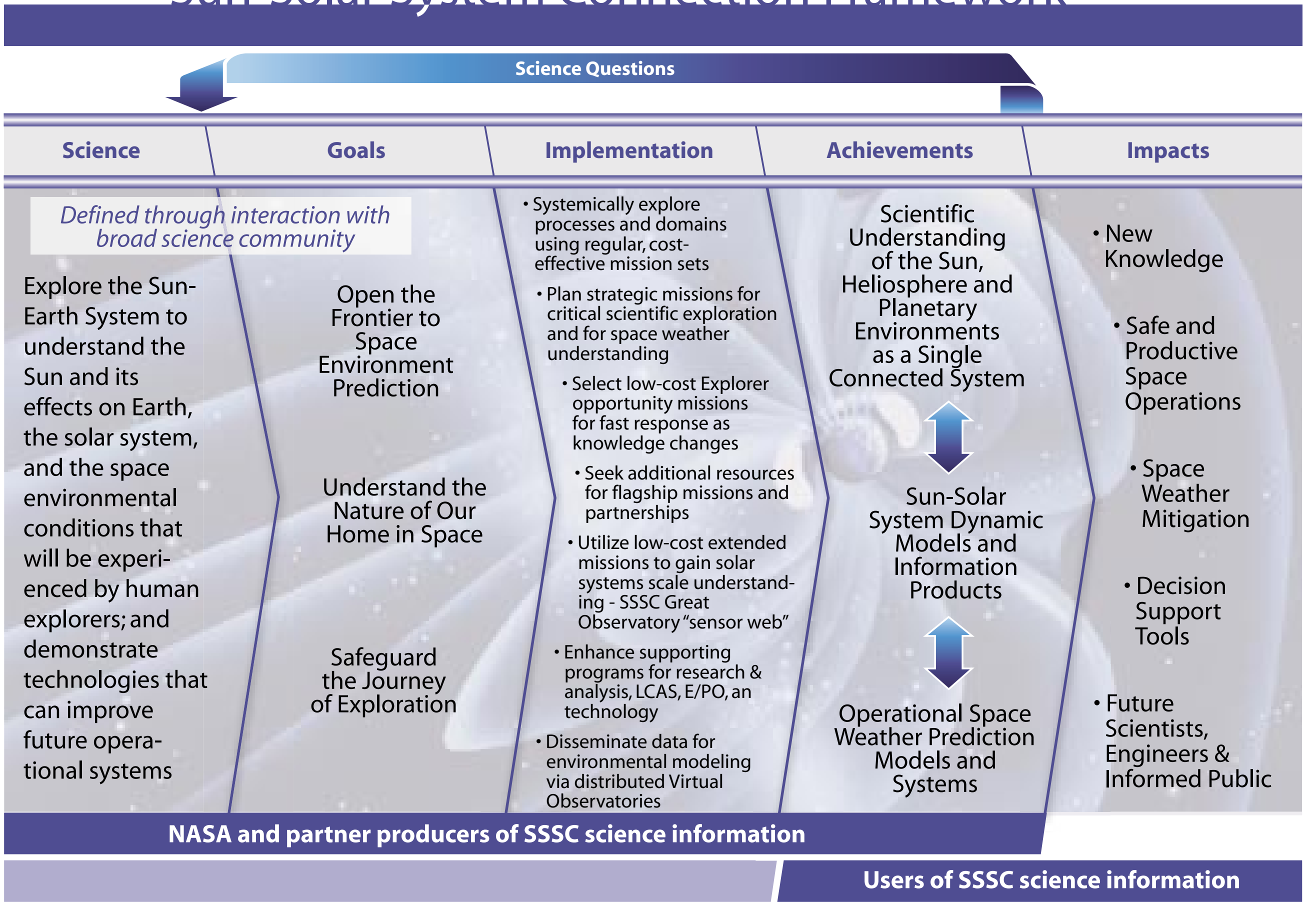
The **Solar-Terrestrial Probe** (STP) missions address fundamental science questions about the physics of space plasmas and the flow of mass and energy through the solar system. Three STP missions already begun can be launched in the next decade. Solar–B, a partnership mission led by Japan, will be launched 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 observe the Sun's interior, surface, and atmosphere continuously 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

Sun-Solar System Connection Framework



Science

Defined through interaction with broad science community

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 human explorers; and demonstrate technologies that can improve future operational systems

Goals

Open the Frontier to Space Environment Prediction

Understand the Nature of Our Home in Space

Safeguard the Journey of Exploration

Implementation

- Systemically explore processes and domains using regular, cost-effective mission sets
- Plan strategic missions for critical scientific exploration and for space weather understanding
  - Select low-cost Explorer opportunity missions for fast response as knowledge changes
  - Seek additional resources for flagship missions and partnerships
  - Utilize low-cost extended missions to gain solar systems scale understanding - SSSC Great Observatory "sensor web"
  - Enhance supporting programs for research & analysis, LCAS, E/PO, an technology
- Disseminate data for environmental modeling via distributed Virtual Observatories

Achievements

Scientific Understanding of the Sun, Heliosphere and Planetary Environments as a Single Connected System

Sun-Solar System Dynamic Models and Information Products

Operational Space Weather Prediction Models and Systems

Impacts

- New Knowledge
- Safe and Productive Space Operations
- Space Weather Mitigation
- Decision Support Tools
- Future Scientists, Engineers & Informed Public

NASA and partner producers of SSSC science information

Users of SSSC science information

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.

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 the timely, on-demand data and analysis to users who enable the practical benefits for 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 lead 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 a natural 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 ΔV 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;
- Analyzing, 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 bemusing 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."

Exploration and Fundamental Science

“ Something hidden. Go and find it. Go and look behind the Ranges---”
- Rudyard Kipling (1865-1936), “The Explorers” (1903)

The primary goal of the Vision for Space Exploration is the implementation of “a sustained and affordable human and robotic program to explore the solar system and beyond.” This simple statement has profound consequences on how to prioritize the science programs that are needed to accomplish the new vision. How is the SSSC community to respond, when its traditional culture has been the scientific investigation of processes fundamental to space physics? Advice came recently from the Space Studies Board of the National Academy of Sciences who offered five guiding principles, the first of which was:

Exploration is a key step in the search for fundamental and systematic understanding of the universe around us. Exploration done properly is a form of science.

The answer for the SSSC community becomes clear when we realize that the converse of the guiding principle also holds: Exploration cannot be done properly without science.

Exploration must be well-planned; history is rife with narratives of expeditions that ended fruitlessly or, even worse, tragically. In reality, properly implies safely, efficiently, and economically. There are many examples of pragmatic problems facing the successful implementation of the Exploration Vision, ranging from the prediction of the space radiation environment to the design of the critical entry of a Crew Exploration Vehicle into the Martian atmosphere. In both cases, the science that enables exploration activities is drawn from the same science that is used to investigate the fundamental processes on the Sun, the planets, and in the heliosphere from its inner boundary to the outer boundary with the interstellar medium.

The pursuit of fundamental science not only enables Exploration but it also transforms our understanding of how the universe works. Current SSSC missions are producing a steady stream of transformational science that is rewriting the textbooks of past decades. Some recent examples:

- Direct evidence from IMAGE and Cluster that magnetic reconnection in the earth’s protective magnetosphere can open “holes” that allow solar wind to leak through continuously for hours – much longer than theorists predicted.

- Surprising information from SOHO about the hidden workings of the subsurface solar dynamo that generates the Sun’s magnetic field.

- A new understanding of the acceleration sites of solar energetic particles based on RHESSI gamma ray observations.

- The puzzling complexities of the outer boundary of the solar wind discovered by the Voyager-1 spacecraft, our most distant explorer.

The new pragmatic challenges of the Vision for Space Exploration will dictate re-focused and intensified scientific exploration. This exploration will bring forth exciting discoveries, but only if it has the same broad scientific base that has nurtured the SSSC community to its current maturity. Why? Because space science is replete with pivotal discoveries that came from unexpected quarters, from areas of sound but seemingly tangential research. We would not now be understanding the details of the acceleration of solar energetic particles revealed by RHESSI if space scientists in the 1970’s had not worked out the details of gamma-ray line emission in the solar atmosphere (a subject that struck many as esoteric in those days).

This SSSC Roadmap differs from its predecessors in that it clearly responds to the new priorities in space science. Nonetheless, it preserves the momentum of our community’s achievements and maintains continuity with past strategic planning. Appropriate missions recommended by previous studies are carried forward, while new missions are put forward that will produce the science required for the success of the Vision for the Moon (2020) and Mars (2035). Each of these new missions is soundly conceived in fundamental science objectives while being efficiently designed to do the science that will support the Vision of Space Exploration. Well-planned science cannot help but generate exciting discoveries while still delivering the promised results.

Part I:
Sun-Solar System Connection:
A New Science for the Age of Exploration

As we leave the protective cocoon of the Earth System, Our Explorers Will Move from a Gravitationally Dominated to a Magnetically Driven Environment

Gravitationally Driven

Familiar Physics - Two Forces:

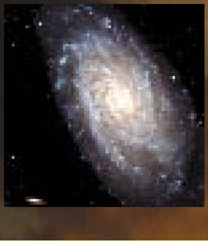
- Gravity
- Pressure

Magnetically Driven

Sun-Solar System Connection Physics- Three Forces:

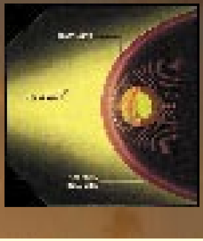
- Gravity
- Pressure
- Magnetism

Galaxies

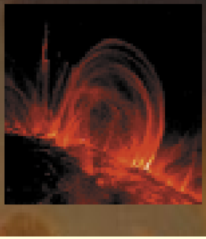


Planets

Heliosphere



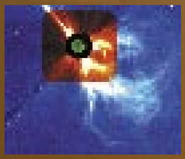
Stellar Magnetism



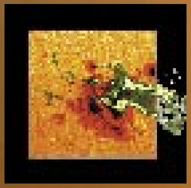
Space Weather

Stars/Sun:

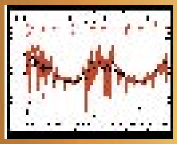
CMEs



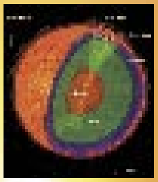
Flares



Total Solar Irradiance / Climate

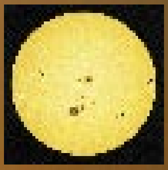


Magnetars



Shocks

Solar Variability

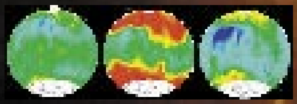


Planets:

Aurorae

Ionospheres

Atmospheric Chemistry



Planetary Magnetospheres & Atomspheres

The dynamic interplay between the three forces (pressure, gravity, and magnetism) in the various venues of the solar system - the Sun's atmosphere; the interplay between the Sun and the heliospgere; the interfaces between planets, their magnetospheres and the heliosphere; and the boundary between the solar system and the galaxy

Part I.

A New Science for the Age of Exploration

Space exploration has transformed our understanding of the solar system. It has revealed a fascinating nested system of systems, so closely connected that an explosive event on the Sun produces measurable effects that span the entire solar system. Through judicious use of a number of operating missions, we have achieved system surveillance over parts of the heliosphere, and have been able to examine the causal linkages between its parts. In late 2003 we observed spectacular coronal mass ejections, power outages on the Earth, degradation of spacecraft solar panels and circuits, destruction of atmospheric ozone, inflation and ablation of planetary upper atmospheres, fatal damage to instrumentation in Mars orbit, auroral displays on Saturn, and, months later, radio disturbances at the edge of the solar system where it meets the interstellar medium. In short, we have observed that space contains weather and that it can affect us.

Classically, the structure and processes of our environment had been understood in terms of gravitation and pressure. Since space exploration began in 1957, we have learned that space is filled with matter and electromagnetic fields whose importance is belied by their invisibility. Unsheltered from the Sun's pervasive UV radiation, matter in space enters the fourth state: a conducting plasma of electrically charged electrons and ions, flowing and reacting to highly variable electromagnetic forces. Common human experience provides little experience or intuition about the behavior of such plasma atmospheres.

Owing to their conductivity, moving plasmas generate electrical currents and magnetic fields. Many exotic phenomena ensue, some of which resemble turbulent fluid flows, but impart so much energy to a subset of particles that they ionize many more atoms when they come in contact with cooler states of matter such as gases, semiconductor circuits, or living tissue. Magnetic field lines act to link their source plasmas into coherent cells, much as droplets of water are defined by surface tension. When such cells of plasma come into contact with each other, their magnetic fields may reconnect, creating a linkage between the two cells and coupling them to each other so that motions of one drive motions of the other. Electrical currents flow to generate the coupling forces, and electromotive forces are generated that accelerate charged particles, sometimes explosively as in solar flares.

The robotic exploration of our universe has clearly shown that electromagnetically driven processes act at the center of every stellar system. Our own solar system is driven by the Sun, a magnetically variable star. The Vision for Space Exploration will eventually free humankind from the gravitational forces that have held us through history. Space explorers will learn to live within the magnetically controlled space environment and, through our NASA exploration missions, every citizen will be able to see and experience these things.

Our program will help assure the assure the safety of the new generation of human and robotic explorers

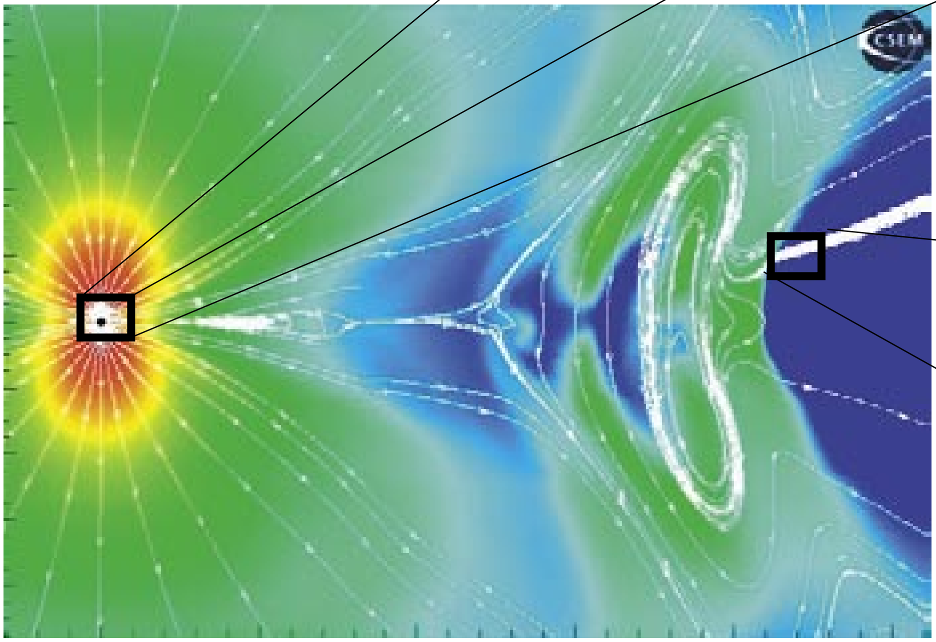
At the same time we will pursue a deeper understanding of the fundamental physical processes that underlie the awesome phenomena of space

We will develop a predictive capability to address hazards to important technological assets closer to home and learn how fundamental space processes may affect the habitability of other distant environments beyond our own solar system

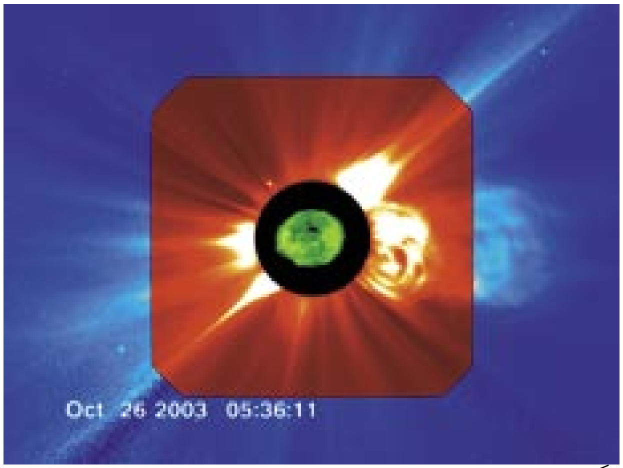
The Earth and Sun are linked together to form the system that has given origin and sustenance to our lives. The story of how this came to be, over the history of the solar system, is nothing less than a Creation Narrative. It is an aspect of the most compelling mystery faced by humankind. The physical processes and the evolutionary paths embedded in this combined system are studied in the Earth-Sun System division of NASA's Science Mission Directorate. We examine the Earth and Sun system today for insights into questions concerning how the system evolved so as to produce and sustain life, what will happen to this unique environment through the course of time, and how it will affect us.

With human space activity restricted to low Earth orbit since the mid-70's, we have been reconnoitering the solar system (and beyond) using robotic spacecraft and telescopes. In 2005, Voyager passed through the solar wind termination shock and into the heliosheath, nearing the outer edge of the solar system. Though we have not visited the inner boundary of the solar atmosphere, the Sun is bright enough to reveal a great deal about itself through remote imaging, spectroscopy, and polarimetry.

The first broad survey of the solar system is essentially complete and we are now beginning to revisit the planets, including Earth, for studies of greater depth. The region around the Earth remains an important astrophysical laboratory for the study of the physical processes that are of broad relevance to astrophysics. Moreover, these processes are by now known to have influenced the habitability of the Earth and are, therefore, relevant to the possible existence of life elsewhere in the solar system or universe. We have barely begun to scratch the surface of the history of our solar system over geologic time and have only recently deterearlier steps



These panels suggest the range of spatial scales relevant to SSSC observers and modelers. The left panel shows a simulation of an interplanetary disturbance approaching the Earth. The two images in the center show the Sun and it's corona (top) and a greatly expanded view of the disturbance reaching Earth; the Sun's diameter is about 100 times the Earth's.



mined that planets are commonplace around other stars. In at least one such case we can discern the signature of an atmosphere being ablated by a stellar wind. In another case, X-rays are emitted from a young star that is not fully ignited, showing that electromagnetic and plasma processes become active very early in the life of a planetary system.

The United States is now embarking on an ambitious new journey of exploration to the Moon, Mars, and beyond. NASA has been challenged to establish a sustained presence on the Moon by the end of the next decade with the purpose of enabling Martian exploration thereafter. The will to achieve this Vision for Space Exploration presents the agency with great opportunity and sobering demands.

Success in this venture requires advanced understanding of the complex physical systems that link the variable star at the center of our solar system with the Earth and other planets. The harsh and dynamic conditions in space must be characterized and understood in some detail if robots and humans are to safely and productively travel and explore the Moon and Mars.

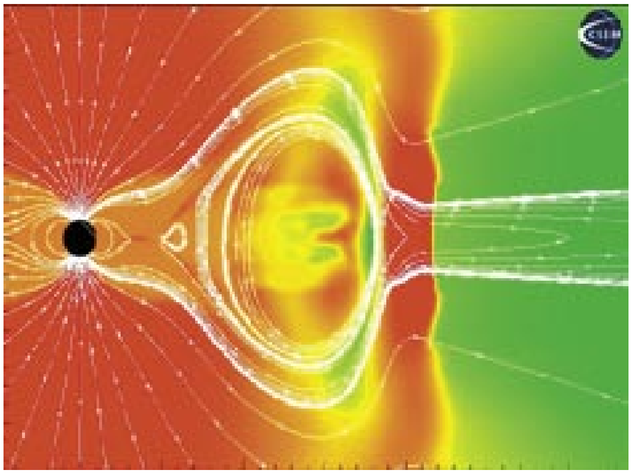
The biological effects of the energetic particle radiation environment outside of low-Earth orbit remain largely unknown. Astronauts aboard the International Space Station (ISS) accumulate significant radiation exposure and energetic particle events impact space station operations. Safe and productive travel outside Earth's protective magnetic cocoon, whether to the Moon or Mars, will require new predictive capability for solar particle events. Even well designed hardware is damaged or degraded by extreme conditions in space. And astronauts spending more than a few days in space will need a way to take shelter from episodic exposure to lethal doses of solar energetic particles.

Space weather and solar variability affect critical technologies used on Earth as well, for example satellite communications, navigation, remote sensing, and power distribution. Increasing reliance on vulnerable global systems demands active management in response to variations in the space environment. In many ways, our space weather approach resembles

Our approach to experimentally probing this vast system of systems is two-fold:

a) identify the weakest links in our understanding of the coupled system, deploy targeted missions to resolve those science questions;

b) utilize all NASA deployed assets as a dustributed sensor net to sparsely sample large scale phenomena and to drive models of system behavior



earlier steps taken by scientists to understand and predict weather in the Earth's atmosphere. We too must observe and understand the detailed phenomena, generate theoretical models that can be validated and verified against observed reality, build data-assimilative predictive systems, and then develop operational decision support systems closely tailored to the needs of end-users and rigorously tested and improved over time. In this way and by these means, NASA's Sun-Solar Systems connections program will bring sound science to serve society.

Space weather is in some ways analogous to the tropospheric weather that is so familiar to us, yet remains difficult to predict beyond a few days. In other ways it is fundamentally different. It is analogous in its nonlinear complexity, though across an even larger range of scales. Systems this large simply cannot be reduced to a linear combination of interacting parts, no matter how detailed the study of those parts. Space weather is fundamentally different in that electricity and magnetism are at least as important as the more familiar forces of gravity and pressure. Measuring, characterizing, and understanding these processes cannot be accomplished with images and common intuition. Localized measurements cannot merely be interpreted to generate a global picture. Conversely, the global picture does not provide insight into the small-scale physical processes of the system. For example, the magnetic reconnection that regulates much of the interaction between the solar wind and the Earth's magnetosphere cannot be observed remotely and it takes place in a rapidly moving location several Earth radii above the planet on a spatial scale of a few kilometers and temporal scale of several milliseconds.

Answering a specific science and/or exploration question often requires a narrowly focused mission to a particular location with a unique instrument. For example, measuring flows in the solar interior requires a long, continuous series of simultaneous velocity measurements at millions of locations on the solar disk. However, Sun – Solar System Connection science increasingly depends on combining multi-point in situ measurements with remote imaging. Again, by analogy with meteorology, combining a network of distributed local observations with global measurements (a meteorological Great Observatory) enables the development and testing of predictive models that improve with time and experience.

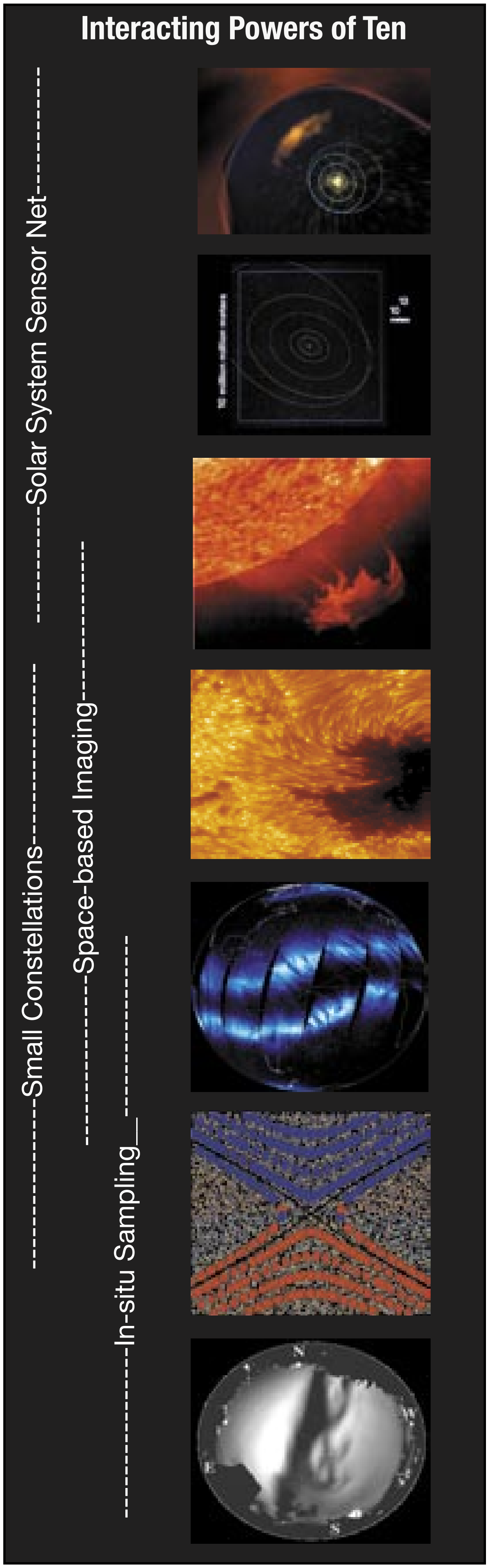
Currently the SSSC Great Observatory includes satellites that (for example) hover near L1 – a million miles upstream in the solar wind, circle over the Sun's poles, orbit the Earth in various configurations, and have just reached the first boundary between the interstellar medium and the Sun's domain, the termination shock. As each set of scientific questions is answered, the SSSC Great Observatory evolves with the addition of new spacecraft. Solar-B will help understand the creation and destruction of solar surface magnetic fields, variations in solar luminosity, and the dynamics of the solar atmosphere. Soon the two STEREO spacecraft will drift away from Earth to provide the first stereoscopic views of the Sun and inner heliosphere. The Solar Dynamics Observatory (SDO) will image the Sun's interior, surface, and atmosphere from geosynchronous orbit. Observing the terrestrial response, the Radiation Belt Storm Probes will investigate the processes that accelerate particles to hazardous radiation levels, and the four Magnetospheric Multi-Scale (MMS) spacecraft will fly in tight formation to explore the multiple scales of reconnection, turbulence, and particle acceleration in the magnetosphere of the Earth. Solar Probe, if funded, will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity.

In this strategic roadmap for the Sun – Solar System Connection we explore the strategic planning consequences of a stated U.S. national objective for NASA: "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 human explorers, and demonstrate technologies that can improve future operational systems." The resulting science and exploration objectives are explained in the next section. Implementation plans follow that span 30 years. The document concludes with an explanation of the links to other NASA activities.

New knowledge of this system enables safe and productive exploration. Exploration enables new scientific understanding. The knowledge has utility for society. Our high priority science and exploration objectives address each of these needs. The program is vital, compelling and urgent.

Challenges to achieving a quatitative, predictive understanding of this complex “system of systems”

- Microphysical processes regulate global & interplanetary structures
- Multi-constituent plasmas and complex photochemistry
- Non-linear dynamic response
- Integration and synthesis of multipoint observations
- Data assimilative models & theory
- Interdisciplinary communities and tools


Interacting Powers of Ten

The images on the right show important physical features with size progressively decreasing from top to bottom: the interaction of the heliosphere with the interplanetary medium (several hundred AU), the orbits of the planets, a mass ejection over the solar limb, part of a sunspot, Earth’s disturbed ionosphere, a model of reconnection, and an all-sky image of the aurora borealis (less than a kilometer in width).

The SSSC Great Observatory in Action: The 2003 Halloween Solar Storms

The violent solar eruptions of late October and early November 2003 are the best observed outbreak of intense solar activity to date. These events, referred to as the 2003 Halloween Storms, are extreme events in terms of both their source properties at the Sun and their heliospheric consequences. The plasma, particle and electromagnetic consequences of these events were felt throughout the heliosphere thanks to the distributed SSSC Great Observatory.

Disturbances associated with two of the solar eruptions arrived at Earth in less than 24 hours, providing benchmark data for space weather purposes. Historically, there have been only 13 such events, including the historic Carrington event of September 1, 1859. Several characteristics of the Halloween Storms displayed extreme behavior, including active region size and potential energy, flare occurrence rate and peak intensity, CME speed and energy, shock occurrence rate, solar energetic particle (SEP) occurrence rate and peak intensity, and the geomagnetic storm intensity.

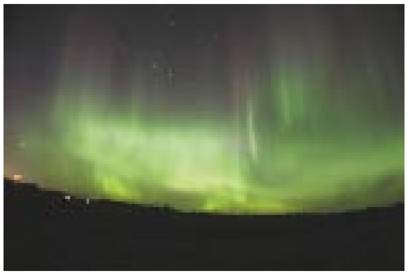
About 59% of the reporting spacecraft and about 18% of the onboard instrument groups were affected by these storms. Electronic upsets, housekeeping and science data noise, proton degradation to solar arrays, changes to orbit dynamics, high levels of accumulated radiation, and proton heating were observed. Most earth-orbiting spacecraft were put into safe mode to protect from the particle radiation. Significant impacts also affected society: about 50,000 people in southern Sweden (Malmoe) experienced a blackout, where the oil in a transformer heated up by 10 degrees; surge currents were observed in Swedish pipelines; numerous occurrences of degradation and outage of GPS systems were reported; and several teams on Mount Everest experienced interference in high-frequency radio communications.

The solar energetic particle event on October 28, 2003 caused a significant ozone depletion between 50 and 80 km from the ground. A ten-fold enhancement in the ionospheric total electron content over the US mainland occurred during October 30-31. Extraordinary density enhancements in both the magnetosphere and ionosphere coinciding with intervals of southward IMF and high-speed solar wind were observed.

When the storms arrived at Mars the MARIE instrument on board the Mars Odyssey succumbed to the onslaught of radiation. The storms continued past the orbits of Jupiter and Saturn as detected by Ulysses and Cassini, respectively. Wind, Ulysses and Cassini radio instruments at widely different vantage points also observed a radio burst resulting from colliding CMEs on November 4, 2003. Finally, after about 180 days, the disturbances reached Voyager 2, piled up together as a single merged interaction region (MIR), which led a large depression in cosmic ray intensity, lasting more than 70 days. Although it is not that unusual for such solar eruptions to occur during the declining phase of the solar cycle, these events bench mark the level of understanding we have on the behavior of the sun over different time scales. The fleet of spacecraft in the Great Observatory helped us not to be taken by surprise by the Halloween Storms.

Dramatic Aurorae Were Observes All Over the Globe

Scotland



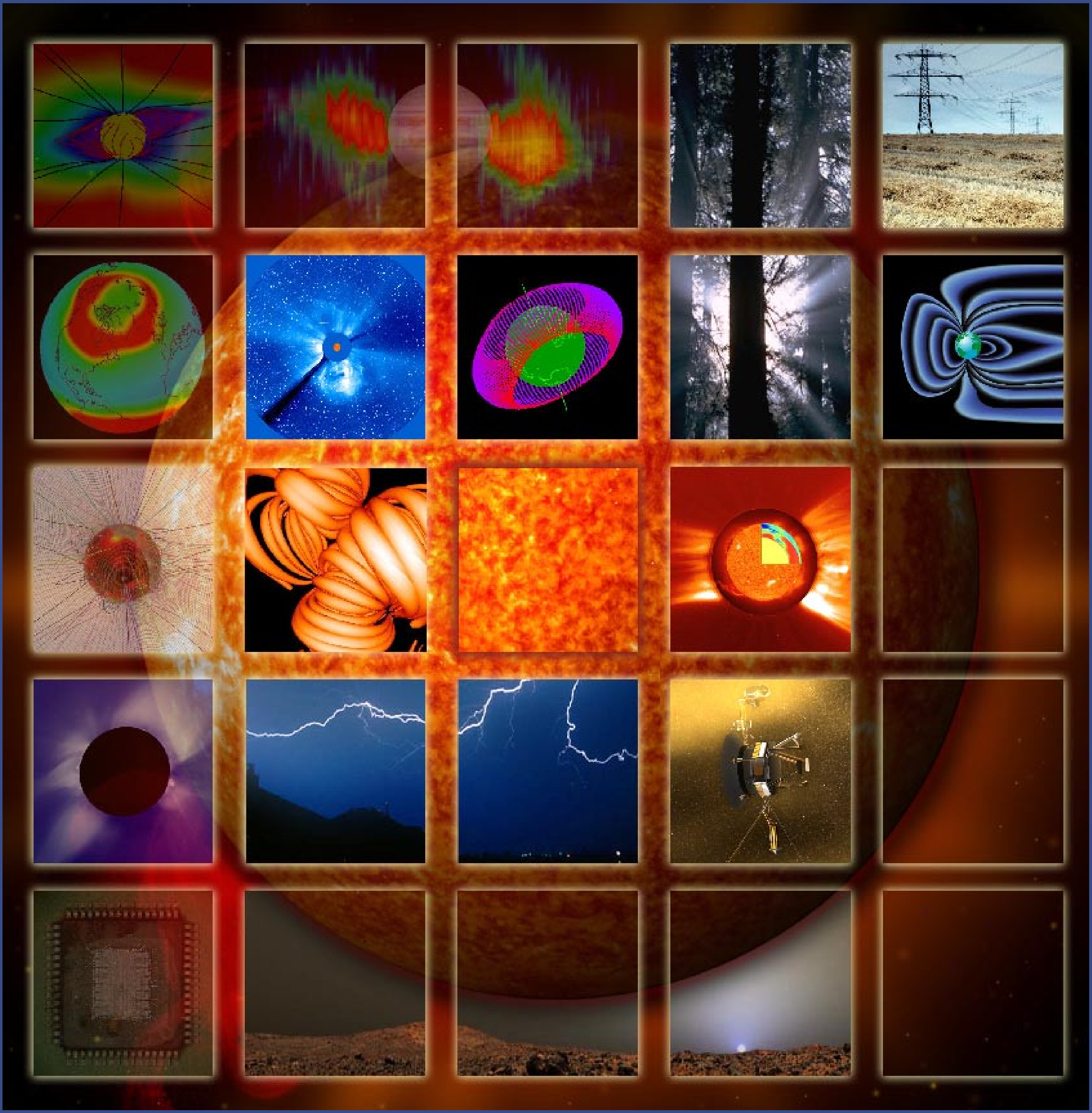
Sweden

California

Quebec

Alaska

Maryland

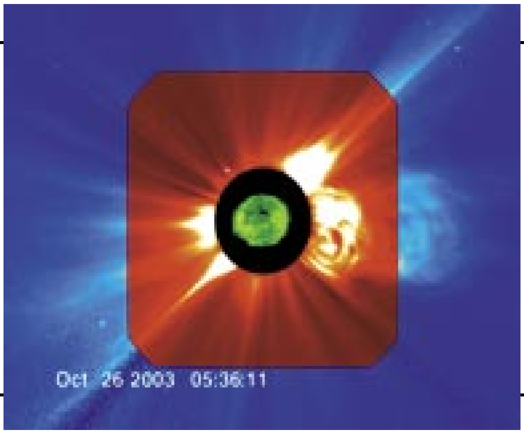


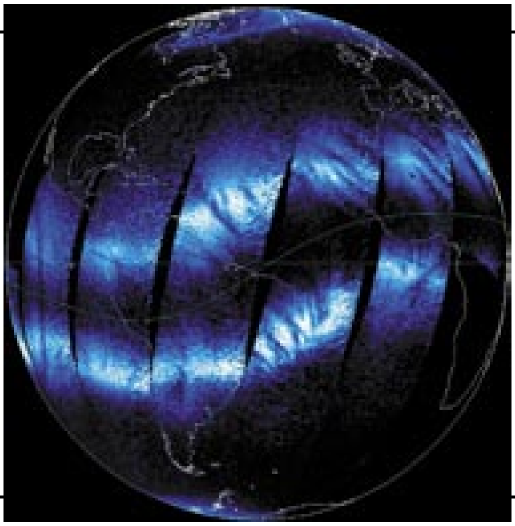
Part II: Achieving the Vision

Science Objectives

Open the Frontier to Space Environment Prediction

Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium



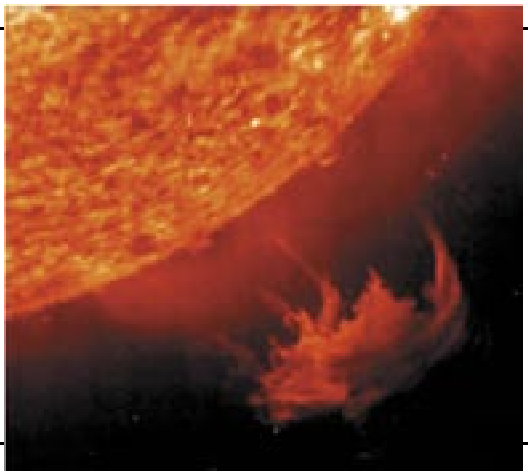


Understand the Nature of Our Home in Space

Understand how human society, technological systems, and the habitability of planets are affected by solar variability and planetary magnetic fields

Safeguard the Journey of Exploration

Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space



Chapter 1

Sun-Solar System Connection: The Science

The present generation of space researchers has inherited a great legacy from the exploratory missions and discoveries of earlier decades. Our success in conducting a robust program of exploration at new scientific frontiers will leave to future generations a similar gift of achievement and inspiration. Because the purpose of exploration is to understand the unknown, the precise benefits of their future space research and their path to success defy prediction. We do know that progress will require constant adaptation to exciting diversions and new directions.

Building on this rich history of exploration, we now seek to transform human understanding of this fascinating system of systems that are so closely connected. The same explosive event on the Sun that produces power outages on Earth can also degrade solar panels on interplanetary spacecraft, produce mission-ending damage to instrumentation at Mars, produce radio waves and aurora at the outer planets, and even change the fundamental interaction of our heliosphere with interstellar media. We will not only develop a predictive capability to address hazards to space travelers and important technological assets closer to home, but we will also learn how the interplay of fundamental space processes affects the habitability of other distant environments. The SSSC strategic plan for the future consists of three encompassing scientific and exploration objectives:

Opening the Frontier to Space Weather Prediction

The Sun, our solar system, and the universe consist primarily of plasma, resulting in a rich set of interacting physical processes and regimes, including intricate exchanges with the neutral environment. We will encounter hazardous conditions on our return to the Moon and our journey to Mars. We must develop a complete understanding of the many processes that occur with such a wide range of parameters and boundary conditions within these systems.

As the foundation for our long-term research program, we plan to develop a complete understanding of the fundamental physical processes of our space environment–from the Sun to the Earth, to other planets, and beyond to the interstellar medium. We will systematically examine similar processes in widely different regimes with a range of diagnostics techniques

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*

F1. Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms

F2. Understand the plasma processes that accelerate and transport particles

F3. Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system

F4. Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.

to both test our developing knowledge and to enhance overall understanding. The universal themes of energy conversion and transfer, cross-scale coupling, turbulence and nonlinear physics have been chosen as near-term priority targets. The five fundamental processes that have been identified as the critical immediate steps are: magnetic reconnection, particle acceleration and transport, the generation and variability of magnetic fields, cross-scale coupling across boundaries and large structures, and nonlinear energy and momentum transport and coupling in atmospheres. Both in situ and remote sensing observations will be required, providing a three dimensional large-scale perspective as well as a detailed small-scale microphysics point of view. With our increasingly sophisticated understanding of such basic processes, we will open the frontier of predictive modeling across the solar system.

Understand the Nature of Our Home in Space

Mankind does not live in isolation; we are intimately coupled with the space environment through our technological needs, the habitability of the planets and the solar system bodies we plan to explore, and ultimately the fate of our Earth itself. We regularly experience how variability in the near-Earth space environment affects the activities that underpin our society.

We plan to better understand our place in the Solar System by investigating the interaction of the space environment with the Earth and the effect of this interaction on humankind. Building on our new knowledge of fundamental processes, we plan to characterize and develop a predictive knowledge of the impact of the space environment on society, technology, and our planet. This will be accomplished both by direct investigation of the local environment and by what can be learned about life on Earth through studying other environments. Human life and society provide the context in which these investigations are conducted.

As we extend our robotic and human presence throughout the solar system, we will be increasingly interested in the planetary environments that await us and how the lessons learned can be applied to our home on Earth.

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*

H1. Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment.

H2. Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.

H3. Understand the role of the Sun as an energy source to Earth's atmosphere, and in particular the role of solar variability in driving change.

H4. Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.

A casual scan of the solar system is sufficient to discover that habitability, particularly for humankind, is a rare congruence of many events. At least some of these factors, especially the role of magnetic fields in shielding planetary atmospheres, are a subject of immense interest. We believe we know some of the features that make planets habitable, but there is much more to be understood.

Safeguard the Journey of Exploration

The great variety of space environment conditions will have a significant impact on our future space explorers, both robotic and human. We plan to pursue, with all due vigilance, the research necessary to assure the safety and the maximum productivity of our explorers. We plan to develop the capability to predict space environment conditions from low Earth orbit to the Moon and Mars. Addressing space weather issues is necessary for optimizing the design of habitats, spacecraft, and instrumentation, and for planning mission and operations scenarios, ultimately contributing to mission success.

Building on our knowledge of fundamental processes, we plan to understand those aspects of the space environment essential for enabling and securing space travel. Good engineering data is already flowing into exploration-oriented planning and implementation because the Sun-solar system community knows how to explore useful scientific directions. Our space plasma research community is poised to provide the next generation of measurements, simulations and models that will be useful to the implementation of manned and robotic missions to the Moon, Mars, and other planetary bodies. Such parameterizations of the space environment will be essential inputs for solutions to the challenging engineering problems that must be solved for successful and economical exploration activities.

Safeguard the Journey of Exploration

Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space

J1. Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

J2. Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

J3. Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

J4. Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

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*

F1. Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms

F2. Understand the plasma processes that accelerate and transport particles

F3. Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system

F4. Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.

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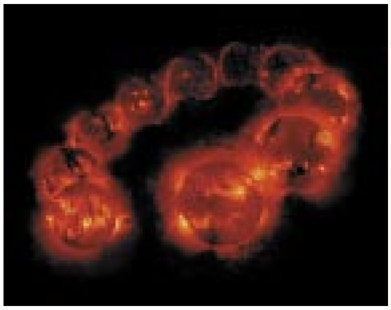
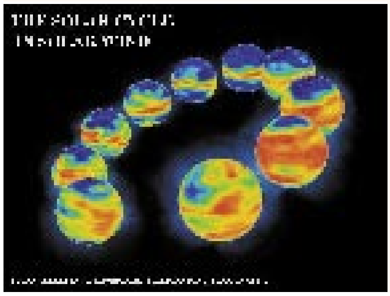
The Calm Between the Storms?

Powerful events such as the 2003 Halloween space storms obviously affect astronauts, satellites, communication and electrical power systems. But it may seem that the space environment is usually benign and unimportant because such storms are rare. In fact, the constant variation of the space environment makes the time between storms anything but calm.

Magnetic active regions on the Sun emerge and decay over days to weeks. The numbers of active regions varies regularly with the 11-year solar cycle and erratically over longer time scales - up to centuries. The patchy distribution of regions over the Sun produces variation at the 27-day solar rotation period. Many phenomena – emission of light, short wavelength radiation, solar wind, and blocking of cosmic rays – vary significantly with the timescales of the solar magnetism, even without storms.



Soft X-ray images from Yohkoh (above) show the change over an 11yr solar cycle, but might look similar over a 27d solar rotation, or a millennium. Solar wind velocity (below) follows a similar pattern.



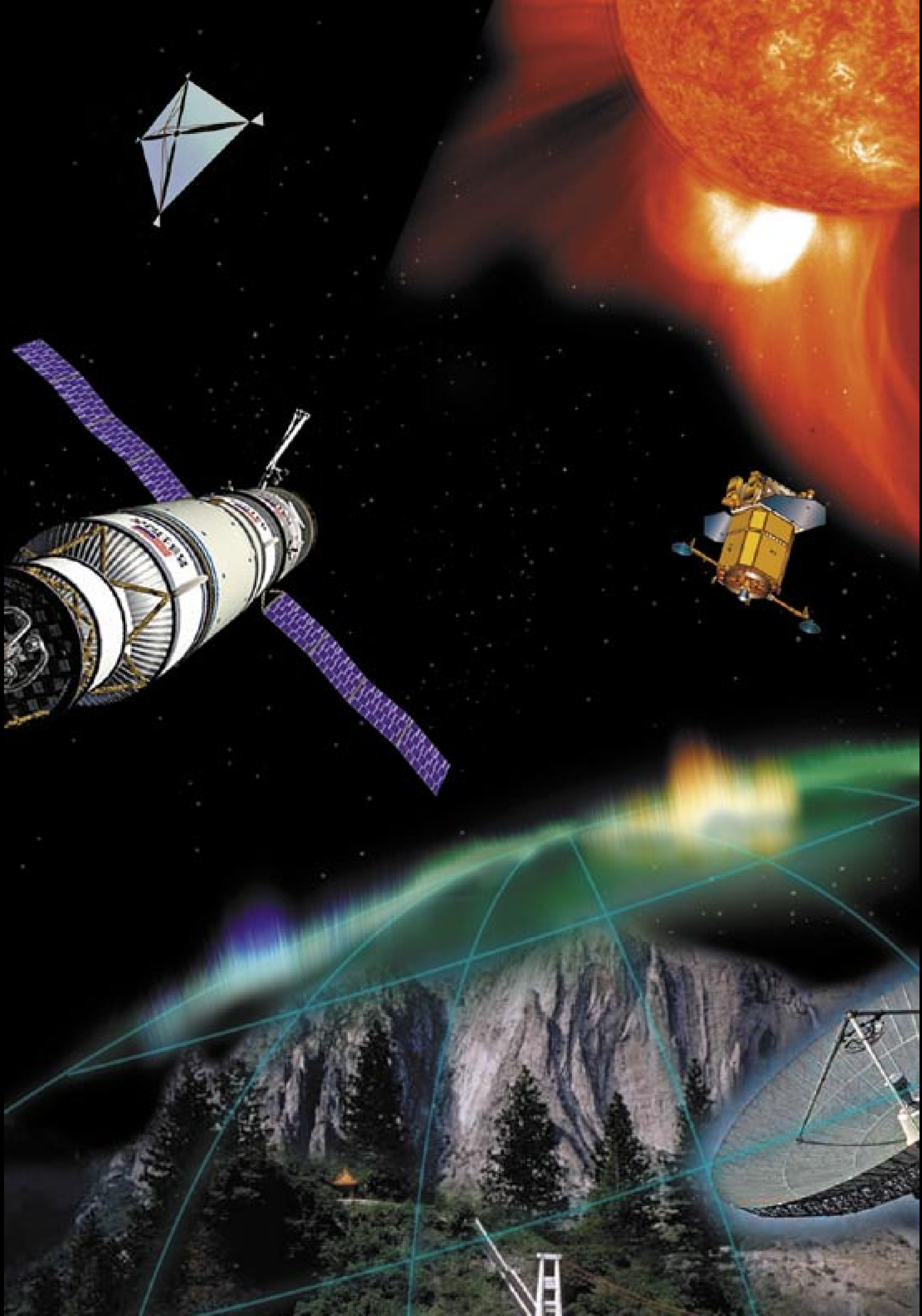
Light from the solar surface directly heats the surface and lower atmosphere. Dark sunspots and bright faculae in magnetic regions alter the emission of light from the surface enough to affect the climate over long intervals.

The corona above magnetic regions is heated to millions of degrees and emits strong and variable X-rays, EUV, and UV radiation. The radiation heats and ionizes the atmospheres of planets, producing our ozone layer, the ionosphere, and the thermosphere. It alters atmospheric chemistry and temperature, which in turn modifies the mixing of molecules over height and latitude. As these layers heat and cool, they become more and less dense, changing the drag that slows satellites until they reenter.

The solar wind, striking Earth's magnetic field, drives the acceleration of energetic particles that fill the radiation belts. By contrast, Mars has no global magnetic field, and the solar wind directly impacts and strips away Mars upper atmosphere. The wind's magnetic field, constantly reshaped by change on the Sun, can power intense geomagnetic storms in absence of solar events, with the whole array of energetic particle acceleration, aurora, and disturbances of satellites systems.

The hot corona powers the solar wind, which carries magnetic fields with it. The solar wind magnetism, filling the heliosphere, blocks many of the cosmic ray particles that fill the rest of the galaxy.

Understanding the varying space environment on all timescales is the motive for our SSSC Great Observatory and for the new missions planned in this Roadmap. From the climate of Sun and Earth, to travel to other planets, and out to the space between the stars, the Sun-Solar System Connection seeks to predict these variations that we know – and those we have yet to discover.



Objective F

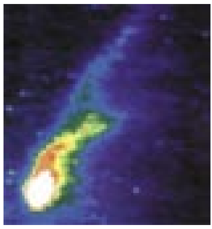
Open the Frontier to Space Weather Prediction

Understand the fundamental physical processes of the space environment - from the Sun to Earth, to other planets, and beyond to the instellar medium.

The Sun, our solar system and the universe consist primarily of plasma. Plasmas are far more difficult to understand than solids, liquids, and gases because the motions of electrons and ions produce both electric and magnetic fields. The electric fields accelerate some of these particles, sometimes to very high energies, and the magnetic fields guide their motions.

This results in a rich set of interacting physical processes, including intricate 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 physical phenomena.

As the foundation for our long-term research program, we will develop a complete scientific understanding of the fundamental physical processes that control our space environment – from the Sun to the Earth, to other planets, and beyond to the interstellar medium. We must be able to predict the behavior of the complex systems that influence the inimical conditions we will encounter on our return to the Moon and journeys to Mars.



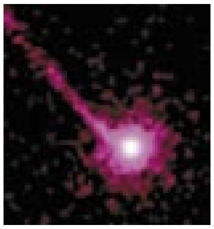
The processes of interest occur in many locations, though with vastly different magnitudes of energy, size, and time. The same processes rule the seething atmosphere and interior of our Sun, the supersonic wind of particles that our star flings outward into space, Earth's cocoon-like magnetosphere, the tenuous upper atmosphere of Mars, and even the fantastically energetic spinning pulsars that spray out beams of x-rays like some kind of hellish fire hose. By quantitatively examining similar phenomena occurring in different regimes through a variety of measurement techniques, we can ultimately identify the important controlling mechanisms and more rigorously test our developing knowledge. Both remote sensing and in situ observations must be utilized to provide the three-dimensional large-scale perspective and the detailed small-scale microphysics view necessary to see the complete picture.

> Prediction provides the ultimate test for scientific understanding.

The strategy for achieving this first science objective focuses on the knowledge gaps most vital to safe and productive exploration via the development of accurate forecasting of the space environment. Four fundamental processes have been identified as crucial immediate steps: magnetic reconnection, particle acceleration, the physics of plasma and neutral interactions, and the generation and variability of magnetic fields with their coupling to structures throughout the heliosphere. Each of these research focus areas (RFA's) involves the universal themes of energy conversion and transport, cross-scale coupling, turbulence, and nonlinear physics – concepts that are fundamental to the understanding of space and planetary systems. In addition they all include processes that can be influenced by large-scale boundaries or by coupling between regions with very different conditions (for example, cold, dense neutral atmospheres with energetic particles).

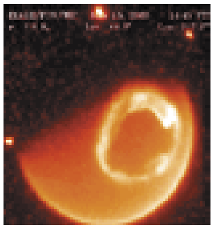
Magnetic Reconnection: Magnetic reconnection occurs in highly localized regions when interacting magnetic fields "snap" to a new, lower energy configuration, as if a pair of twisted rubber bands broke and relinked to form two new relaxed bands. Magnetic reconnections release vast amounts of stored energy and are responsible for solar flares, CME's and geospace storms. An explosive release of energy can be potentially devastating to space assets and voyaging humans, and seriously affect worldwide communications. Although we have developed an initial picture of where reconnection may occur and the observable results, the detailed physical mechanisms, in particular, the microphysical processes and the role of large-scale topology are not understood. This focus area (RFA F.1) will deliver a fundamental understanding of this universal process in the very different regimes where it occurs.

Plasmas are conductive assemblies of charged particles and neutrals that exhibit unfamiliar collective effects. Plasma systems carry electrical currents, generate magnetic fields, and can interact explosively. The solar system is the only directly accessible laboratory for exploring the behavior of astrophysical plasmas. We must prepare our space explorers to live and work in this harsh alien environment.



Particle Acceleration: By far the most distinguishing characteristic of plasmas, in contrast to the neutral states of matter of planets, is that plasmas produce prodigious amounts of radiation. Because this radiation has the most direct impact on human and robotic space explorers, detailed understanding of the particle acceleration processes that produce radiation, the regions in which these processes operate, and the boundary conditions that control them is crucial to the exploration of space. RFA F.2 will investigate the mechanisms that accelerate particles within the solar system, including small-scale waves, shocks, and quasi-static electric fields. Radiation can be produced almost instantaneously through explosive processes, but also built up stepwise by processes acting under more benign conditions. Providing essential predictions of the radiation environment along the end-to-end path of space explorers will involve accounting for particle acceleration in all its forms and locations.

Plasma-Neutral Interactions: The Sun-Solar System Connection requires understanding of the fundamental physics of plasma and neutral particle coupling. This coupling encompasses a variety of mechanisms and regions from turbulence and charge exchange in the solar wind to gravity waves and chemical/collisional interactions in planetary atmospheres. Space plasmas are often in a non-equilibrium state and they can be a highly nonlinear medium. Many of the techniques developed for understanding nonlinear systems resulted from basic plasma research – chaos theory is one example; another is the understanding of turbulence, which is so important to safer air travel. The goal of RFA F.3 is a comprehensive understanding of how nonlinear processes influence plasma-neutral interactions from atmospheric to heliospheric scales. This work has specific applicability to the operation of satellites in the Martian atmosphere, the mitigation of the effects of global change, as well understanding how habitable planets retain their atmospheres.



Magnetic Dynamos: Understanding the variations of the magnetic fields of the Sun and planets on both long and short time scales is the key element of the Sun-Solar System connection addressed by RFA F.4. The creation of these fields – the magnetic dynamo problem

Priority Research Focus Areas & Investigations

F1. Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms
  1. What are the fundamental physical processes of reconnection on the small scales where particles decouple from the magnetic field?
  2. What is the magnetic field topology for reconnection and at what size scales does magnetic reconnection occur on the Sun?

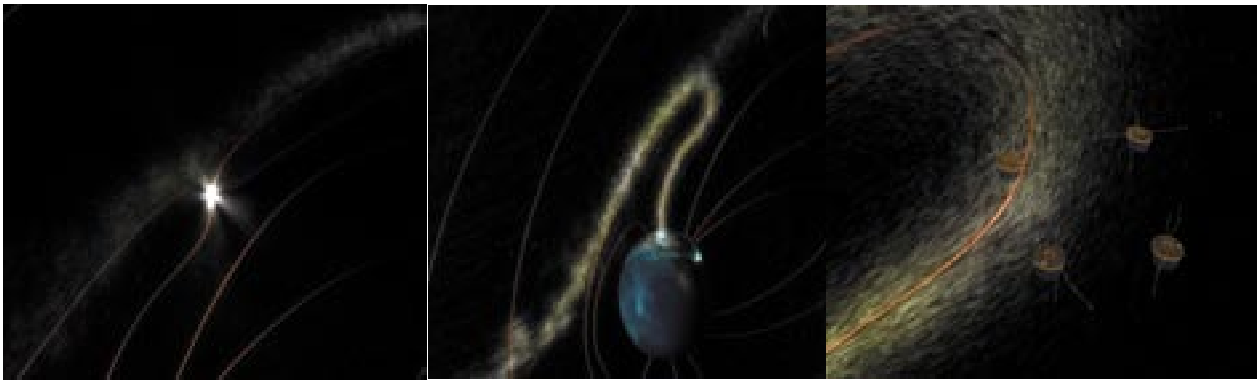
F2. Understand the plasma processes that accelerate and transport particles
  1. How are charged particles accelerated to high energies?
  2. How are energized particles transported?
  3. How is the solar wind accelerated and how does it evolve?
  4. How are planetary thermal plasmas accelerated and transported?

F3. Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system
  1. What governs the coupling of neutral and ionized species at various spatial and temporal scales?
  2. How do energetic particles chemically modify planetary environments?
  3. How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?
  4. How do the heliosphere and the interstellar medium interact?
  5. How do the neutral environment in planetary and cometary systems affect the global morphology through charge exchange and mass loading processes?

F4. Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.
  1. How do subsurface flows drive the solar dynamo and produce the solar cycle?
  2. How do solar and stellar dynamos evolve on both short and long-term time scales?
  3. How are open flux regions produced on the Sun, and how do variations in open flux topology and magnitude affect heliospheric structure?
  4. How do planetary dynamos function and why do they vary so widely across the solar system?
  5. Understand the ionosphere-thermosphere dynamo interaction, and its variability

– remains one of the outstanding problems in physics. How dynamos operate in such widely disparate systems – from stellar interiors to planetary cores – is poorly understood. Dynamos determine the characteristics of the solar activity cycle. The Sun's magnetic field controls the structure of the heliosphere and, thus, regulates the entry of galactic cosmic rays into the solar system. Therefore, it is imperative that we understand the origin and variability of solar magnetism. The Earth's interior dynamo sustains the geomagnetic field and provides the shield that enables life to flourish in the harsh radiation environment of space. Understanding how dynamos are created and sustained, how they affect the nearby space environment, how to predict their variations and ultimately their demise is at the heart of understanding our own destiny.

With our increasingly sophisticated understanding of these fundamental physics process, we will open the frontier to the development of truly predictive space weather models.



One type of reconnection takes place when the Earth's usually impenetrable magnetic field fractures and has to find a new stable configuration. Until the field mends itself, solar protons leak through the gap and jet into Earth's atmosphere, creating aurora and ionospheric currents. For a predictive capability, very high time resolution, 3D measurements of particles and fields from multiple satellites with variable separations are needed reveal the micro- to meso-scale processes needed to directly probe the electron diffusion region. [Image Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio]

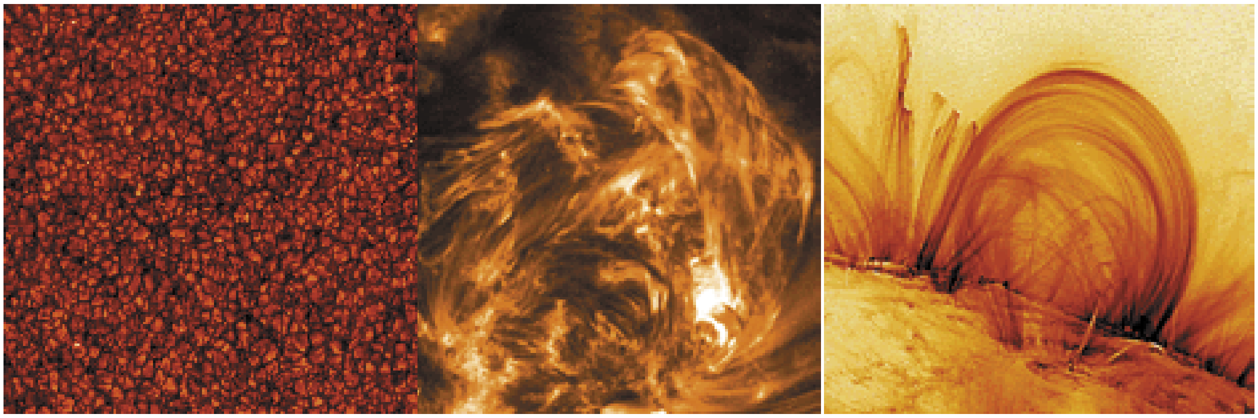
RFA F.1. Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms.

Reconnection is the rapid conversion of magnetic energy into particle energy. It is an important, cross-scale coupling process in a variety of space plasmas ranging from the magnetotail of the Earth to solar flares. Reconnection can accelerate particles to very high energies and, because it changes the magnetic field topology, it can dramatically alter the regions of space that are accessible to those particles. In the corona reconnection can sever large clouds of dense plasma from the magnetic fields that anchored them. Solar flares, coronal mass ejections, and geospace storms are all initiated and energized by reconnection – often with potentially devastating effects to space systems.

The explosive conversion of magnetic energy originates in a volume of space known as the diffusion region. This region is very small when compared to the large scales in space. For example, reconnection at the Earth's magnetopause surface (the boundary separating the solar wind and terrestrial magnetic fields) occurs in a region with an area of the order of hundreds of square kilometers compared to a total surface area of approximately 60 billion square kilometers. Properly instrumented spacecraft have not yet sampled the diffusion regions in the near-Earth environment directly and imaging of the Sun does not currently have the ability to resolve the diffusion region associated with solar flares. Thus, the physical processes that initiate and control reconnection remain to be measured.

Most of our basic theoretical understanding of reconnection comes from an MHD perspective. Although this approach has provided important insight, it is inherently limited in that it cannot examine the very small scales on which ions and electrons decouple from the magnetic field or predict the particle energization process. Important questions that remain unanswered include: what initiates the reconnection process? what are the kinetic processes that occur and what is their role? what is the range of scale sizes of the region over which reconnection occurs in different regimes? is reconnection quasi-steady or bursty? what mechanisms or boundary conditions control the spatial and temporal scales? and what is the 3D structure of the reconnection region and how does this structure affect particle acceleration?

Priority investivations are:	***Relevant Missions:***
Investigation F1.1. What are the fundamental physical processes of reconnection on the small-scales where particles decouple from the magnetic field?	MMS, MTRAP
Investigation F1.2. What is the magnetic field topology for reconnection at the Earth and at what size scales does magnetic reconnection occur on the Sun?	MagCon, Solar-B; CLUSTER, DBC, DOPPLER, IMAGE, MMS, MTRAP, POLAR, RAM, SDO, SEPM, SHIELDS, SIRA, STEREO, THEMIS, TIMED, TRACE



Granulation on the solar surface reveals Texas-sized convective cells produced by hot columns of rising gas. (left) The cells originate just below the visible photosphere and only last for about five minutes. The emergence of active regions disrupts this steady state and stores energy in the overlying atmosphere (center) Eventually this leads to dramatic energy releases in the form of flares and coronal mass ejections (right). Various acceleration mechanisms have been proposed to explain the highly efficient energy conversion in these eruptions, including strong electric fields induced by reconnection in current sheets.

RFA F.2. Understand the plasma processes that accelerate and transport particles.

High-energy particles accelerated at the Sun and within interplanetary space, as well as cosmic rays from outside the solar system, pose a serious hazard to the human and robotic exploration of our solar system. Energetic particles produced or trapped within planetary magnetospheres can have deleterious effects on important technological assets in those locations. Predicting these effects requires a fundamental understanding of where and how particles are accelerated and how they are transported.

More than one mechanism can operate to produce a given energetic particle population at a given location and the nature of the seed population from which the accelerated particles are drawn is a critical part of the puzzle. Important processes for near-term investigation include quasi-static electric fields parallel to the background magnetic field, wave parallel electric fields, stochastic (Fermi) acceleration, and the drift of particles along a component of the electric field. such as occurs in shocks and the magnetotail. The Earth's aurora provides a unique opportunity to understand acceleration by parallel electric fields and waves. Particle acceleration at CME shock fronts is a leading candidate for the production of gradual solar energetic particle (SEP) events.

Energetic particles accelerated both at localized sites (solar flares, magnetotail reconnection sites, auroral double layers), and globally (coronal and interplanetary shocks, co-rotating interaction regions and global merged interaction regions in the solar wind, and the termination shock) need to be understood. An understanding of the acceleration of thermal plasmas is also vital to meeting NASA objectives. For example, both the interaction of the Sun with planets and the transport of solar energetic particles are mediated by the solar wind. Successful progress on the understanding of solar wind acceleration will significantly improve the predictive capability for determining the severity of solar wind disturbances. The origin of the solar wind is not well understood and represents a large gap in our knowledge of fundamental processes.

Priority investivations are:	***Relevant Missions:***
Investigation F2.1. How are charged particles accelerated to high energies?	SEPM, IHS, AAMP, SIRA; ACE, GEC, Heliostorm, L1 Observations, RHESSI, SPI, STEREO, SWB, Telemachus, TRACE, Wind
Investigation F2.2. How are energized particles transported?	IH Sentinels, ITSP, RBSP, SIRA, SWB; AAMP, GEC, HIGO, IBEX, ISP, SEPM, SOHO, SPI, STEREO, Telemachus, WIND
Investigation F2.3. How is the solar wind accelerated and how does it evolve?	Solar Probe, Doppler, IH Sentinels, Solar Orbiter, SWB; Heliostorm, L1 Observations, Pluto-Kuiper, SEPM, SHIELDS, SOHO, SPI, STEREO
Investigation F2.4. How are planetary thermal plasmas accelerated and transported?	MagCon, DBC, IMC; AAMP, ADAM, CLUSTER, IMAGE, ITMC, ITMWaves, MARS, POLAR, THEMIS, TIMED

RFA F.3. Understand the role of plasma and neutral interactions in the nonlinear coupling of regions throughout the solar system

Plasma populations are embedded in a background neutral gas throughout the solar system, from the solar transition region, to planetary upper atmospheres, to the heliosphere's interface with the interstellar medium. These populations transfer energy and momentum through multi-scale, nonlinear interactions which act to redistribute the bulk flows that, in turn, feed energy back into the original coupling system.

For example, the upper atmospheres of planets are dramatically affected by energetic inputs originating at the Sun in the form of photons, particles, and fields. However, there are many pathways by which that solar energy is transformed and redistributed throughout the atmosphere until the energy is ultimately re-radiated to space. Connected with these processes is much of the inherent variability of the atmosphere over daily to millennial time scales.

The atmosphere is periodically pumped and heated, giving rise to a spectrum of small-scale gravity waves and longer-period oscillations. These waves can propagate into the mesosphere and thermosphere depositing momentum into the atmosphere. The atmospheric mean circulation is thereby modified, resulting in vertical winds, changes in the temperature structure, and the redistribution of radiation

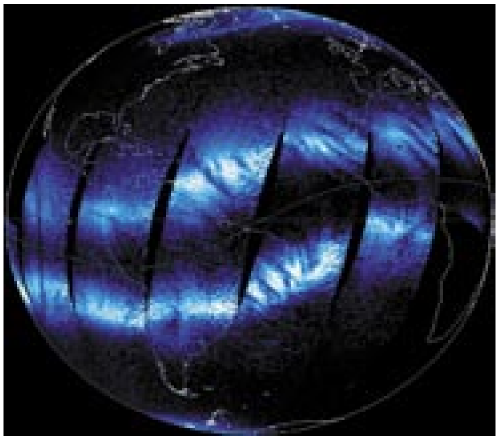


Image of electron density enhancements (equatorial arcs) in the Earth's ionosphere. The transport of plasma away from the equator results in traveling densities enhancements and depletions in bands poleward of the equator. These exist during the daytime and most of the night and create enhanced media transmission errors in navigation and communication signals.

absorbers. The mean wind and temperature structures in turn influence the propagation of the waves and the manner in which they couple the lower and upper atmosphere. Similar processes and scenarios are also key to understanding the upper atmosphere weather and climate on Mars and Venus.

Turbulence is another example of a very important multi-scale, nonlinear process that transports particles and fields effectively, but is not well understood. Numerical simulations and laboratory experiments demonstrate that, in the presence of rotation or magnetic fields, turbulent motions create small-scale and large-scale dissipative structures.

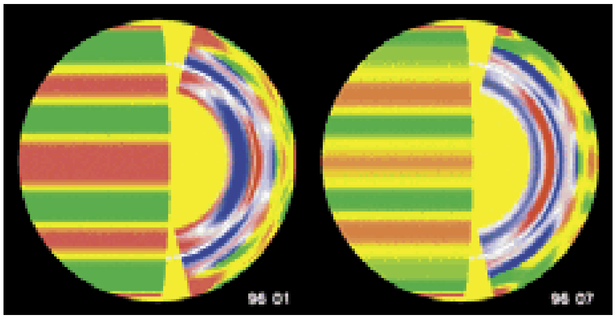
In addition, electrodynamic and mass coupling along magnetic fields are fundamental physical processes that cut across many disciplines of space science. The interface between the heliosphere and the interstellar medium is a coupling region about which we are just beginning to learn.

Finally, mass loading through ionization and charge exchange is a phenomenon of broad interest from planetary and cometary atmospheric erosion to energetic particle creation and loss.

Priority investivations are:	***Relevant Missions:***
Investigation F3.1. What governs the coupling of neutral and ionized species at various spatial and temporal scales?	ITSP, GEC, ADAM, ITMWaves, ITMC, MTRAP; VAP, MARS, Solar B, Doppler
Investigation F3.2. How do energetic particles chemically modify planetary environments?	SECEP, ADAM, ITMWaves, TIMED, MARS, Io-E
Investigation F3.3. How do the magnetosphere and the ionosphere-thermosphere (IT) systems interact with each other?	GEC, AAMP, ITSP, RBSP
Investigation F3.4. How do the heliosphere and the interstellar medium interact?	ISP, HIGO, IBEX, Voyagers 1&2, Pluto-Kuiper
Investigation F3.5. How do the neutral environment in planetary and cometary systems affect the global morphology through charge exchange and mass loading processes?	VAP, STEREO, SCOPE

RFA F.4. Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.

The Sun's variable magnetic field is the energy source for solar particle acceleration and its structure controls the entry of galactic cosmic rays into the solar system. Helioseismic data from SOHO and ground-based observatories have revolutionized dynamo theories by placing the solar-cycle dynamo action at the base of the convection zone, in the rotationally sheared layer called the tachocline. Having the correct meridional circulation has proven to be a key ingredient for determining the length of the solar cycle. For the first time models can now use the meridional flow patterns from previous cycles to estimate the length of the next cycle. However, although these dynamo models can now forecast the cycle length, neither the amplitude nor details, such as whether the cycle will be double peaked, are within our predictive capability. For example, we do not know why the last two solar cycles have had relatively small maxima for the sunspot number. We know even less about activity cycles on other stars, though comparative stellar dynamo studies should reveal much about the long-term behavior of stars and the Sun. Developing the understanding of dynamo process to enable this kind of prediction is important for long-term planning for solar activity and would have obvious applications in trying to understand past and future periods of abnormally reduced solar activity and concomitant affects on terrestrial climate and planetary habitability.

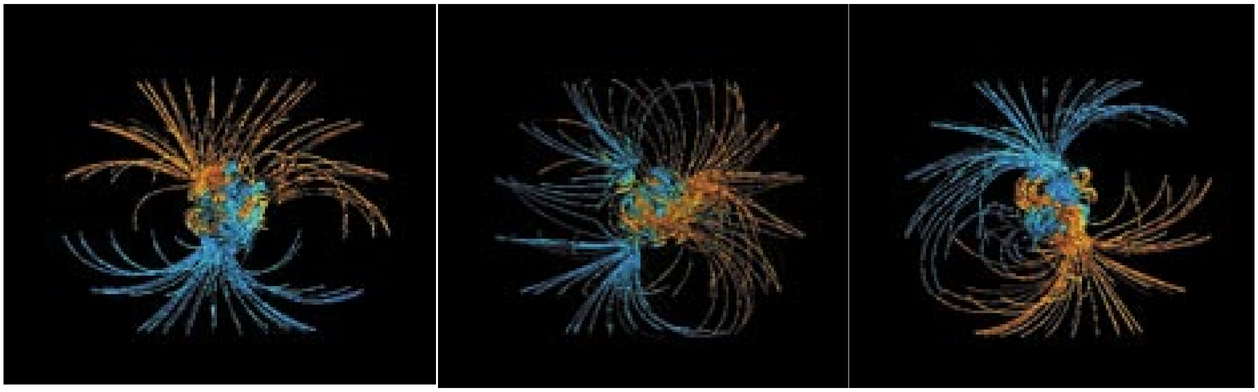


About one-third of the way down toward the center of the Sun (white line), the rotational flows change markedly over 6 months. Red regions rotate faster than the long-term average; blue and green go slower. Material below the line (initially blue) speeds up as the overlying gas (red) slows down. Near the surface the rotational bands of faster (red) and slower (green) gas move towards the equator. They indicate a "heartbeat" of the Sun at one pulse per 15-16 months in the equatorial regions. Revelation of solar dynamo behavior comes from helioseismology, which analyzes motions of the surface due to sound waves reverberating through the Sun's interior.

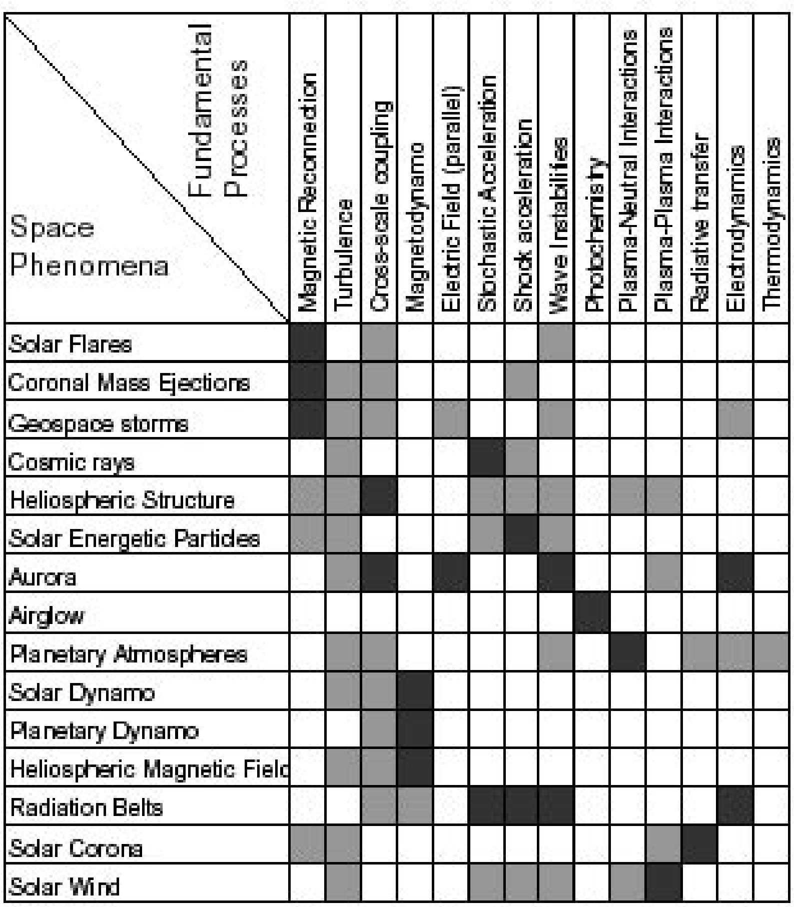
Closer to home, reversals and other large variations of Earth's magnetic field can lead to periods of reduced protection from the harsh radiation environment of space. The process responsible for the existence and behavior of these magnetic fields – the dynamo – involves the twisting and folding of weak fields so as to change and amplify them. Solving the problem of just how dynamos operate in such widely different environments, from planets to stars, will allow better predictions of the effects of magnetic field changes at both the Earth and the Sun. This understanding is essential to describing the coupled Sun-Solar System Connection and has important implications for the exploration of our solar system.

There are four investigations that address these issues.

Priority investivations are:	***Relevant Missions:***
Investigation F4.1. How do subsurface flows drive the solar dynamos and produce the solar cycle? How do solar and stellar dynamos evolve on both short and long-term time scales?	SDO, Solar Orbiter, Stellar Imager; RAM, Solar-B, SOHO, SPI, Telemachus
Investigation F4.2. How are open flux regions produced on the Sun, and how do variations in open flux topology and magnitude affect heliospheric structure?	STEREO, Solar Orbiter, Farside, SHIELDS, Solar Polar Imager, Telemachus; ACE, IH Sentinels, SOHO, SWB, TRACE, Ulysses
Investigation F4.3. How do planetary dynamos function and why do they vary so widely across the solar system?	Cassini, Juno/JPO, Messenger, ACE, ADAM, SECEP, WIND
Investigation F4.4. Understand the ionosphere-thermosphere dynamo interaction, and its variability.	GEC, ITSP, ITMC



Simulated reversal of Earth's magnetic field, with inward (blue) and outward (yellow) directed field lines. The location of the core-mantle boundary is evident where the structure becomes complex. We seek to understand the effects of such magnetic field variations on the formation and retention of planetary atmospheres. [Image credit: Gary Glatzmaier, Los Alamos National Laboratory]



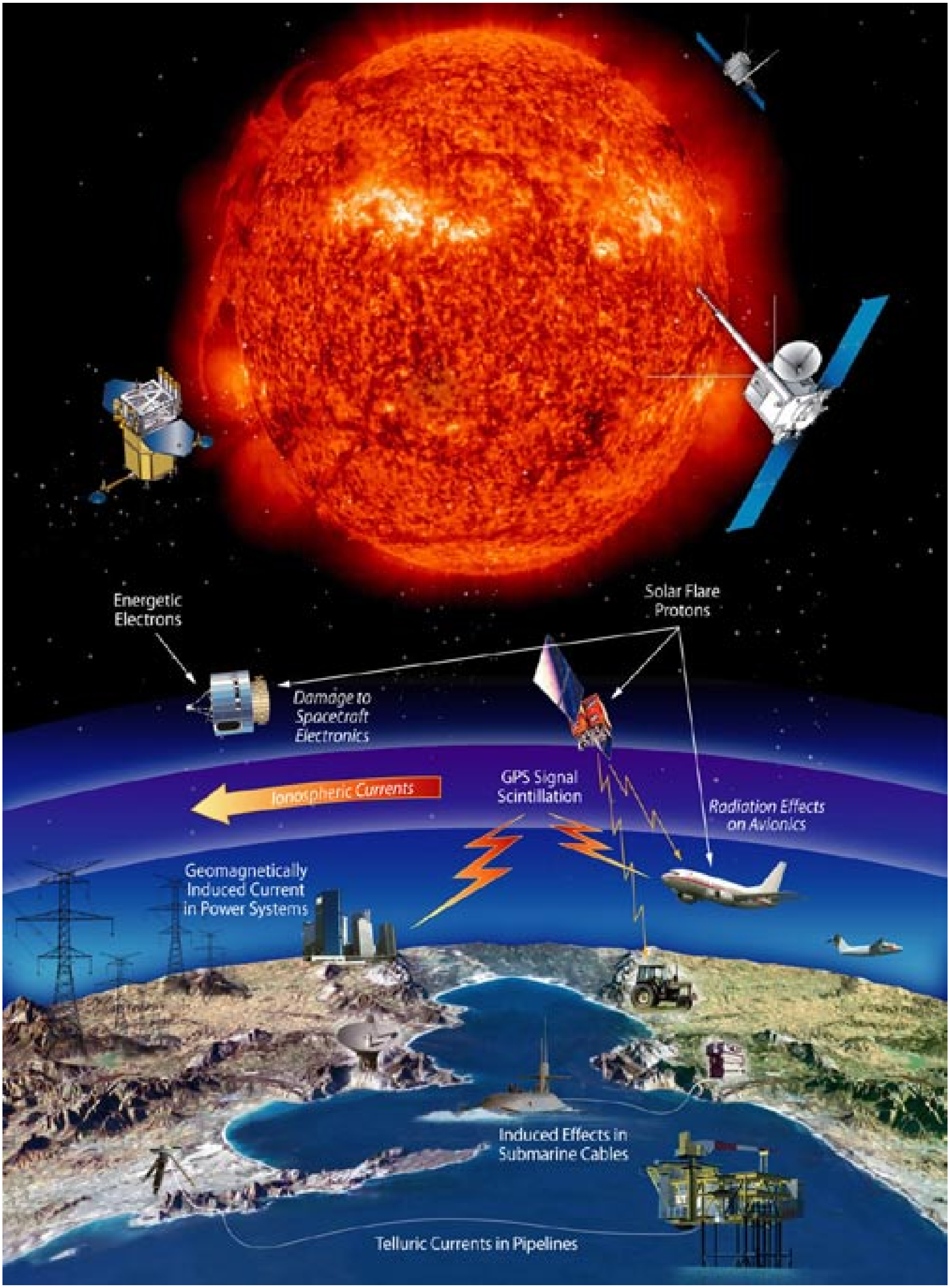
Fundamental Processes / Space Phenomena	Magnetic Reconnection	Turbulence	Cross-scale coupling	Magnetodynamo	Electric Field (parallel)	Stochastic Acceleration	Shock acceleration	Wave Instabilities	Photochemistry	Plasma-Neutral Interactions	Plasma-Plasma Interactions	Radiative transfer	Electrodynamics	Thermodynamics
Solar Flares	■		▨					▨						
Coronal Mass Ejections	■	▨	▨				▨							
Geospace storms	■	▨	▨		▨			▨					▨	
Cosmic rays		▨				■	▨							
Heliospheric Structure	▨	▨	■			▨	▨	▨		▨	▨			
Solar Energetic Particles	▨	▨				▨	■	▨						
Aurora		▨	■		■			■			▨		■	
Airglow									■					
Planetary Atmospheres		▨	▨					▨		■		▨	▨	▨
Solar Dynamo		▨	▨	■										
Planetary Dynamo			▨	■										
Heliospheric Magnetic Field		▨	▨	■										
Radiation Belts			▨	▨		■	■	■					■	
Solar Corona	▨	▨									▨	■		
Solar Wind		▨				▨	▨	▨		▨	■			

Table: Metrics of space phenomena versus fundamental science

■ Primary science

▨ Secondary science

The shaded boxes indicate the scientific dependencies of important space phenomena on the fundamental physical processes the Sun-Solar System Connection needs to understand more completely.


Energetic Electrons
Solar Flare Protons
Damage to Spacecraft Electronics
GPS Signal Scintillation
Ionospheric Currents
Radiation Effects on Avionics
Geomagnetically Induced Current in Power Systems
Induced Effects in Submarine Cables
Telluric Currents in Pipelines

Objective H

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.

We do not live in isolation. Our past, present, and future are intimately coupled to the relationship between the Earth and Sun - and with the universe beyond. Increasingly we are sensitive to changing conditions on the Sun and in the space environment because of our technology; increasingly we have a practical interest in the habitability of planets and solar system bodies we plan to explore; and increasingly we recognize how astrophysical phenomena influence life and climate on our home planet. Variability in this environment affects the daily activities that constitute the underpinning of our society, including communication, navigation, and weather monitoring and prediction. We are living with a star.

Solar Sail Thumbnail here.

With this objective SSSC researchers strive to understand our place in the Solar System. We investigate the interaction of the space environment with Earth and its impact on us and on our home, either directly or by what can be learned about life on Earth by studying other environments in our solar system and beyond. This effort builds on the understanding of the fundamental physical processes addressed in Objective F. Our scientific goal is to understand the web of linked physical processes connecting Earth with the space environment. Our applied goal is to protect society and its technological infrastructure from space hazards and understand the external drivers of long-term climate change. We will improve technological efficiency of future operational systems by exploiting our understanding of Earth and its place in space. Human life and society provide the context for our investigations.

This context is not limiting. As we extend our presence throughout the solar system, we are interested in the planetary environments awaiting us and how the study of these environments can be applied to our home on Earth. Habitability, for humankind in particular, requires a rare congruence of many factors. These factors, especially the role of the Sun as a source of energy to planets and the role of magnetic fields in shielding planetary atmospheres, are a subject of immense importance. We understand some of the features contributing to make planets habitable, but key questions remain.

The interactive couplings of solar system processes, in the Sun and interplanetary space, with the interstellar medium, and throughout the near-Earth environment, require comprehensive study of these linked systems through a series of investigations covering these regions. Investigations of impacts on humankind must begin with the Sun, understand the cause of eruptive events and solar variability over multiple time scales, follow propagation and evolution of solar wind disturbances and energetic particles through the heliosphere to Earth, and finally investigate the interaction of solar radiative emission and the solar wind with Earth's coupled magnetosphere-ionosphere-atmosphere system.

Our four Research Focus Areas (RFAs) have been formulated to understand: the Sun so we can predict solar variability and the evolution of solar disturbances as they propagate to the Earth; the response of the coupled near-Earth plasma environment to space weather and the impacts on society; the role of the Sun as the principal energy source in our atmosphere, including the impact of long-term solar variability on Earth's climate; and, in a broader context than just the Earth, the solar photon and particle impact on other solar system bodies and how stellar activity and magnetic fields affect the evolution of planetary habitability over time.

It is not enough to study just variability and change. Coupled systems have complex internal forcings, e.g. gravity waves breaking in the upper atmosphere. The internal dynamics of the near-Earth coupled systems that protect us must be understood, even in the absence of solar variability. The program outlined below focuses on both internal linkages and external forcing mechanisms.

Thumbnail of CME here

Solar Variability & Heliospheric Disturbances. RFA H.1 aims to understand the Sun, determine how predictable solar activity truly is, and develop the capability to forecast solar activity and the evolution of solar disturbances as they propagate to Earth. It focuses on both short-term and long-term variability. X-ray flares can immediately and severely degrade radio communications through ionospheric effects. Precursors to solar disturbances observable above and below the solar surface will initially serve as predictive tools for disruptive events. Coronal mass ejections that create large magnetic storms at Earth evolve significantly over their multi-day travel time to Earth. We will learn how disturbances initiate, propagate, and evolve from the Sun to Earth and incorporate this knowledge into a predictive model of geoeffectiveness at Earth to enable a warning and mitigation system for our technological assets. Solar energetic particle events can pose serious threats to technological assets and astronauts in near-Earth orbit; we will learn how particles are accelerated in the inner heliosphere and how they propagate. We must also understand the long-term changes in total and spectral irradiance and the solar cycle variations that have significant impacts on Earth's climate and human society.

Priority Research Focus Areas & Investigations:

H1. Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment.
  1. How do solar wind disturbances propagate and evolve from the Sun to Earth?
  2. What are the precursors to solar disturbances?
  3. Predict solar disturbances that impact Earth.

H2. Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.
  1. What role does the electrodynamic coupling between the ionosphere and the magnetosphere play in determining the response of geospace to solar disturbances?
  2. How do energetic particle spectra, magnetic and electric fields, and currents evolve in response to solar disturbances?
  3. How do the coupled middle and upper atmosphere respond to external drivers and with each other?

H3. Understand the role of the Sun as an energy source to Earth's atmosphere, and in particular the role of solar variability in driving change.
  1. How do solar energetic particles influence the chemistry of the atmosphere, including ozone densities
  2. What are the dynamical, chemical, and radiative processes that convert and redistribute solar energy and couple atmospheric regions?
  3. How do long-term variations in solar energy output affect Earth's climate?

H4. Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.
  1. What role do stellar plasmas and magnetic fields play in the formation of planetary systems?
  2. What is the role of planetary magnetic fields for the development and sustenance of life?
  3. What can the study of planetary interaction with the solar wind tell us about the evolution of planets and the implications of past and future magnetic field reversals at Earth?

Thumbnail of airplane here

Variability in the magnetosphere, ionosphere, and upper atmosphere. RFA H.2 will develop understanding of the response of the near-Earth plasma regions (magnetosphere, ionosphere, and thermosphere) to space weather. This complex highly coupled system protects Earth from the worst solar disturbances, but it also redistributes energy and mass throughout. A key element involves distinguishing between the responses to external and internal drivers, as well as the impact of ordinary reconfigurations of environmental conditions, such as might be encountered when Earth crosses a magnetic sector boundary in the solar wind. This near-Earth region harbors space assets for communication, navigation, and remote sensing needs and conditions there can adversely affect their operation. Ground based systems, such as the power distribution grid, can also be affected by ionospheric and upper atmospheric changes. Investigations emphasize understanding the nature of the electrodynamic coupling throughout geospace (the near-Earth plasma environment), how geospace responds to external and internal drivers, and how the coupled middle and upper atmosphere respond to external forcings and how they interact with each other.

Thumbnail of storm cloud here

Solar Variability and Atmospheric Responses. RFA H.3 addresses the role of the Sun as the primary energy source for Earth's atmosphere. We seek to understand not only the atmospheric response to solar variability, but also the importance of steady-state processes in maintaining our atmosphere. It also considers long-term climatic impacts of solar variability on humankind. We need to understand the changing inputs - both spectral changes in the electromagnetic radiation and changing levels of energetic particles throughout the atmosphere. Two fundamental problems are delineating what processes convert and redistribute solar energy within the atmosphere and determining how this is accomplished. Other specific processes can have significant impact on Earth's atmosphere and climate and merit dedicated investigations. For example, the role of energetic particles from aurora, the radiation belts, and solar flares on ozone chemistry in the upper atmosphere is not well understood. As another example, non-solar external processes, for example cloud nucleation from galactic cosmic rays, may affect Earth's climate but the details of this impact are uncertain.

Thumbnail of the aurora here

Stellar Variability and Magnetic Shielding. Other planets and other stars provide illuminating perspectives for understanding the Earth and Sun. RFA H.4 addresses the long-term impact of interactions of the solar wind with Earth and other solar system bodies and the study of activity on stars other than our Sun. We need to understand the role plasmas and magnetic fields play in planetary formation and in the evolution of planetary atmospheres because this relates to the ultimate habitability of planets. A particular goal is to understand the importance of planetary magnetic fields for the development and sustenance of life. Observing activity on other stars will tell us how conditions change with time. One applied investigation that stems from these studies is to determine the implications of past and future magnetic field reversals at Earth. Such investigations provide important opportunities for linkages with other NASA fields of study.

RFA H.1. Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment

The climate and space environment of Earth are primarily determined by the impact of plasma, particle, and electromagnetic radiation outputs from the Sun. The solar output varies on many time scales: from explosive reconnection, to convective turn over, to solar rotation, to the 22-year solar magnetic cycle, and even longer, irregular fluctuations, such as the Maunder minimum. The variability is linked to the emergence of magnetic field from below the photosphere, its transport and destruction on the surface, and the eruption into the heliosphere of energy stored in the atmosphere as flares and coronal mass ejections. The large-scale heliosphere also modulates the propagation of incoming galactic cosmic rays. Longer-term changes that can affect Earth's climate include solar total and spectral irradiance.

The solar wind, embedded disturbances, and energetic particle populations evolve as they travel through the heliosphere. Shocks accelerate particles and interact with other irregularities. CME's can even interact with each other. Current observations generally depend only on near-Sun and 1AU observations. Understanding the three-dimensional time-varying propagation of solar disturbances is one of the greatest challenges facing us. Understanding the internal configuration of the structures is another.

Precursors will provide useful information about solar and interplanetary events; however more complete predictive models based on physical principles are required. Like terrestrial weather, it is not yet clear how long in advance solar activity is predictable. Improved continuous observations of the solar vector magnetic field and high resolution observations of the atmosphere are as critical for resolving this question as helioseismology is for revealing the subsurface conditions.

Three investigations are associated with this RFA:

Priority investivations are:	***Relevant Missions:***
Investigation H1.1. What are the precursors of solar disturbances?	Future enabling missions: Solar B, STEREO, SDO, SIRA, SHIELDS/Farside, and SEPP. SSSC Great Observatory missions supporting this investigation include: SOHO, TRACE, and RHESSI.
Investigation H1.2. How do solar wind disturbances propagate and evolve from the Sun to Earth?	Future enabling missions: STEREO, SOLAR-B, SDO, IH Sentinels, SIRA, SEPP, Doppler, SHIELDS, Solar Orbiter, Heliostorm/L1, and Solar Weather Buoys. SSSC Great Observatory missions supporting this investigation include: ACE, RHESSI, SOHO, TRACE, Ulysses, and Wind.
Investigation H1.3 - Predict solar disturbances that impact Earth.	Future enabling missions: SDO, Solar-B, STEREO, IH Sentinels, Heliostorm/L1, SEPP, SHIELDS, and SIRA. SSSC Great Observatory missions supporting this investigation include: ACE, RHESSI, SOHO, TRACE, and Wind.

RFA H.2. Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.

The near-Earth space environment, geospace, is unique in the solar system and central to the protection of Earth and its inhabitants. This region includes the magnetosphere, ionosphere, and thermosphere (MIT) bound together as a tightly coupled system that interacts with the neutral atmosphere below and the Sun and heliosphere above. The variability within geospace and the nearby interplanetary environment is our local space weather. Much of space weather is driven by the external processes discussed in the previous section. In addition, internal drivers of the MIT region such as the upward propagation of gravity waves, wave-particle interactions, and auroral current systems are equally important and must be investigated. The consequence of internal drivers is that even in quiet solar wind conditions, there can be significant variability within the MIT region.

Geospace is the location of most of our space activities. Communication, navigation, Earth weather and remote sensing, emergency location, defense reconnaissance, and NASA missions are all affected by space weather. Space weather also causes disturbances of electric power grids and sensitive electronic systems on the ground. These include navigation systems used by commercial airliners. The technological systems sensitive to disturbances in geospace are increasing in importance and urgency to human society.

The detailed nature of the electromagnetic coupling between the inner and outer regimes of geospace is not well understood. We need to understand how mass and energy are exchanged between these regions in quiescent conditions and during disturbed times. Chemistry and pressure forces become increasingly important in understanding linkages with the middle atmosphere, down to 50 km altitude.

Three investigations are associated with this RFA:

Priority investivations are:	***Relevant Missions:***
Investigation H2.1 - What role does the electrodynamic coupling between the ionosphere and the magnetosphere play in determining the response of geospace to solar disturbances?	Future enabling missions include both geospace storm probes, RBSP and ITSP, MMS, GEC, GEMINI, and MagCon. SSSC Great Observatory missions supporting this investigation include: Cluster, IMAGE, Polar, and TIMED.
Investigation H2.2 - How do energetic particle spectra, magnetic and electric fields, and currents evolve in response to solar disturbances?	Future enabling missions include both geospace storm probes, RBSP and ITSP, MMS, GEC, GEMINI, and MagCon. SSSC Great Observatory missions supporting this investigation include: Cluster, IMAGE, Polar, and TIMED.
Investigation H2.3 - How do the coupled middle and upper atmosphere respond to external drivers and with each other?	Future enabling missions include ITSP, ITM Waves, SECEP, Tropical ITM Coupler. SSSC Great Observatory missions supporting this investigation include: AIM, IMAGE, Polar, and TIMED.

Research Focus Area H3: Understand the role of the Sun as an energy source to Earth's atmosphere, and in particular the role of solar variability in driving change.

Solar energy in the form of photons and particles drives the chemical and physical structure of Earth's atmosphere. For example, ultraviolet and more energetic radiation deposited globally throughout the stratosphere, mesosphere, and thermosphere is responsible for formation of the ionosphere. Also, while particles primarily deposit their energy at high latitudes, the resulting ionization, dissociation, and excitation of atoms and molecules can have a global effect due to dynamical processes that transport energy around the globe. Ultimately these processes combine to drive the temperature and chemical composition of the entire Earth's atmosphere. A key example of how atmospheric modification by the Sun affects life is stratospheric ozone, which acts as a human UV shield. The very existence of the ozone layer is a direct result of solar energy deposition. Nitric oxide created at higher altitudes by processes involving solar energy may be transported to lower altitudes where it can destroy ozone.

Because life depends on the atmosphere and its climate, study of solar energy driven atmospheric variations is critically important. Solar energy and its changes have effects throughout the atmosphere including the troposphere where humans live. Despite this, the strength and variability of atmospheric solar energy deposition remain poorly understood. In addition, coupling processes that spread effects of energy deposition in altitude and latitude are not well understood. Addressing these issues requires spectral observations of solar energy deposition resolved in space and time as well as theory and modeling of dynamical processes that distribute effects of solar energy.

Three investigations are associated with this RFA:

Priority investivations are:	***Relevant Missions:***
Investigation H3.1 - How do solar energetic particles influence the chemistry of the atmosphere, including ozone densities?	Future enabling missions are AIM, ITSP, GEC, L1-Monitor, SECEP, ITM Waves, and CNOFS. SSSC Great Observatory missions supporting this investigation include: IMAGE and TIMED.
Investigation H3.2 - What are the dynamical, chemical, and radiative processes that convert and redistribute solar energy and couple atmospheric regions?	Future enabling missions are ITSP, GEC, L1-Monitor, SECEP, ITM Waves, and CNOFS. SSSC Great Observatory missions supporting this investigation include: AIM, IMAGE and TIMED.
Investigation H3.3 - How do long term variations in solar energy output affect Earth's climate?	Future enabling missions are AIM, ITSP, GEC, L1-Monitor, SECEP, ITM Waves, and CNOFS. SSSC Great Observatory missions supporting this investigation include: IMAGE and TIMED.

Research Focus Area H4: Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability.

Plasmas and their embedded magnetic fields affect the formation, evolution and destiny of planets and planetary systems. Our habitable planet is shielded by its magnetic field, protecting it from solar and cosmic particle radiation and from erosion of the atmosphere by the solar wind. Planets without a shielding magnetic field, such as Mars and Venus, are exposed to those processes and evolve differently. And on Earth, the magnetic field changes strength and configuration during its occasional polarity reversals, altering the shielding of the planet from external radiation sources. How important is a magnetosphere to the development and survivability of life? Planetary systems form in disks of gas and dust around young stars. Stellar ultraviolet 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. The study of similar regions in our solar system, such as dusty plasmas surrounding Saturn and Jupiter, will help explain the role of plasma processes in determining the types of planets that can form, and how they later evolve.

Four investigations study how and when planets become habitable:

Priority investivations are:	***Relevant Missions:***
Investigation H4.1 - What role do stellar plasmas and magnetic fields play in the formation of planetary systems?	Future enabling missions are SDO, Solar Probe, RBSP, ADAM, Jupiter Polar Orbiter/Juno, Stellar Imager. Future contributing missions are Widefield Infrared Survey Explorer, Space Interferometry Mission, Terrestrial Planet Finder, and the James Webb Space Telescope. SSSC Great Observatory missions supporting this investigation include: TIMED.
Investigation H4.2 - What is the role of planetary magnetic fields for the development and sustenance of life?	Future enabling missions are ITSP, GEC, SDO, L1 Monitor, ADAM, and the Venus Aeronomy Probe. SSSC Great Observatory missions supporting this investigation include: TIMED and ACE.
Investigation H4.3 - What can the study of planetary interaction with the solar wind tell us about the evolution of planets and the implications of past and future magnetic field reversals at Earth?	Future enabling missions are: ITSP, GEC, SDO, L1 Monitor, ADAM, L1 Mars, VAP. SSSC Great Observatory missions supporting this investigation include: ACE and TIMED.

Objective J

Safeguard the Journey of Exploration

Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space.

Harsh conditions in the space environment pose significant risks for the journey of exploration. Like seafaring voyagers, space explorers must be constantly aware of the current space weather and be prepared to handle the most extreme conditions that might be encountered. The important considerations include sudden changes in energetic particle and electromagnetic radiation, encounters with plasmas that cause spacecraft charging and discharging, and the uncertain response of neutral atmospheres to variable energy inputs.

The first step toward safeguarding astronauts and robotic assets in space is to characterize the extremes and ranges of variability that can occur in the space environment to help establish appropriate design requirements for vehicles, electronics, and habitats. This requires not only measurements in various locations at different times, but also an understanding of the physical processes that both cause temporal fluctuations and limit the range of responses of the system to those inputs.

The next milestone requires the ability to determine current conditions in key locations from an affordable set of available measurements – nowcasting of the space environment. This provides the critical operational knowledge that productive work can proceed at the time. The set of observations must be carefully chosen and the physical system must be modeled well enough to give confidence that the results can be extrapolated to the relevant location.

Finally, we must develop the capability to forecast the dynamic conditions in space. Forecasting quiet times may be as useful as forecasting disturbances. Initial reliance on empirical relationships will give way to high-fidelity physics. As our understanding of the fundamental processes improves, through comparison of predictive models with reality, we will gradually improve the accuracy and extend the duration of our predictions, and provide key support to implementing the Vision for Space Exploration. As with terrestrial weather in the past several decades, progress will be made, but it will be difficult because the systems are more diverse, the measurements are more sparse, and the physics is more complex.

Humans will work with robots and vehicles on Mars. Safe and productive expedition activity will depend on accurate forecasting of surface and space weather conditions that mitigates risks but avoids false alarms.

These steps are not necessarily sequential and some capability already exists in each area. One of the first major challenges is to determine more precisely what capabilities are needed and when. Our Objective J focuses on the science necessary to ensure safety and maximize productivity of both human and robotic space explorers. This objective includes both near-Earth and planetary environments, especially as they affect the robotic and technological systems that support human space flight. Benefits of addressing these issues include the optimization of spacecraft and instrument design, improved planning of mission and operations scenarios, ensuring the safety and maximizing the success and productivity of both robotic and human exploration.

Though much of the dramatic variability in the space environment is driven by solar activity, such as flares and coronal mass ejections or energetic particles accelerated by shocks in the heliosphere, understanding the more routine variations driven by rotation or slowly evolving structures is also important. For example the changing density of the Martian upper atmosphere depends on many uncertain factors in addition to solar activity. The underlying thread that links all three of the SSSC roadmap objectives is working to achieve a detailed understanding of the basic physical processes required to enable prediction. While Objective H focuses on the science needed to understand the processes in the near-Earth space environment that affect life and society, Objective J emphasizes understanding the variability of the space environment and its potential hazards with the purpose of enabling and securing space travel across the inner solar system, which affects primarily astronauts and their supporting assets in space.

Objective J is divided into four priority Research Focus Areas (RFAs). The first aims to adequately characterize the important environments. The second and third build on the first and focus on developing the capability to predict solar activity and understand the propagation and evolution of consequential events in the inner heliosphere. The final RFA will target the environmental variability at planets (Earth and Mars) that impact exploration activities.

[[Thumbnail of Damaged Electronic Components]]

Characterization of Space Environments. RFA J.1 focuses on determining the full range of extreme conditions that may occur in the inhospitable environments that human and robotic explorers will encounter. Learning these limits takes more than just observational surveys; it requires basic understanding of the dynamics of each space environment. This entails developing an understanding of the internal mechanisms, the critical boundary conditions, and the external drivers – the sources of external variability at the Sun and the interplanetary medium which modulates its extremes. This knowledge feeds into the design of safe and productive exploration activities and equipment. Practical understanding of the physical conditions and processes that modulate various space environments will lead to a capability to nowcast and forecast both safe and hazardous intervals.

[[Thumbnail of Filament Eruption]]

Prediction of Hazardous Solar Activity. RFA J.2 aims to develop the capability to forecast solar activity and the onset of the solar disturbances that are sources of potentially hazardous space weather. Successful prediction begins with reliable characterization of impulsive solar disturbances and their global effects on the corona and solar wind through which they propagate. Presently solar flares and CME's are no more predictable than earthquakes or volcanic eruptions. Complex active regions and other features with high potential for eruption can be identified on the visible solar disk and, absent such regions, it is quite feasible to announce "all clear" periods, when sensitive activities can be safely accomplished. However, during most of the 11-year solar activity cycle, when active regions are almost continuously present or could emerge at any time, even short-term forecasting is unreliable with our current level of knowledge. On longer time scales, we need to develop the ability to predict when and where active regions will arise, when the magnetic field will become unstable, and what the heliospheric consequences will be. This requires spacecraft observations of the entire solar surface both to follow the evolution of active regions over the full solar disk and to observe complex active regions that may be magnetically connected to human or robotic explorers far from Earth.

[[Thumbnail of snowed-out LASCO image]]

Propagation to Explorers. Disturbances interact with the solar wind. Particles and fields can be swept up and shocks associated with

CME's can accelerate particles to dangerous energies. To maximize the safety and productivity of explorers, we need to develop observational and modeling tools to more accurately predict the arrival times, durations, and severity of solar energetic particle impacts. In addition, exposure to high-energy galactic cosmic rays accumulates over long intervals to dangerous doses. Cosmic rays are modulated by the large-scale field and diverted by disturbances in the outer heliosphere, so they are of less concern during intervals of high solar activity. RFA J.3 entails development of an understanding of heliospheric acceleration mechanisms, the propagation of solar disturbances, and local acceleration of particles by plasma interactions in the disturbed solar wind. All are needed for a practical predictive understanding of these events.

[[Thumbnail of Space Shuttle Re-entry Vapor Trail]]

Space Weather Effects on Planets. Hazards in planetary environments must be understood, characterized, and mitigated to make human and robotic exploration safe, productive, and affordable. RFA J.4 targets how space weather impacts planetary environments in ways that affect exploration activities, such as spacecraft staging in low Earth orbit, or entry, descent, and landing (EDL) at Earth and Mars. Reliable communications and navigation for spacecraft and surface crews will require improved understanding of Earth's and Martian ionospheres. While the Sun and its variability drive these environments, many internal processes must also be understood. Planetary space weather develops through the interaction of the solar wind with the planetary magnetic fields and plasmas, the interaction of solar photons with plasma and neutral gas populations, interactions with the lower atmosphere, and via internal processes such as dynamos, wave interactions, magnetic reconnection, electric fields, transport, and chemistry. Because geospace is the site of initial staging activities and transport of human and robotic explorers, as well as their return to Earth, understanding this environment is particularly important.

Priority Research Focus Areas & Investigations

J1. Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.
  1. What is the variability and extremes of the radiation and space environment that will be encountered by future human and robotic explorers, both in space and on the surface of target bodies?
  2. How does the radiation environment vary as a function of time and position, and how should it be sampled to provide situational awareness for future human explorers?
  3. What is the relative contribution to the space radiation environment from Solar Energetic Particles and Galactic Cosmic Rays and how does this balance vary in time?

J2. Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.
  1. What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances, and what determines their magnitude and energetic particle output?
  2. What heliospheric observations, and empirical models are needed to enhance the predictive capability required by future human and robotic explorers?
  3. What geospace and planetary atmospheric observations, and empirical models are needed to provide the predictive capability required by future human and robotic explorers?

J3. Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.
  1. How are Solar Energetic Particles created and how do they evolve from their coronal source regions into interplanetary space?
  2. How do solar magnetic fields and solar wind plasma connect to the inner heliosphere and what is the nature of the near-Sun solar wind through which solar disturbances propagate?
  3. How are energetic particles modulated by large-scale structures in the heliosphere and what determines the variations in the observed particle fluxes?

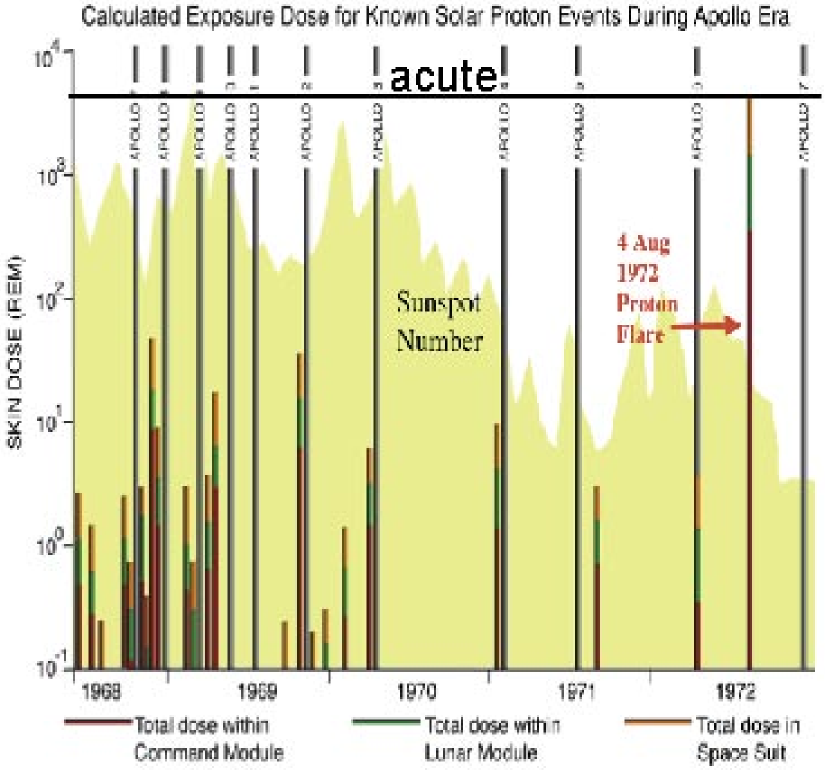
J4. Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.
  1. To what extent does the hazardous near-Earth radiation environment impact human and robotic explorer's safety and productivity?
  2. What level of characterization and understanding of the dynamics of the atmosphere is necessary to ensure safe aerobraking, aerocapture and EDL operations at Mars?
  3. To what extent do ionospheric instability, seasonal and solar induced variability affect communication system requirements and operation at Earth and Mars?
  4. What are the effects of energetic particle radiation on the chemistry and the energy balance of the Martian atmosphere?
  5. What are the dominant mechanisms of dust charging and transport on the Moon and Mars that impact human and robotic safety and productivity?

Research Focus Area J1: Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

Mitigating future risks to long-duration space flight requires knowledge of two elements for operational planning: the anticipated background environment and the worst-case transient event environment. The primary goal of space environment characterization is to establish the range of variability both for system design purposes as well as to develop and refine comprehensive models for predictive capabilities. This characterization must be conducted over a sufficiently long time frame. We also need to be able to nowcast the space environment in real time, so astronaut explorers can react to current conditions.

Energetic particles from the Sun generally propagate along the spiral magnetic field embedded in the solar wind. However, CMEs routinely disrupt the field lines and solar wind flow. Further complicating our understanding of this relatively straightforward view are recent observations of significantly elevated proton levels without any activity observed on the Earth-facing side of Sun. Activity on the far side of Sun can have effects throughout the inner heliosphere. Future spacecraft in transit to Mars will undergo a 6-9 month cruise phases far from either Earth or Mars, requiring the support, characterization and forecasting capability from their own, remote location, independent of Earth-local forecasting. Measurements from a wide range of longitudes will be required to accurately characterize, and ultimately predict the conditions throughout this region of the inner solar system.

Understanding the near-Sun source region of the space environment is ultimately required to provide the boundary conditions to enable accurate predictive modeling. This region pro-



The radiation dose to astronauts during the Apollo era missions is plotted with the sunspot count. This plot graphically highlights the profound difference between short Apollo-like expeditions to the Moon and the longer duration stays anticipated as part of the Vision for Space Exploration, where sporadic risks will become certain events.

duces solar energetic particles with energies as high as 1 GeV/nucleon. Beyond ≈15 Rs from the Sun, the solar wind speed is higher than any of the embedded wave speeds, so it is not possible to extrapolate back from in situ measurements made outside this region to determine the physical mechanisms at work there. A near-Sun mission is the only way to provide the direct observations necessary to understand the physics of this critical region.

The continuous galactic cosmic ray background radiation is modulated by the heliosphere. Progress in understanding the modulation requires measurements far from the ecliptic plane and from the inner and outer reaches of the heliosphere.

Characterizing the hazardous radiation environments within the Earth's magnetosphere is also an integral part of safeguarding the journey of exploration. For example, currently we do not understand the formation of new radiation belts.

Three investigations are associated with this RFA:

Priority investivations are:	***Relevant Missions:***
Investigation J1.1 - What is the variability and extremes (worst case) of the radiation and space environment that will be encountered by future human and robotic explorers, both in space and on the surface of target bodies?	Future enabling missions: THEMIS, RBSP, ITSP, IH Sentinels, SWB, L1/HelioStorm, MSL, LRO. SSSC Great Observatory missions supporting this investigation include: ACE, Wind, Polar, Cluster, TIMED
Investigation J1.2 - How does the radiation environment vary as a function of time and position, and how should it be sampled to provide situational awareness for future human explorers?	Future enabling missions: SWB, IH Sentinels, L1/Heliostorm, Solar Probe, MARS, MMS, RBSP. SSSC Great Observatory missions supporting this investigation include: ACE, Wind, Ulysses
Investigation J1.3 - What is the relative contribution to the space radiation environment from solar energetic particles and galactic cosmic rays and how does this balance vary in time?	Future enabling missions: IH Sentinels, L1/Heliostorm, SWB, Solar Probe, MARS, Telemachus, Solar Orbiter. SSSC Great Observatory missions supporting this investigation include: ACE, Wind, SOHO, ULYSSES, Voyager

Research Focus Area J2: Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

The energetic particles in impulsive solar particle events produced near the Sun by flares or by CMEs in the low corona have 1 AU transit times of minutes to hours, whereas the gradual events associated with interplanetary CME shocks arrive hours or days later. It may be possible to use coronagraph observations of a CME leaving the Sun to give 1-2 day warning of the gradual events, but to give warning of the near-relativistic impulsive events, or to increase the warning time of CMEs and gradual events, it is necessary to develop the capability to forecast the origin and onset of solar activity and disturbances from observations of the Sun itself. Successful forecasting of space weather requires knowledge of solar disturbances as well as the global corona and solar wind through which they propagate. This RFA focuses on the onset of solar activity; the next RFA focuses on the propagation of the solar disturbances.

We already have some empirical understanding of the regions that generate solar activity: large, complex active regions are likely to produce flares and CMEs. Both are driven by magnetic energy release, but neither the stabilizing mechanism allowing energy to accumulate, nor the release processes are understood well enough to predict eruption reliably. At present, the best indicators of oncoming geoeffective coronal disturbances are morphological. New physical diagnostic measurements in the photosphere, sub-photosphere, and solar atmosphere may hold the key to more reliable prediction. We need to develop the ability to predict the evolution of active regions and CME-producing regions from observations of the solar and corona magnetic fields. We need to understand how changes in the magnetic configurations lead to flares and CMEs.

Another critical need for exploration will be the capability of predicting "all clear" periods when extravehicular activities (EVAs) can be safely accomplished. This will require spacecraft observations of the entire solar surface, both to follow the evolution of active regions that are otherwise hidden on the back side of Sun and to observe complex active regions that may be magnetically connected to human or robotic explorers far from the Earth-Sun line. On a longer time scale, we need to develop the ability to predict the when and where active regions will arise. This will require development of helioseismology techniques and also observation of the Sun from multiple view points. Research focus areas from Objective

Showing an active sun with numerous active regions that are likely to erupt and produce hazardous heliospheric conditions.

F provide the foundation for understanding the fundamental processes related to long term variations in solar activity.

In order to develop the methodology and tools required during the first human exploration operations on the Moon, currently scheduled near the solar maximum of 2020, these investigations need to begin at or just after the time of the next solar maximum (2011-2015).

Two investigations are associated with this RFA:

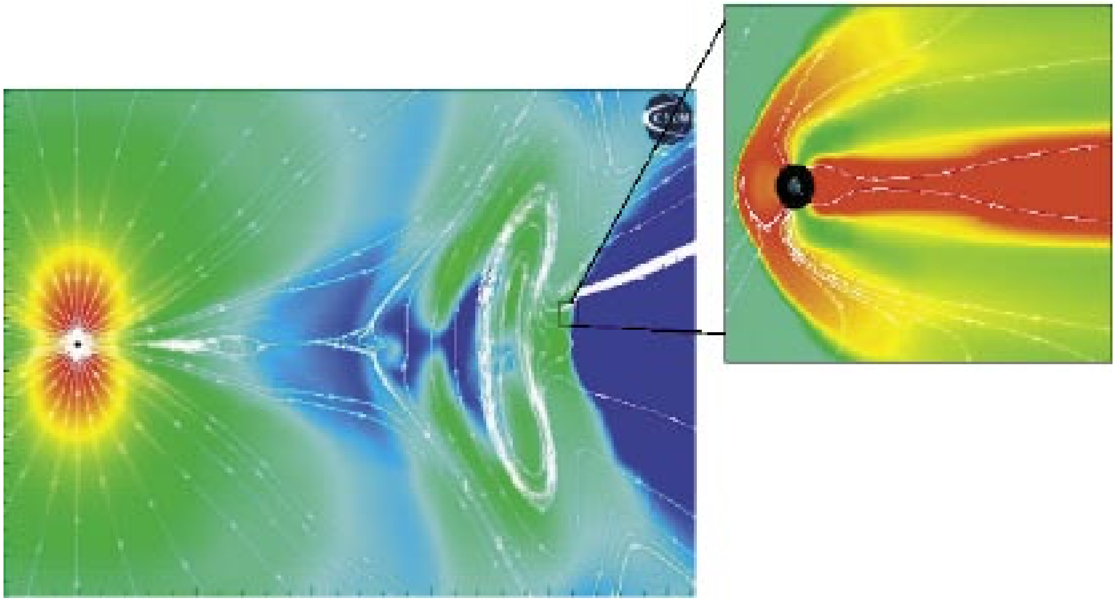
Priority investivations are:	***Relevant Missions:***
Investigation J2.1 - What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances, and what determines their magnitude and energetic particle output?	Future enabling missions: STEREO, IH Sentinels, SEPM, Doppler, SHIELDS, RAM SSSC Great Observatory missions supporting this investigation include: SOHO
Investigation J2.2 - What heliospheric observations, and empirical models are needed to enhance the predictive capability required by future human and robotic explorers?	Future enabling missions: IH Sentinels, SEPM, Solar Probe, SWB, L1/ HelioStorms, ADAM, LRO, RBSP, ITSP+ITImager, GEMINI, MagCon, MMS, THEMIS STEREO. SSSC Great Observatory missions supporting this investigation include: ACE, Wind, SOHO, Polar, TIMED, Cluster

Research Focus Area J3: Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

Predicting the heliospheric radiation environment requires an understanding of how solar energetic particles (SEPs) are produced, how solar disturbances evolve as they propagate outward, and how solar disturbances modulate galactic cosmic rays (GCRs). The investigations described below, along with the fundamental physical understanding provided by the Objective F investigations, are the necessary steps required for transitioning to predictive understanding.

Solar energetic particles (SEPs) can be grouped into two classes: impulsive events and gradual events. Impulsive events are associated with flares or current sheets in CME's. Gradual events are associated with CME shocks and some are produced farther out in the heliosphere by corotating interaction regions (CIRs). Gradual events produce greater risks to explorers because they extend tens of degrees in latitude and longitude and can last for days as a disturbance propagates through the interplanetary medium. We must characterize the coronal and interplanetary SEP source regions and the properties of the resulting SEPs in order to understand the important factors that determine their composition, flux, energy spectrum, and duration. In situ measurements within 0.3 AU are needed in order to characterize the particles before they are scattered in the interplanetary medium.

The evolution of solar disturbances depends on the pre-existing state of the solar wind and the background magnetic fields through which they propagate. Knowledge of the bulk properties of the solar wind is important for determining the strengths of shocks involved in energetic particle acceleration. On smaller spatial scales, wave turbulence processes play a role in particle heating and acceleration. In situ measurements taken more than about 0.1 AU from the Sun cannot be extrapolated back to determine the physical mechanisms at work in the coronal source regions. Remote sensing measurements, both spectroscopic and imag-



A simulated visualization of a Coronal Mass Ejection, as it begins to engulf the magnetosphere of Earth, which is expanded in the inset figure. CMEs and high speed solar wind streams drive a large fraction of the space weather effects in geospace because they carry large deflections of the interplanetary magnetic field along with strong enhancements of the dynamic pressure of the solar wind. These effects simultaneously compress the magnetosphere, produce large amounts of ionospheric heating and outflow into geospace, and excite strong circulation of plasma from the magnetotail through the magnetosphere toward the subsolar magnetopause, accelerating energetic particles within the magnetosphere.

ing, can tell us much about the region nearest the Sun. However the regions of the outer corona that provide the interface between the inner corona and the heliosphere (solar wind) are best studied with direct in situ measurements. Understanding the physics of these critical regions is necessary to predict the radiation environment throughout the solar system.

Galactic cosmic rays (GCRs) and other energetic particles are affected by disturbances in the heliosphere. The outer heliosphere shields us from much of the nearly continuous GCR flux, as much as 90% at 100 MeV/nucleon. The remaining flux is modulated by variations in heliospheric structure over the solar cycle and by sporadic events such as coronal mass ejections (CMEs). Near Earth substantial variability (factors of up to 10 over the solar cycle) is observed in the differential fluxes of GCRs with energies below several hundred MeV/nucleon. The modulation is not completely understood. Global measurements of the heliospheric structure with concurrent measurements of in situ energetic particle fluxes are needed. In particular, missions that travel outside of the ecliptic plane and to the inner and outer reaches of the heliosphere provide essential boundary conditions necessary to constrain models.

Three investigations are associated with this RFA:

Priority investivations are:	***Relevant Missions:***
Investigation J3.1 - How are Solar Energetic Particles (SEPs) created and how do they evolve from their coronal source regions into interplanetary space?	Future enabling missions: IH Sentinels, SEPM, SWB, DOPPLER, SIRA, Solar Probe, STEREO, L1/HelioStorm. SSSC Great Observatory missions supporting this investigation include: ACE, WIND, RHESSI, SOHO, Ulysses
IInvestigation J3.2 - How do solar magnetic fields and solar wind plasma connect to the inner heliosphere and what is the nature of the near-Sun solar wind through which solar disturbances propagate?	Future enabling missions: Solar Probe, IH Sentinels, SEPM, STEREO, DOPPLER, Solar Orbiter. SSSC Great Observatory missions supporting this investigation include: SOHO
Investigation J3.3 - How are energetic particles modulated by large-scale structures in the heliosphere (magnetic fields throughout the solar system) and what determines the variations in the observed particle fluxes?	Future enabling missions: STEREO, IH Sentinels, MMS, MagCon, SWB, L1/HelioStorm SSSC Great Observatory missions supporting this investigation include: Ulysses, Wind, ACE

Research Focus Area J4: Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

Human and robotic exploration of our solar system will necessarily be influenced by the planetary environments encountered. Both the plasma and neutral atmospheres of the planets, including Earth and Mars, impact the safety and productivity of exploration activities. Surface-to-orbit and surface-to-surface communications depend on space plasma variability. Spacecraft control in low orbits and aerobraking parking orbits depend on the upper atmospheric density. Asset staging and operations, as well as astronaut health and safety, are impacted by planetary radiation environments. The radiation environment at the Moon varies as it traverses in and out of the Earth's magnetosphere. The plasma and ultraviolet radiation environment at the Moon's surface contributes to the known problem of lunar dust grain adhesion to space suits and particulate contamination of instrumentation.

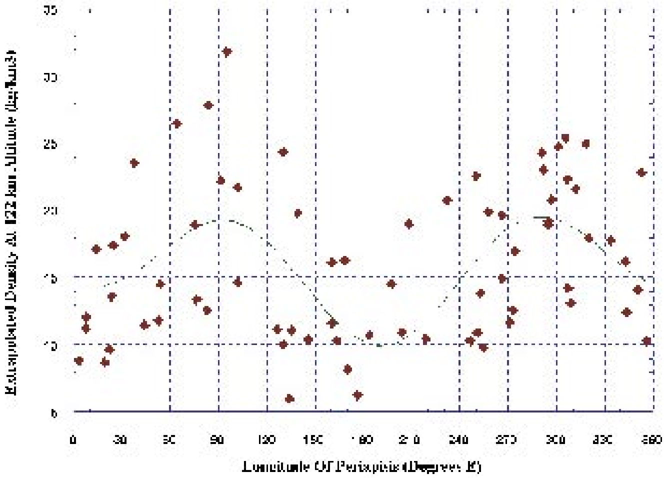
Planetary environmental conditions develop through the interaction of the solar wind with the planetary magnetic fields and plasmas as well as through the interaction of solar photons with plasma and neutral populations and with the atmosphere below. To understand the planetary conditions essential for exploration, scientific investigations target the "near-planet" environments of the Earth and other planetary systems. Because initial staging activities and transit of human and robotic explorers will occur in geospace, including at the Moon, understanding of this environment is particularly important (Investigation J.4.1). Furthermore, near-Earth characterization and understanding provides an essential baseline for modeling the impact of space weather in other planetary environments. As exploration proceeds at other planets, our understanding of the near-Earth environment will guide the development of follow-on planetary missions. In addition, comparison with other planetary environments will inform our understanding of our home planet. Understanding and characterizing the effects of near planet interactions and environments is essential to maximize the safety, productivity, and risk mitigation of hazardous conditions for exploration activities. A manned mission to Mars will require some combination of both orbiting and landing crews. Improved knowledge of the Mars atmosphere for aerocapture, entry, descent, and landing (Investigation J.4.2), improved knowledge of densities in the aerobraking regime (90 - 170 km), and in a possible low-altitude (200-300 km) station orbit are all required for safe operation of spacecraft.

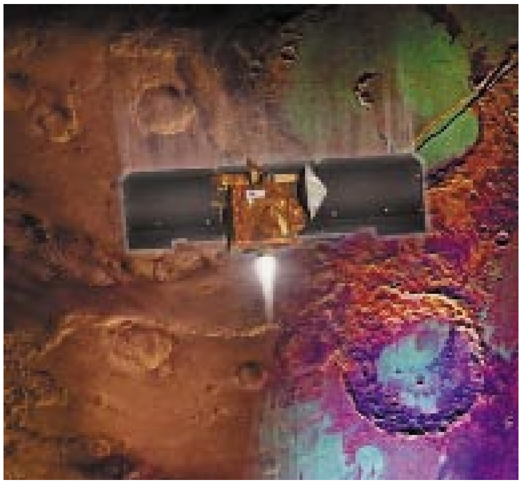
Reliable communications and navigation between orbiting and surface crews, and with Earth, are essential, requiring improved understanding of the Martian ionosphere (Investigation J.4.3). Neutral density variability at aerobraking altitudes is predominantly controlled by dynamical influences from below and can be addressed by extending the same basic connections and measurements to higher altitudes.

Orbiting crews may be affected by various space weather effects involving interaction between the solar wind and the partially-magnetized ionosphere and exosphere of Mars. For example, energetic particle events are of concern for astronaut safety, and the variability of radiation dosage when at the surface is poorly constrained (Investigation J.4.4).

The lunar surface that is encountered by the human and robotic explorers contains fine dust grains. Due to the lack of any appreciable atmosphere, the grains are exposed to a plasma and solar ultraviolet radiation environment. This creates a known problem of dust grain adhesion on astronaut suits and instrumentation that is not fully understood or resolved (Investigation J.4.5).

Five investigations associated with this RFA:

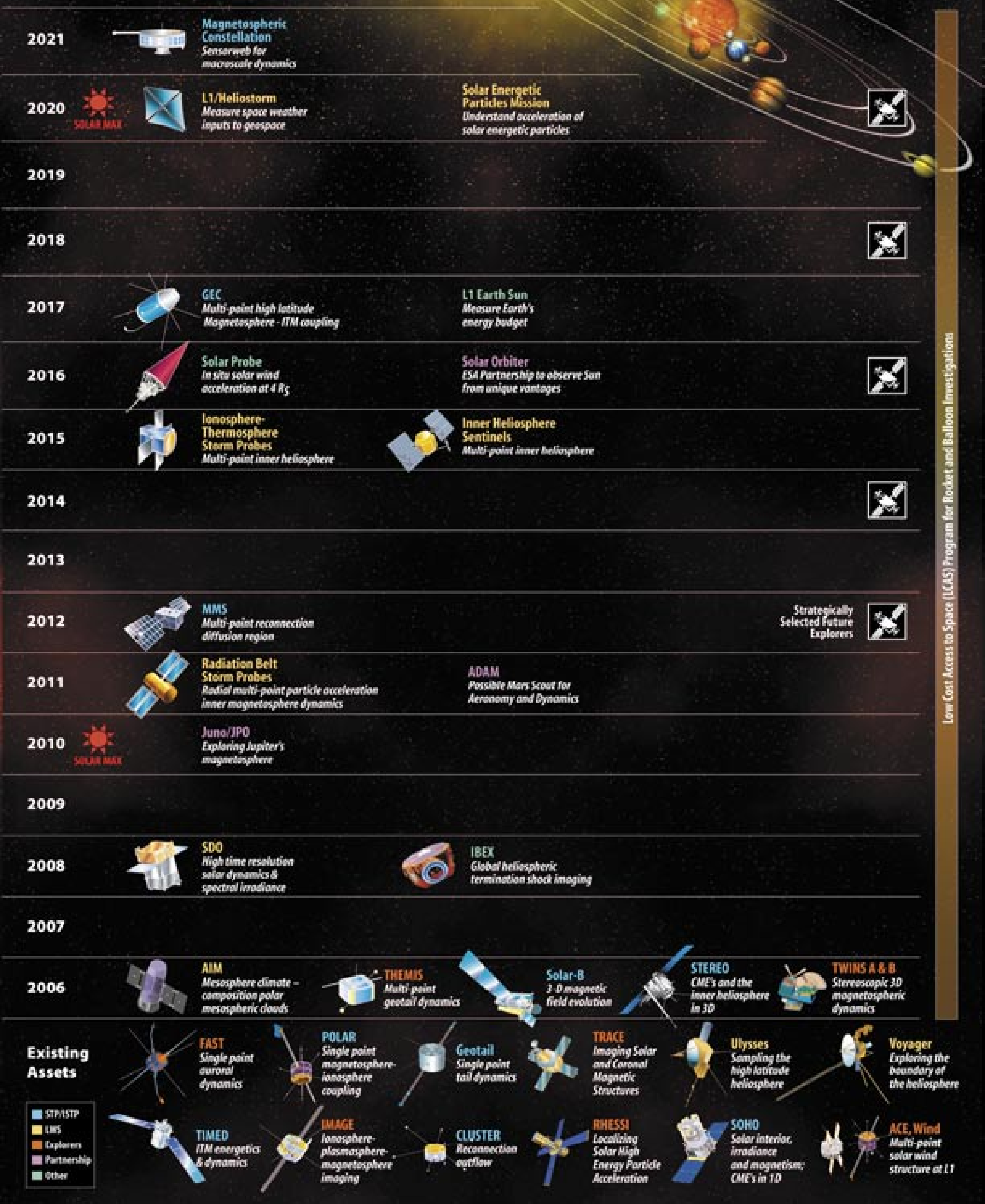




The atmospheric density encountered by the MGS mission during its aerobraking phase. The density varied by an order of magnitude relative to the predictions, illustrating why current atmospheric prediction science makes for a very tricky science of aerobraking and aerocapture. MGS required far more thruster operation than anticipated, as a result of this uncertainty in atmospheric drag, and may have suffered minor damage to appendages. Human landings on Mars will require significantly better knowledge of its atmospheric structure and dynamics to minimize fuel consumption while assuring safety.

Priority investivations are:	***Relevant Missions:***
Investigation J4.1 - To what extent does the hazardous near-Earth radiation environment impact the safety and productivity of human and robotic explorers?	Future enabling missions: THEMIS, MMS, RBSP, MagCon, IMC, GEC, AAMP, ITSP, L1/HelioStorm. SSSC Great Observatory missions supporting this investigation include: Polar, ACE, Wind, Geotail
Investigation J4.2 - What level of characterization and understanding of the dynamics of the atmosphere is necessary to ensure safe aerobraking, aerocapture and EDL operations at Mars?	Future enabling missions: GEC, C/NOFS, ADAM, MARS, ITM-Waves. SSSC Great Observatory missions supporting this investigation include: TIMED
Investigation J4.3 - To what extent does ionospheric instability, seasonal and solar induced variability affect communication system requirements and operation at Earth and Mars?	Future enabling missions: CNOFS, ITSP+IT Imager, L1/HelioStorm, ADAM, MARS SSSC Great Observatory missions supporting this investigation include: TIMED
Investigation J4.4 - What is the effect of energetic particle radiation on the chemistry and the energy balance of the Martian atmosphere?	Future enabling missions: AIM, MSL, ADAM, MARS, Mars GOES, GEC, SECEP, ITMC SSSC Great Observatory missions supporting this investigation include: TIMED
Investigation J4.5 - What are the dominant mechanisms of dust charging and transport on the Moon and Mars that impact human and robotic safety and productivity?	Future enabling missions: ADAM, MARS, Mars Goes, LRO, plus Moon and Mars Landers and Rovers, Laboratory SR&T program

Evolving SSSC Great Observatory



2021

Magnetospheric Constellation
Sensorweb for macroscale dynamics

2020 SOLAR MAX

L1/Heliostorm
Measure space weather inputs to geospace

Solar Energetic Particles Mission
Understand acceleration of solar energetic particles

2019

2018

2017

GEC
Multi-point high latitude Magnetosphere - ITM coupling

L1 Earth Sun
Measure Earth's energy budget

2016

Solar Probe
In situ solar wind acceleration at 4 R_S

Solar Orbiter
ESA Partnership to observe Sun from unique vantages

2015

Ionosphere-Thermosphere Storm Probes
Multi-point inner heliosphere

Inner Heliosphere Sentinels
Multi-point inner heliosphere

2014

2013

2012

MMS
Multi-point reconnection diffusion region

Strategically Selected Future Explorers

2011

Radiation Belt Storm Probes
Radial multi-point particle acceleration inner magnetosphere dynamics

ADAM
Possible Mars Scout for Aeronomy and Dynamics

2010 SOLAR MAX

Juno/JPO
Exploring Jupiter's magnetosphere

2009

2008

SDO
High time resolution solar dynamics & spectral irradiance

IBEX
Global heliospheric termination shock imaging

2007

2006

AIM
Mesosphere climate – composition polar mesospheric clouds

THEMIS
Multi-point geotail dynamics

Solar-B
3-D magnetic field evolution

STEREO
CME's and the inner heliosphere in 3D

TWINS A & B
Stereoscopic 3D magnetospheric dynamics

Low Cost Access to Space (LCAS) Program for Rocket and Balloon Investigations

Existing Assets

FAST
Single point auroral dynamics

POLAR
Single point magnetosphere-ionosphere coupling

Geotail
Single point tail dynamics

TRACE
Imaging Solar and Coronal Magnetic Structures

Ulysses
Sampling the high latitude heliosphere

Voyager
Exploring the boundary of the heliosphere

TIMED
ITM energetics & dynamics

IMAGE
Ionosphere-plasmasphere-magnetosphere imaging

CLUSTER
Reconnection outflow

RHESSI
Localizing Solar High Energy Particle Acceleration

SOHO
Solar interior, irradiance and magnetism; CME's in 1D

ACE, Wind
Multi-point solar wind structure at L1

- 🟦 STP/ISTP
- 🟨 LWS
- 🟧 Explorers
- 🟪 Partnership
- 🟩 Other

Chapter 2

Sun-Solar System Connection: The Program

Principles and Policies

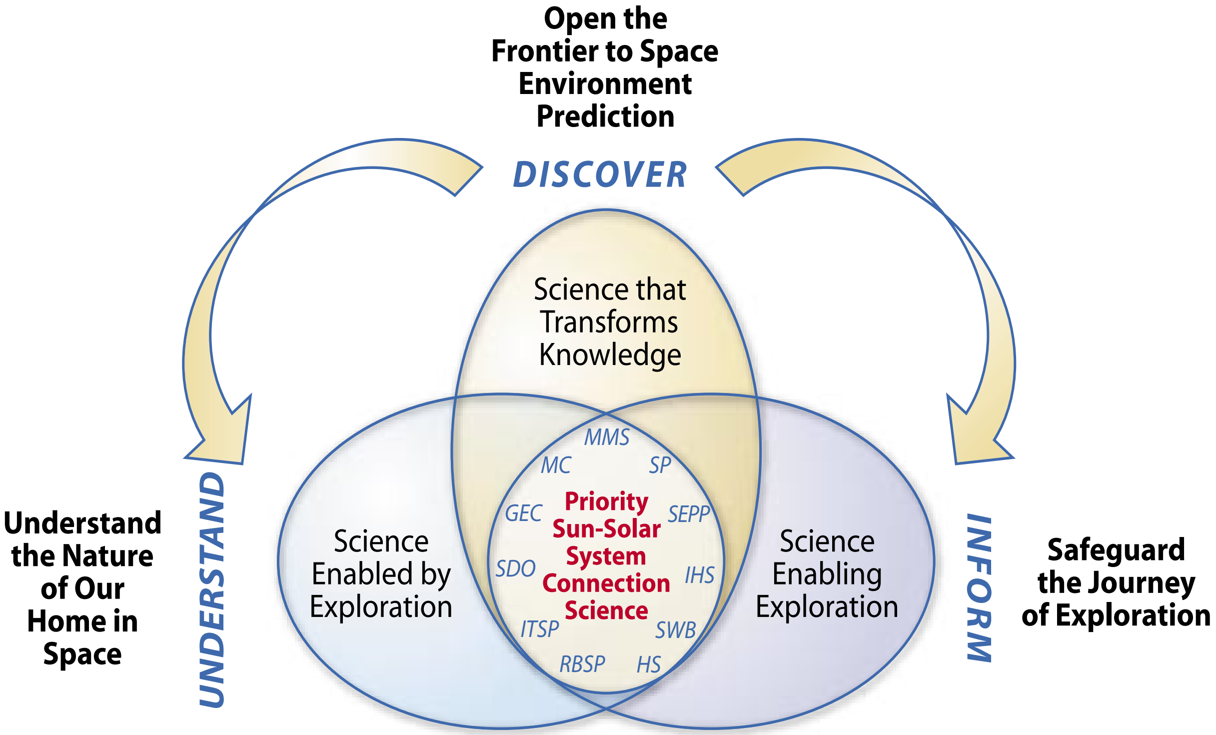
The strategy presented in this document has been derived from the NASA Objective for SSSC to address the vital, urgent, and compelling needs of the nation. The community based SSSC Roadmap committees have solicited input from the constituents of the program, both internal and external, in formulating the plan. The proposed SSSC Program implements the best science and exploration effort that can be accomplished within the budget constraints of the program. The recommended program has two options, one that fits within the expected resource cap with some specifically identified augmentations, and another that is optimized to address the science goals in a more reasonable time frame with increased mission synergy. The program is highly responsive to the requirements for the Vision for Space Exploration and consistent with the recommendations of the relevant decadal surveys of the National Academies and previous Roadmaps.

Implementation Strategy

The science and exploration program described in the previous chapter occupies a valuable niche in the NASA Science Mission Directorate. SSSC research will develop knowledge that transforms our understanding of the universe and our place in it. SSSC investigations provide practical understanding and measurements of areas that affect our technological society and enable safe and productive exploration of the Moon, Mars, and beyond. The missions and technology developed to explore the solar system enable the science of the division.

The interplay of exploration, discovery, and understanding provide guidance for prioritizing the program elements. Exploration of Mars and other destinations in the solar system provides the opportunity to measure conditions in different environments that help us understand our own world. New physical understanding of the Sun and its interactions with planetary magnetospheres provide information about the habitability of worlds near other stars. Understanding our space environment to the point of prediction contributes to developing future operational systems that support the needs of our increasingly technological society.

The objectives, research focus areas, and investigations defined in the previous chapter describe realms of scientific inquiry that will take decades to complete. The road to progress has been charted by identifying a series of targeted outcomes necessary to accomplish the desired objectives. The targeted outcomes in the accompanying table have been established after careful consideration of the research focus areas, consolidation of investigation requirements, anticipation of the capabilities likely to be available and required at different times, and estimation of available resources. The outcomes have been ordered in phases to develop the scientific understanding necessary to support the needs of society and the exploration program.



Science that is Vital, Compelling, and Urgent

The intersecting ovals illustrate the intersection of three categories of science: discovery science that is enabled by exploration, science that transforms our understanding, and science that informs to enable exploration. At the intersection is the ‘sweet spot’ where the highest priority SSSC missions lie.

Strategic Considerations

The SSSC objectives identify robust goals that are vital, urgent and compelling. Obviously no unique strategy exists now that addresses the scientific and programmatic needs, fits within the anticipated budget profile, and anticipates all developments over the next 30 years. The developing requirements of the Vision for Space Exploration, the increasing need for understanding external influences on our home planet, and the transformational science required to develop predictive capabilities for the space environment require a broad approach to address interlocking needs and demand considerable flexibility in the implementation.

The program relies on several elements: strategically planned missions in the Solar Terrestrial Probes (STP) and Living With a Star (LWS) lines to address widely recognized critical problems; competitively selected Explorers to optimize responsiveness to strategic needs; continued operation of existing space assets as part of the SSSC Great Observatory; low cost access to space for unique science, community health, and instrument development needs; technology development; supportive, targeted research and analysis programs; and a strong effort in education and public outreach. Partnerships with other areas of NASA and other agencies, both U.S. and international, are essential. Each of these program elements is described in more detail below.

Flagships missions address very difficult problems in scientific areas that confront major road blocks to future progress. Flagship missions have great promise for scientific advance, but may cost four or more times as much as an Explorer. Missions of this scope cannot be accomplished within the current resource limits of the program without fatally compromising the rest of the program. Flagship missions are identified separately as top priorities for additional funding.

Science by Phase

The Roadmap committees considered three decade-long phases in formulating a plan. The achievements of each phase inform decisions made about implementation in subsequent phases. The phases roughly correspond to development cycles in the Exploration Initiative. Phase 1 ends in 2015 and includes missions launched by that date; Phase 2 ends in 2025 and Phase 3 in 2035. Achievements identified in Table 2.1 correspond fairly well to these phases.

Our Phase 1 program presumes the continued operation of missions in the Great Observatory. The baseline Phase 1 program includes only new missions that are already in development or whose announcement is expected in the very near future. STEREO, Solar-B, and MMS in the STP program, SDO and RBSP in the LWS program, and the selected Explorers: AIM, THEMIS, and IBEX. Additional Explorers will close gaps in the program. The solar sail demonstration mission and the ADAM Mars Scout mission also occur in Phase 1. Solar Probe should be launched in this phase, though data from the first plunge through the corona will not be available until Phase 2. This set of investigations provides a very powerful tool for accomplishing the achievements listed in Table 2.1. An optimized program would accelerate these and some of the missions identified for early in Phase 2. The multiple synergies and comprehensive views afforded by the Great Observatory as it evolves and develops during this interval are a testimonial to the investments and achievements of the past decade in Sun Earth Connection science at NASA. The first crucial set of questions required to open the frontier to space weather predictions, understand the nature of our home planet, and safeguard our outward journey have been largely anticipated in the existing program plan. SSSC is clearly poised to make significant progress in the next 10 years on these important questions.

Phase 2 includes missions scheduled for launch between 2015 and 2025. GEC and MagCon address the next set of fundamental problems in the STP program. They too depend on continued context observations from the evolving SSSC Great Observatory. The LWS Program plans to launch two missions relatively early - the Inner Heliosphere Sentinels and ITSP. These rely on measurements from SDO and RBSP to realize their full potential. Later two smaller missions, SEPM and Heliostorm/L1 will address questions about hazardous space weather directed toward the Earth-Moon system. Toward the end of Phase 2 a choice between terrestrial and heliospheric mission priority will need to be made (as described in the previous section). The pace of launches is somewhat slower and the comprehensive coverage of the connected system available early in phase 2 will likely diminish toward the end of the decade if missions do not continue to function past their expected life times.

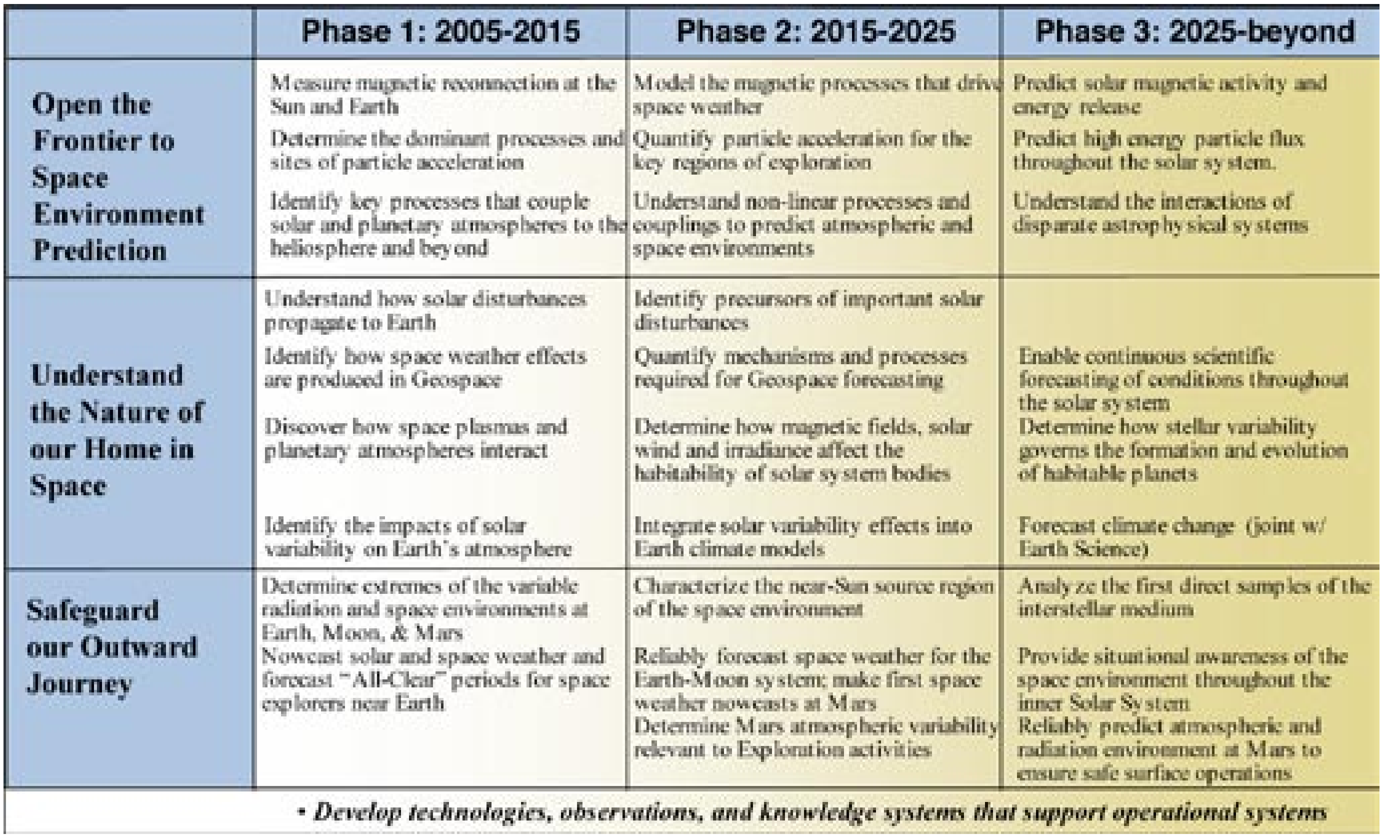
Missions beyond 2025 in Phase 3 have been identified in the previous section because we already know many of the scientific questions that will probably remain unanswered. The priorities will be adjusted depending on what is learned and on progress in the Exploration Initiative, but it is clear that constellations of spacecraft will be required in new regions to resolve spatial and temporal changes in the magnetosphere and in interplanetary space where remote global sensing is not possible. Technological development and selection of Explorers may allow some objectives to be achieved earlier.

Several missions of great interest cannot be implemented even during this time period. A few are limited by technology, but more are limited by resources, particularly those having to do with comparative magnetospheres and planetology.

The SSSC Roadmap promises significant accomplishment. Most of the science requirements derived from the national objectives for NASA can be accomplished with the resources available. With additional resources an optimized plan has been crafted that will be significantly more productive. The near term course is clear and decision points for the future have been identified.

Program Elements

The implementation of the SSSC program is currently funded though several sources. Missions come from the Solar-Terrestrial Probe Program, the Living With a Star Program, and the Explorer Program. Rockets and balloons provide low-cost rapid access to space. The fleet of existing missions makes up a Great Observatory that evolves as new missions are



	Phase 1: 2005-2015	Phase 2: 2015-2025	Phase 3: 2025-beyond
Open the Frontier to Space Environment Prediction	Measure magnetic reconnection at the Sun and Earth Determine the dominant processes and sites of particle acceleration Identify key processes that couple solar and planetary atmospheres to the heliosphere and beyond	Model the magnetic processes that driv space weather Quantify particle acceleration for the key regions of exploration Understand non-linear processes and couplings to predict atmospheric and space environments	Predict solar magnetic activity and energy release Predict high energy particle flux throughout the solar system. Understand the interactions of disparate astrophysical systems
Understand the Nature of our Home in Space	Understand how solar disturbances propagate to Earth Identify how space weather effects are produced in Geospace Discover how space plasmas and planetary atmospheres interact Identify the impacts of solar variability on Earth's atmosphere	Identify precursors of important solar disturbances Quantify mechanisms and processes required for Geospace forecasting Determine how magnetic fields, solar wind and irradiance affect the habitability of solar system bodies Integrate solar variability effects into Earth climate models	Enable continuous scientific forecasting of conditions throughout the solar system Determine how stellar variability governs the formation and evolution of habitable planets Forecast climate change (joint w/ Earth Science)
Safeguard our Outward Journey	Determine extremes of the variable radiation and space environments at Earth, Moon, & Mars Nowcast solar and space weather and forecast "All-Clear" periods for space explorers near Earth	Characterize the near-Sun source region of the space environment Reliably forecast space weather for the Earth-Moon system; make first space weather nowcasts at Mars Determine Mars atmospheric variability relevant to Exploration activities	Analyze the first direct samples of the interstellar medium Provide situational awareness of the space environment throughout the inner Solar System Reliably predict atmospheric and radiation environment at Mars to ensure safe surface operations

- ***Develop technologies, observations, and knowledge systems that support operational systems***

Each anticipated achievement in the table has been thoroughly considered. Each targeted outcome requires advances in understanding of physical processes. Measurement capabilities must be available to develop that knowledge. Deployment of missions, development of theoretical understanding, and availability of infrastructure systems are required to provide that measurement capability. For each outcome in the table the necessary understanding, capabilities, and implementation have been traced. The scientific flow-down charts are available at the SSSC 2005 Roadmap web site (sun.stanford.edu/roadmap) and an example chart will be found in an Appendix. The requirements in the flow-down charts often overlap; so the results have been consolidated. Finally a balanced set of missions was chosen to address the most critical science and exploration topics in each phase. The missions have been assigned to program elements and resources identified to implement them. Information gained in earlier missions must be used to decide the selection and ordering of later flight opportunities.

launched and new combinations of observations are made. Focused research and analysis programs lead to new understanding and contribute to new investigation requirements. The support of data, computing, and community infrastructure ensures that progress will continue to be made. Each of these program elements is described below. We first describe briefly the mission strategy for each line. We then discuss each phase of the program and how the proposed mission set meets the requirements in the tables described above.

Solar Terrestrial Probes

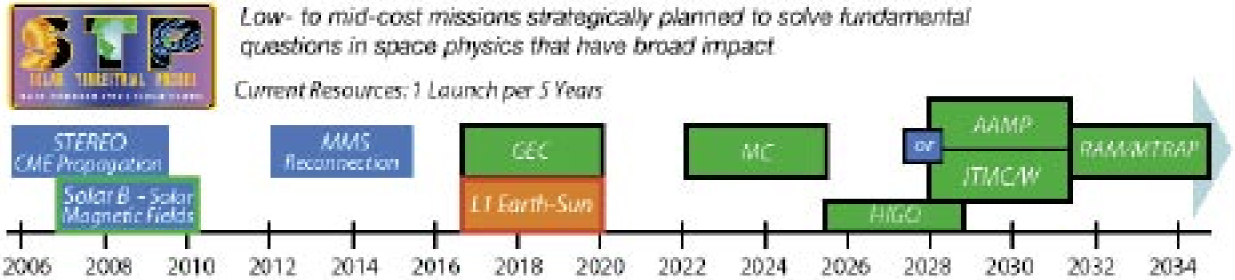
The Solar Terrestrial Probe investigations focus on specific scientific areas required to advance our fundamental understanding of the Sun – Solar System Connection. Subsequent missions target the 'weakest links' in the chain of understanding. STP missions are strategically defined and investigations are competitively selected.

STP is one of two strategic lines for the Sun-Solar System Connection. Strategic mission lines afford the space physics community the opportunity to plan specific large missions to address one or more of the research focus areas and thus make significant progress in elucidating the fundamental processes of the coupled Sun-Earth system. In addition, such capable spacecraft missions often result in unexpected new discoveries.

The future and existing mission priority has been re-evaluated in light of the new priorities at NASA that are reflected in the objectives derived in this Roadmap and in the reduced funding available for this line. STP missions currently in development are STEREO, Solar-B, and MMS. The first STP mission, TIMED, was launched in 2001 to study the influences of the Sun and humans on the mesophere and lower thermosphere/ionosphere. These missions strongly support the current objectives explained in this Roadmap and musts be completed as scheduled. Solar-B is a joint mission with the Japanese space agency, JAXA, and it will provide the high-resolution solar observations needed to understand magnetic energy storage and release in the solar atmosphere. STEREO will observe coronal mass ejections and other structures moving in the interplanetary medium from two spacecraft in solar orbit to understand how CME's reach Earth. The set of four MMS spacecraft will probe the most critical regions of geospace to measure magnetic reconnection.

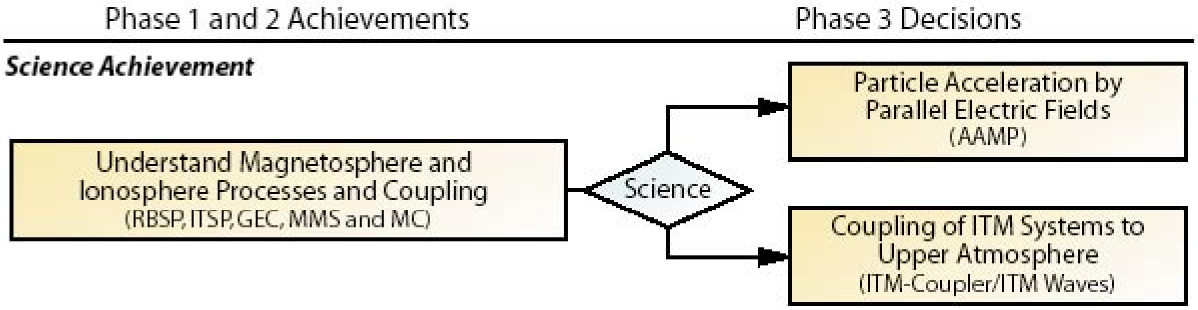
In order to support the fundamental science necessary to open the frontier for prediction of space weather effects, this Roadmap identifies GEC and MagCon as the next two STP missions. GEC will measure the poorly observed region just below stable satellite orbits where the interactions of the charged and neutral components of the atmosphere become more important – the linkage between the ionosphere and magnetosphere. MagCon, now slated for launch in 2022, provides comprehensive measurements of processes in the magnetosphere with a fleet of spacecraft. These and the other missions we identify are described in more detail in the next Section.

Coupled with the rest of the program, these missions promise the best assault on the important problems facing SSSC. The slowed five-year spacing between launches in the current budget is not ideal, not only because progress is slow, but because synergy between missions is curtailed. We have identified participation in the L1 Earth-Sun mission that is being proposed in the Earth Science roadmap as one exciting candidate for augmentation of the STP line. Measurements of the external radiation and particle inputs to the Earth environment are essential for understanding the radiation budget. The scope of the SSSC portion of this mission will depend on the timing and capabilities of the Earth science mission.



The figure shows the STP missions identified for flight through 2035 in our current budget projection. Blue boxes represent anticipated SSSC resources, in units of medium sized missions. Mission names in blue boxes indicate that these resources are committed and development is underway. Green boxes represent new missions assigned here to blue box resources. When two green boxes appear above a blue box resource, a decision is to be made, based on information to become available in the future. Orange boxes represent Flagship or Partnership missions dependent upon anticipated resources from outside current SSSC Programs.

If additional funds can be made available to restore the planned 2.5 year cadence of STP missions the MMS, GEC, and MagCon missions should be flown more quickly. They should be followed by Doppler & SEPM, two smaller missions candidates that could be combined to obtain measurements for understanding the initiation (DOPPLER) and the coronal evolution (SEPM) of flares, current sheets, and CME shocks that produce solar energetic particles. These two missions particularly benefit from overlap with the inner heliospheric and solar missions planned in the LWS line. Next, AAMP focuses on particle acceleration too, but in the auroral region around Earth. Two more small missions, HIGO and ITM Waves, complete phase 2 of our plan in this optimized scenario. A revamped HIGO complements the IBEX Explorer recently selected to explore the outer boundary of the heliosphere; HIGO will measure the components of the interstellar medium that survive into the sub-Jovian solar system. ITM Waves concentrates on the wave processes fundamental to the coupling between distinct altitude regions and on the overall dynamics of the Earth's atmosphere.



Schematic illustrating a decision point for selecting a future mission.

Phase 3 STP missions will measure reconnection near the Sun and observe lower latitude disturbances in the ionosphere-thermosphere-mesosphere; a stellar imager (likely a flagship mission) will resolve activity on other stars to enable us to complete our objectives. Even later, more ambitious missions to explore the interactions of external drivers with other worlds in the solar system, specifically Titan, Venus, and Io, could be accomplished in partnership with others to address questions of habitability and atmospheric evolution. Larger telescopes to remotely probe the solar transition region would complete our understanding of how energy propagates from the Sun outward and remote sensing of other planetary environments would close the path at the receiving end.

Measurements of the Solar Wind Up-stream from Earth

Partnerships and Decision Points for SSSC Near L1:

In principle the operational solar wind monitoring function should be the responsibility of other U.S. government agencies. However, the L1 vantage point remains critical to SSSC science because in situ solar wind conditions about an hour upstream from the Earth can be continuously determined by a single spacecraft. Without knowledge of the external drivers, understanding space weather effects in geospace is problematic. Reliable prediction of geospace conditions requires accurate measurements of the incoming solar wind parameters. Short-term forecasts based solely on solar observations will never be detailed enough for terrestrial space weather needs. This Roadmap identifies three possible L1 partnering options for long-term replacement of the continuous solar wind monitoring currently provided by the ACE and WIND spacecraft.. Only one mission needs to be implemented by SSSC.

Heliostorm uses solar sails to hover twice as far upstream as an L1 mission. The mission will measure the same solar wind parameters as L1-Heliostorm. This is the preferred option.

L1-Heliostorm provides basic measurements of the solar wind plasmas, fields, and energetic particles from the L1 position using conventional technology.

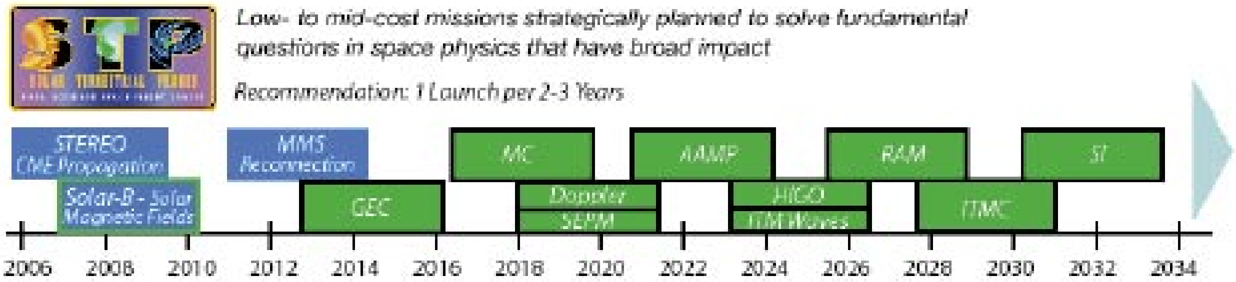
L1 Earth-Sun is a joint Earth-Sun Science mission that includes an in situ solar wind package. The mission simultaneously conducts spectral imaging from XUV to IR of both the Earth and the Sun.

Decision Points and Partnerships:

If the Solar Sail Demonstration is successful, then Heliostorm would use a solar sail to provide double the time interval for forecasting and data assimilation into nowcasting models. The SSSC mission cost would be similar to an Explorer if NOAA and DoD partner with NASA.

If the Solar Sail Demonstration does not fly or is not successful, then L1-Heliostorm will use conventional technology at L1 to provide operational solar wind data. The mission cost is small and should be very small to SSSC when shared with DoD and NOAA partners.

If L1 Earth-Sun goes forward as a science mission in partnership with Earth Science, then the total SSSC component should be of moderate cost; the SSSC cost for the solar wind component should be small. L1-Heliostorm would not be necessary in this case.



The figure shows the mission identified for flight through 2035 in our optimized scenario. The synergy of mission is apparent.

Living with a Star

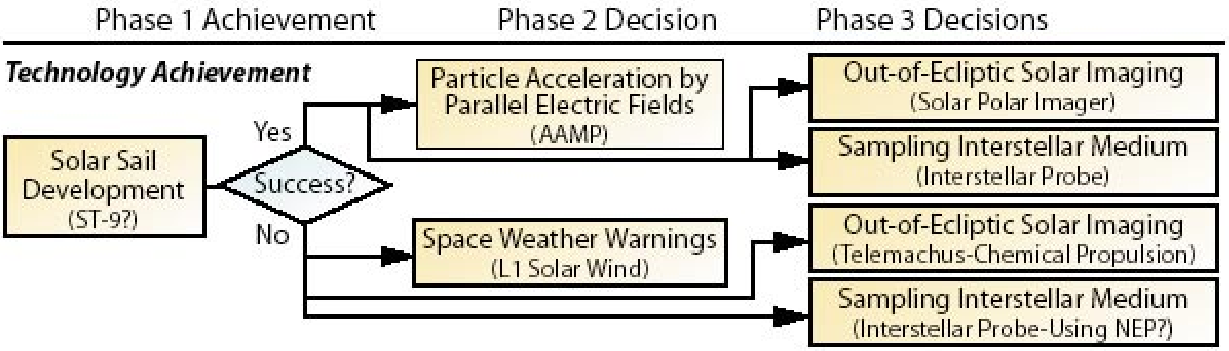
The Living With a Star program emphasizes the science necessary to understand those aspects of the space environment that affect life and society. The ultimate goal is to provide a predictive capability for the space weather that affects us. LWS missions have been formulated to answer specific science questions needed to understand the linkages among the interconnected systems that affect us. LWS investigations build on the fundamental knowledge gained by the STP missions and very directly address the needs of the Vision for Space Exploration and Objectives H and J of this Roadmap. Significant planning has already informed the crafting of a coordinated LWS program that includes strategic missions, targeted research and technology development, a series of space environment test bed flight opportunities, and partnerships with other agencies. Partnerships are crucial to LWS because the vast number of complex physical connections between and within the Sun-Earth system cannot be addressed by a few missions.

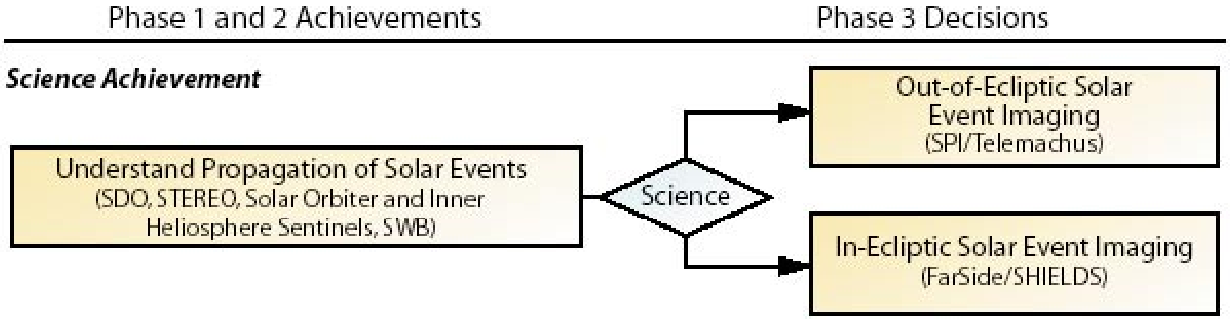
Two missions are currently in development or about to be announced: the Solar Dynamics Observatory (SDO) and the Radiation Belt Storm Probes (RBSP). The first LWS mission, SDO, is expected to launch in 2008 to understand the mechanisms of solar variability by measuring the solar interior, atmosphere, and EUV spectral irradiance. Two pairs of geospace storm probes complement SDO to measure the terrestrial environment at the same time. The first, RBSP, is planned for a 2011 launch; it will quantify the source, loss, and transport processes that generate Earth's radiation belts and cause them to decay. The second, the Ionosphere-Thermosphere Storm Probes (ITSP) also includes a separate imaging instrument.

Our Roadmap concurs with earlier recommendations that the next two LWS missions should complete the geospace storm probes by launching ITSP and explore radial evolution of structures with the Inner Heliosphere Sentinels (IHS) mission. The priority of the ITSP mission is driven by the very practical need to aid communications and navigation; ITSP will survey the global distribution of ionospheric and thermospheric densities, ionospheric irregularities, and geomagnetic disturbances as a function of varying solar and geospace conditions. The Exploration Initiative raises the priority of the IHS mission because hazardous space weather near Earth cannot be understood without it. In our realistic scenario for LWS these two missions are launched within a year of each other in 2015 and 2016. Our optimized scenario moves these missions up to increase the synergy with RBSP and SDO and to provide earlier information for the design of systems for the return to the Moon later in the decade. We also identify an important partnership opportunity with ESA's Solar Orbiter mission that complements the IHS in situ measurements and will provide solar observations from a different vantage point.

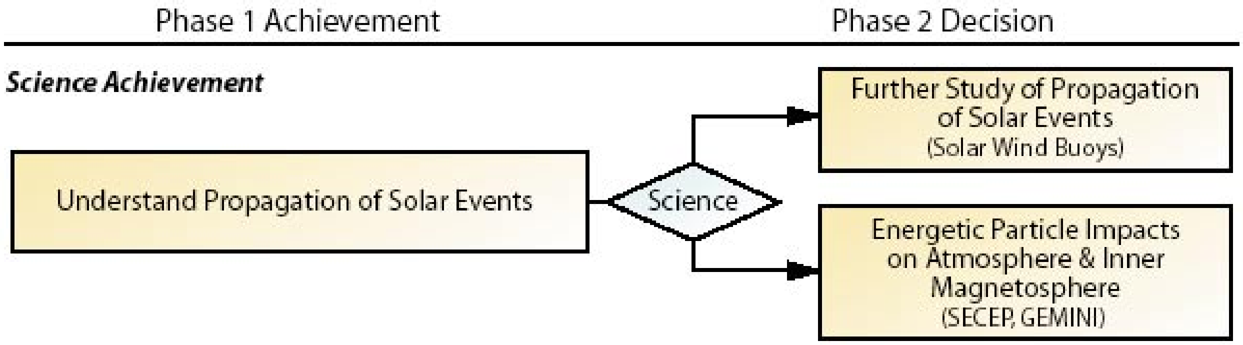
The next LWS missions in Phase 2 address understanding energetic particle production near the Sun with the Solar Energetic Particle Mission (SEPM) and better measurement of the solar wind and energetic particle inputs to geospace with Heliostorm or an L1 Mission. These two missions can be smaller in cost than typical strategic missions. The choice between Heliostorm and an L1 mission is complex. Heliostorm would use solar sails to hover another

hour or two upstream of the L1 point in the solar wind; this mission depends on a timely demonstration flight of solar sail technology. Measurement of incoming solar wind parameters is crucial to many other investigations, so depending on Heliostorm, the status of the Earth Science L1-Earth-Sun mission, the lifetime of existing assets, and partnerships with other agencies, we have reserved some small amount of resources for L1 observations.



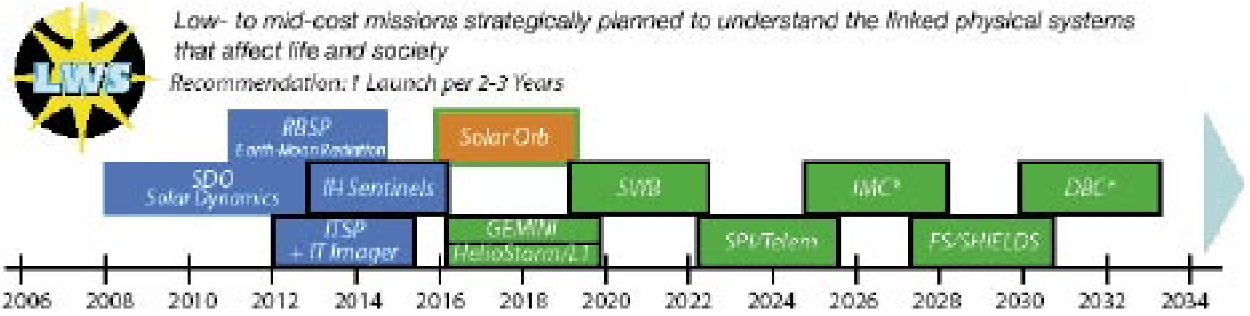


Subsequent Phase 2 mission selection in the LWS program depends on future developments in the program. Priorities will shift based on progress of the Exploration Initiative and what we learn from spacecraft launched in the next ten years. Our baseline program shows a choice preceding the 2022 launch of either Solar Weather Buoys (SWB) or a pair of smaller missions, SECEP and GEMINI. The SWB mission provides for about a dozen in situ observing platforms circling the Sun near 1 AU to fully understand how the solar wind and hazardous disturbances propagate outward from the Sun. SWB could become part of the early warning system needed to support safe and productive journeys to Mars and beyond. SECEP (Sun Earth Coupling by Energetic Particles) will explore the destruction of ozone by solar energetic particles; SECEP will measure the precipitating energetic particle influx as well as the descending odd nitrogen and odd hydrogen compounds and ozone densities. The Geospace Magnetosphere-Ionosphere Neutral Imagers (GEMINI) will provide the first 3-D observations of the global geospace dynamics in response to external solar drivers and internal coupling. The decision will be based on what is learned from STEREO, SDO, and the IHS missions on the one hand and MMS, RBSP, ITSP, and GEC on the other.



Later Phase 3 choices in the LWS program would select among high-latitude solar observations necessary to understand the solar cycle and interior, two or three solar imagers stationed far from Earth to provide global coverage, a constellation of spacecraft to understand the inner magnetosphere, and exploration of the day-side boundary layer where energy from the solar wind crosses the magnetopause. The prioritization of these missions depends on results from earlier investigations.

In our optimized scenario the ordering changes slightly as shown in the accompanying chart. The SEPM mission has moved to the STP timeline to improve its overlap with the IH Sentinels and Solar Orbiter.



The Explorer Program

The Explorer program is an indispensable element of the strategic Roadmap plan. Explorer missions fill important gaps in the proscribed program. These investigations target very focused science topics that augment, replace, or change strategic line missions. Highly competitive selection assures that the best strategic science of the day will be accomplished.

Missions currently in development, AIM, THEMIS, and IBEX, address important targeted outcomes. AIM (Aeronomy of Ice in the Mesosphere) will explain polar mesospheric clouds formation and variability as well their relationship to global change in the upper atmosphere and the response of the mesosphere to solar energy deposition. THEMIS (Time History of Events and Macroscale Interactions during Substorms) addresses the spatial and temporal development of magnetospheric substorms – one of the fundamental modes of the magnetosphere. IBEX, the Interstellar Boundary Explorer, will image the entire 3D configuration of the boundary region of our heliosphere, the vast (~100AU thick) region where the solar wind decelerates because of the pressure of the local interstellar plasma.

Because future selections are determined competitively in response to evolving strategic conditions, identification of specific future accomplishments at this time is impossible; however, numerous candidate missions have been identified (see the SSSC Roadmap web site for examples). The Explorer program has long been critical to maintaining the strength of the Sun-Earth Connection (now Sun-Solar System Connection) science program. It affords a regularly recurring opportunity to fly exciting new missions, selected by peer-review for the best science with a relatively short response time, utilizing state-of-the-art instrument development. In addition, the program provides the opportunity for instrument teams to participate in missions-of-opportunity provided by other agencies (DOD, etc.) or international programs. These missions-of-opportunity allow the space physics community to obtain the data necessary for specific strategic goals at a fraction of the cost of a dedicated mission. SEC Explorers have been responsible for major scientific achievements that have profoundly transformed our understanding of the Sun-Earth system. Some highlights include: visualization of the global dynamics of the geospace system by IMAGE, the first solar gamma ray imaging by RHESSI, discovery of coronal magnetic complexity by TRACE, discovery of trapped anomalous cosmic rays in Earth's magnetosphere by SAMPEX, and discovery of small-scale size parallel electric fields in the auroral acceleration region by FAST.

Explorers demonstrate the ability of the science community to respond rapidly to decision points, an important element in the strategy put forth in the Vision for Space Exploration initiative. Decision points can allow us to take advantage of a new scientific discovery that suggests the need for a new mission, new instrumentation development that provides the opportunity to address questions previously not accessible, or new technologies or analysis techniques that enable a less costly mission. Enabling rapid response of the SSSC community to such promising scientific opportunities ensures that science goals are met in the most cost and time effective manner. Results from such missions in turn may lead to development of new strategic missions or modifications of existing ones.

The Explorer program also plays a key role in developing and maintaining the scientific and engineering community needed to meet the objectives of the Roadmap, NASA, and the nation. Explorers provide hands-on training of instrumentalists, both scientists and engineers, thus enabling SSSC strategic missions, and directly contributing to the NASA Mission element: "to inspire the next generation of explorers". Managing cost-constrained missions such as Explorers requires specialized expertise.

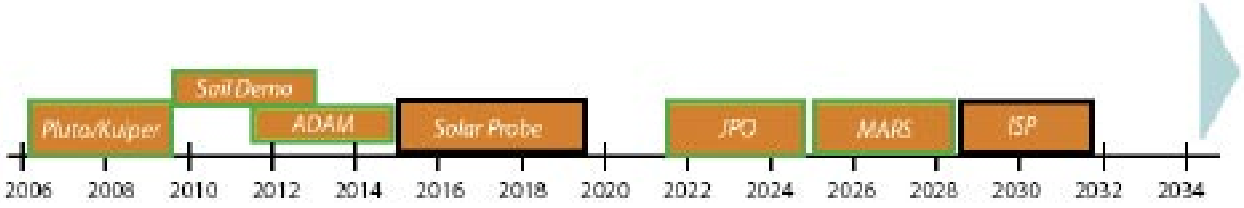
Flagship and Partnership Missions.

Urgent need for progress across a range of topic areas means that all of the SSSC resources cannot be applied to a single problem for an extended interval. Yet some major roadblocks to progress simply cannot be overcome with missions supportable in the strategic lines available to SSSC. Solar Probe in the immediate term, and Interstellar Probe and Stellar Imager in the more distant future are flagship missions that address such problems.

Solar Probe will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity. Solar Probe is the first flight into the Sun's corona, only 3 solar radii above the solar surface. Accurate predictions of events that disturb both Earth's human systems and affect deep space explorers require this understanding. Solar Probe can only be achieved with specific budget augmentation owing to the cost of ensuring its survival in an extreme environment. That said, the science and technology definition team currently investigating Solar Probe concludes that the mission is ready for a new start now. The decadal surveys and this roadmap identify Solar Probe as the highest priority flagship mission requiring an augmentation in funding.

Interstellar Probe will be the first mission to leave our heliosphere and directly sample and analyze the interstellar medium. It requires an advanced in-space propulsion system, such as a solar sail or nuclear electric propulsion, to reach the upstream interstellar medium at a distance of 200 AU within 15-20 years. The mission will be the first specifically designed to directly measure the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields. On its way, it will provide only the second opportunity after Voyager to directly observe the region of interaction between the solar wind and the interstellar medium, from the termination shock to the heliopause and beyond.

Stellar Imager (SI) is a challenging mission that will obtain the first direct resolved (1000 pixel) images of surface magnetic structures in stars like the Sun. The SI will develop and test a predictive dynamo model for the Sun and Sun-like stars using asteroseismology and by observing the patterns in surface magnetic fields throughout activity cycles on a large sample of Sun-like stars.



Partnerships provide another method to increase scientific return. Several missions have been identified in our plan that rely on partnerships with other parts of NASA, as well as other U.S. government and international agencies. Within NASA the solar sails demonstration project will lay the ground work for Heliostorm, Solar Polar Imager, and Insterstellar Probe. The Jupiter Polar Orbiter (JUNO) planned by the solar system exploration division has direct relevance to understanding planetary magnetospheres. Pluto-Kuiper will provide another opportunity to explore the outer heliosphere. Multiple opportunities for partnership have been identified as part of the International Living With a Star (ILWS) program. Partnership with ESA on Solar Orbiter should be explored in the very near term as a way to optimize and enhance the IHS, SEPM, and SHIELDS investigations.

Enabling information about the aeronomy and dynamics of the Mars atmosphere is required for aerocapture, entry, descent, and landing. The Mars Scout program provides an opportunity for a collaborative mission such as ADAM. Future missions to refine our knowledge of the interaction of the Martian environment with the Sun will also be collaborative. The SECEP mission, designed to understand ozone production, is a prime candidate for collaboration with our Earth Science colleagues. The L1-Earth-Sun mission to understand the Earth's radiation budget is another potential partnership with Earth Science.

The Sun-Solar System Connection Great Observatory – Evolving to Meet the Needs of the Vision for Exploration

The strategic objective addressed in this roadmap is intrinsically one of connections, of influences extending over vast distances to produce dramatic effects throughout the solar system. Because these connections are generally mediated extremely locally by largely invisible agents -- plasmas and magnetic fields -- the science of Sun-Solar System Connections must rely on multi-point in situ measurements and remote sensing measurements from platforms deliberately distributed throughout the solar system.

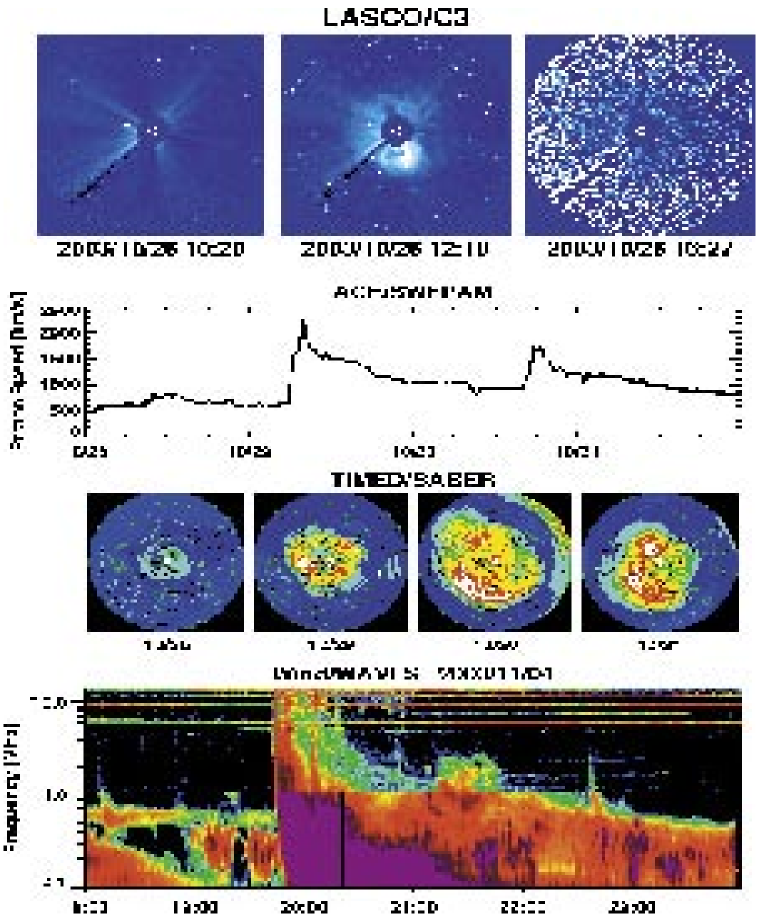
In recent years the power of simultaneous observations at multiple vantage points has been clearly demonstrated by what we now call the Sun-Solar System Connection "Great Observatory." Our Great Observatory is a fleet of solar, heliospheric, geospace, and planetary spacecraft working together to help understand solar activity and its interaction with geospace and other planetary systems throughout the solar system. Like NOAA's system for observing and predicting terrestrial weather, this observatory utilizes remote sensing, in situ measurements, data analysis, and models to provide physical understanding and predictive capability for space weather. The diverse measurements across distributed spatial scales are linked by a variety of improving models that serve to fill in the gaps in the observations and help predict tomorrow's space weather. The measurement capabilities include imaging the Sun; sensing in situ and remotely the disturbances in interplanetary space; and measuring particles, fields, and radiation in geospace, remotely and in situ. Continuing and evolving this distributed observatory to meet the needs of the Vision for Space Exploration is one of the community's highest priorities.

The very large "Halloween Solar Superstorms" described in the next section demonstrate the unique and powerful capability of the SSSC Great Observatory to view a system of systems. The effects of the solar storms from the Sun to the Earth and beyond were observed simultaneously in key regions and from specific vantages. It would not have been possible to link the consequences of these superstorms at Earth and Mars to the solar drivers without this collection of satellites and the human and computational resources to interpret the data. The power of the Great Observatory comes from the combination of multiple operational assets, focused and large-scale models, and associated data analysis. Many of the spacecraft are SSSC missions, but additional "observation posts" are provided by spacecraft such as Mars Global Surveyor (MGS), Cassini and the Hubble Space Telescope. For example, from MGS, we learned that the fluxes of solar energetic particle radiation caused by the superstorms were quite different at Mars and Earth. Our Great Observatory will need to evolve and expand to fully understand why these responses were different in order to meet the needs of the Vision for Space Exploration.

The Great Observatory is vital to explain fundamental physical processes at work throughout the complex, coupled system that is the Sun-Solar System. For example, magnetic reconnection between the interplanetary and terrestrail magnetic fields is the critical physical process determining the size of a geomagnetic storm. We have greatly increased our understanding of the role of this process by relating upstream solar wind measurements to in situ data near the small dayside reconnection site and to satellite-based images of the corresponding ionospheric airglow emissions. Similarly, using assets spread throughout the solar system, we have significantly improved our understanding of how solar activity modulates galactic cosmic rays. These discoveries about the foundational physics of our solar system were made possible by the combined resources of our Great Observatory: the coupled observations, the detailed data analysis, the extensive modeling efforts, and the knowledge of the underpinning theory. The resultant increase in knowledge improves our capability to predict the space environment that human and robotic explorers will experience and provides the foundation for future operational systems.

The Great Observatory will continue to evolve as new spacecraft join and older ones retire or change their operating modes. Missions both in their prime phase and in extended phases (supported by MO&DA) provide the variety of observation posts needed to study the Sun-Solar System Connections, as demonstrated by the 2003 Halloween Storms. A great strength of the Great Observatory fleet is that it is regularly evaluated and reviewed by the community to maximize the return on the agency investments. The Senior Review process determines which spacecraft are most necessary to meet the needs of the Sun-Solar System Connection program as defined by the community-developed Roadmap document. The criteria for continuation include relevance to the goals of the SSSC; impact of scientific results as evidenced by citations, press releases, etc.; spacecraft and instrument health; productivity and vitality of the science team (e.g., publishable research, training younger scientists, education and public outreach); promise of future impact and productivity (due to uniqueness of orbit and location, solar cycle phase, etc.); and broad accessibility and usability of the data.

New missions are selected for inclusion in the Great Observatory on the basis of their demonstrated ability to satisfy the same criteria discussed above for successful operating missions. The most important of these, from the perspective of strategic planning, is relevance. To meet the new needs of the Vision for Space Exploration as articulated in this road map, new missions will be needed in order to characterize, understand and predict the dynamic environmental conditions in space to maximize the safety and productivity of both human and robotic space explorers. At the same time, some existing missions are demonstrably vital and irreplaceable and will need to be maintained in order to meet the agency objectives.



The solar corona from SOHO before, during and after the fast halo coronal mass ejection (CME) on October 28, 2003 (top row). The image taken after the CME is seriously degraded by the energetic particles from the CME. This CME and the next one on October 29 resulted in record solar wind speeds as measured by the Advanced Composition Explorer near L1 (second row). Outgoing energy flux radiated by atmospheric nitric oxide at 5.3 micron as measured by TIMED increased drastically during the October 2003 storms (third row). The fastest CME of this period occurred on November 4; shortly thereafter it collided with a preceding CME and produced an intense radio signature detected by the Wind spacecraft (bottom). This signature was also detected by Ulysses and Cassini spacecraft from distant locations in the heliosphere.

Low Cost Access to Space

The Low Cost Access to Space (LCAS) program, whose key elements are the sounding rocket and balloon (suborbital) programs, is an essential component of NASA's space physics research program. LCAS provides cutting-edge new science discoveries utilizing state-of-the art instruments developed in a rapid turn-around responsive environment. These investigations, selected for the best science, serve two additional important purposes that can not be adequately addressed in other flight programs - training of experimental space physicists and engineers and the development of new instruments and instrumental approaches that are verified by actual spaceflight.

A recent example of this three-pronged role is the new understanding of auroral physics obtained in a series of rocket flights that developed both the state-of-the-art instrumentation and the pathfinding science discoveries that led to one of the first NASA small explorers, FAST. Figure 1 [to be provided in the final roadmap] shows how new, higher altitude rockets demonstrated the importance of microphysics and the need to make extremely high time resolution measurements to elucidate the acceleration processes. The 'top hat' plasma detectors, developed by for these rockets, are now common on space plasma missions, providing 3D, high time resolution electron and ion measurements. The rocket program provided the investigator (who became the FAST PI after a long association with the sounding rocket program) with the opportunity to develop project management skills and also provided the hand-on training of graduate students who became the instrument leads on the FAST satellite.

The other key component of LCAS are solar physics balloon missions, which have an outstanding record of scientific discoveries. For example, the LASCO coronagraph on board the SOHO spacecraft enabled systematic studies and arrival time predictions of coronal mass ejections aimed at Earth. The solar telescopes on the RHESSI Explorer mission used hard X-ray imaging spectroscopy, high-resolution nuclear gamma-ray line spectroscopy, and gamma-ray line flare imaging to observe the surprising energy release process in solar flares in greater detail than ever before. These achievements trace their heritage to balloon-borne instruments flown in the continental U.S. and in Antarctica.

An essential ingredient of the Vision for Exploration is a source of well-trained engineers and scientists who understand the demands of building and delivering spaceflight systems and hardware. The LCAS program provides an important, hands-on training ground for these human resources. Graduate students participate in the entire life cycle of a scientific space mission, from design and construction to flight, and data analysis. No other flight programs have time scales that fit that of a Ph.D. thesis. The rocket program alone has resulted in more than 350 Ph.D.s. In addition, a rocket or balloon project offers the chance for younger scientists to gain the project management skills necessary for larger projects such as Explorers or larger missions.

The combination of science, advanced instrument development, and training makes LCAS a critical path item for achieving NASA's national space science goals.

Scientific Research and Analysis

Achieving NASA's objectives requires a strong scientific and technical community to envision, develop, and deploy space missions, and to apply results from these missions for the benefit of society. Such a community currently exists within the United States. It is a world leader in space physics research and exhibits a diverse spectrum of sizes and specialties, based at universities, government facilities, and industrial labs.

The continued health of our research community, and thereby the ability to achieve NASA objectives, is dependent on many factors. These factors include a robust infrastructure of funding opportunities and resources to enable and maintain research initiatives; low-cost access to space for science, prototype development, and training; and a strong education and public outreach program to inspire and recruit new scientists and engineers.

The term infrastructure often refers to tangible assets, such as launch facilities, design and test facilities, or communications enabled by the Deep Space Network (DSN). These assets are a critical element of mission conception and execution. For example, long before major strategic missions are selected an extensive development program begins with first generation 'brass board' instrument concepts; this is followed by near-Earth testing exploiting Low Cost Access to Space (LCAS) opportunities. More mature concepts can be tested in Explorer-class missions. The IMAGE and STEREO mission concepts provide two excellent, current examples of this process.

However, in addition to investing in hard assets and flight missions, NASA must invest heavily in intellectual infrastructures through its programs of research grants: SSSC Supporting Research and Technology (SR&T), LWS Targeted Research and Technology (TR&T), SSSC Theory Program, Applied Information Systems Research (AISR), Guest Investigator (GI), etc.

NASA must also invest in analysis infrastructures that support computing and data analysis efforts. This is a critical element in the symbiotic advance of scientific understanding through mission design: scientists use data from existing missions to improve theories and models, which then suggest measurements for the next mission. Large-scale numerical calculations, such as the temporal evolution of fundamental equations in three dimensions, require massive supercomputers. Without a cutting edge computing infrastructure such computations are not possible. A strong computing structure is also needed to support data analysis and data assimilation, especially for increasingly large and complex data and modeling structures.

Fortunately, much of this supporting infrastructure is in place, as evidenced by examples ranging from computing architectures such as the Columbia supercomputing project, the Community Coordinated Modeling Center (CCMC), and NASA's Applied Information Systems Research Program, to strong EPO efforts and innovative programs such as NASA's Summer Faculty Fellowship program.

Nonetheless, our research community faces significant challenges in the immediate future, challenges that directly affect our ability to meet NASA's goals and support national objectives. The most significant challenges are those of training new researchers while maintaining the corporate memory of an experienced work force. NASA and its supporting contractors will soon have large portions of their work force eligible for retirement. By some estimates the services of as much as two-thirds of the most experienced scientists, technicians, and managers could be lost in the near future.

Support for a competitive number of research teams and investigators is of paramount importance to a healthy and robust scientific community. There is a real danger that the loss of 'critical mass' of research teams will begin to impinge on NASA's science and exploration goals. This is especially important for hardware development teams that have a high startup investment and have difficulty retaining technical expertise in uncertain funding cycles. NASA support for low-level hardware development is generally deemed insufficient to support truly innovative instrument development. Only the largest teams are perceived as capable of competition for hardware development. Paradoxically, the opposite can be said about modeling support, in that large-scale modeling efforts are not sufficiently funded for the tasks they face. In all cases, there must be a balance between large and small research efforts, as well as between pure and applied science.

Training opportunities at the graduate and undergraduate levels provide an introduction to all aspects of space missions, including instrument development, mission operations, data analysis, and theory and modeling. These often provide the first opportunities for students to experience the excitement of working in space physics and provide the primary means of recruiting these students into the space physics community. NASA programs that provide low-cost access to space such as rocket, balloon, and airplane missions, are especially useful for training in that students can contribute to mission design and operations while obtaining data in a timely fashion for analysis. This is particularly important in light of the long development times for complex missions that can exceed the normal tenure of graduate education.

Universities have traditionally provided the bulk of the training function, though innovative co-operative programs provide additional training opportunities in non-University settings. The needs for a robust training program are necessarily tightly linked to the health and number of graduate education programs and to the education and public outreach goals that attract students.

The challenges discussed above are not new. The community has previously considered these problems and voiced concerns and suggested mitigation efforts through community efforts such as the recent NRC Decadal Survey, which offered specific recommendations to improve education and public outreach efforts as well as strengthening the solar and space physics enterprise. These recommendations remain relevant and are endorsed by this Roadmap.

NASA's SR&T, TR&T, and GI programs are the traditional underpinning of most research teams and individual investigators and have been repeatedly recognized as such in community strategy documents. These content of these competitively selected programs continuously evolves to address new question with innovative new methods. They have provided a significant contribution to the vast body of knowledge needed for direction and implementation of NASA's initiatives. It is worse than foolish to collect expensive data and not provide adequate resources to exploit it. Unfortunately, recent budget pressures have forced delays in some of these programs and the potential impact of these delays must be acknowledged.

NASA SSSC also benefits from research funded by other agencies, such as NSF's CEDAR, GEM, and SHINE research programs and the Center for Integrated Space-Weather Modeling (CISM), an NSF Science and Technology Center. In light of the importance of non-NASA research to NASA's research infrastructure, inter-agency cooperative programs must be supported.

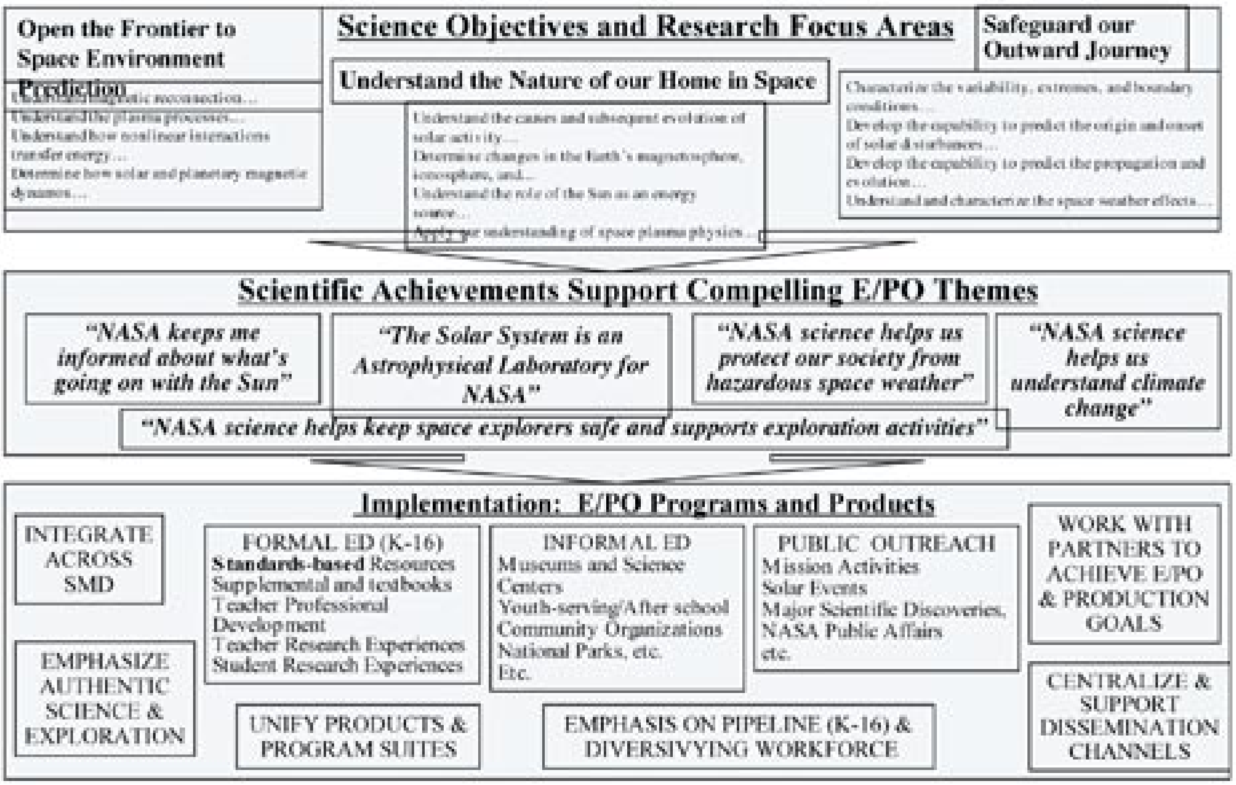
In summary, this Roadmap recommends that NASA pursue programs across a broad spectrum of size and duration and that a portion of the budget be reserved for small levels that might otherwise be overlooked. NASA should also seek to expand current partnerships with industry, universities, and other agencies. For example, current successful EPO efforts tend to focus on K-12 levels without adequate resources for the critical later years when college students are making career decisions and may need additional inspiration to continue toward a career in space physics.

Education and Public Outreach

Unique Education and Public Outreach (E/PO) opportunities associated with Sun-Solar System Connection Science

The top-level objectives, research focus areas and science achievements that constitute the Sun-Solar System Connection Strategic Roadmap for the next 30 years provide powerful opportunities for Education and Public Outreach from the SSSC scientific community (Chart A).

Chart A: Flow-down chart demonstrating that the Scientific Objectives and associated Research Focus Areas lead to E/PO themes that inform implementation

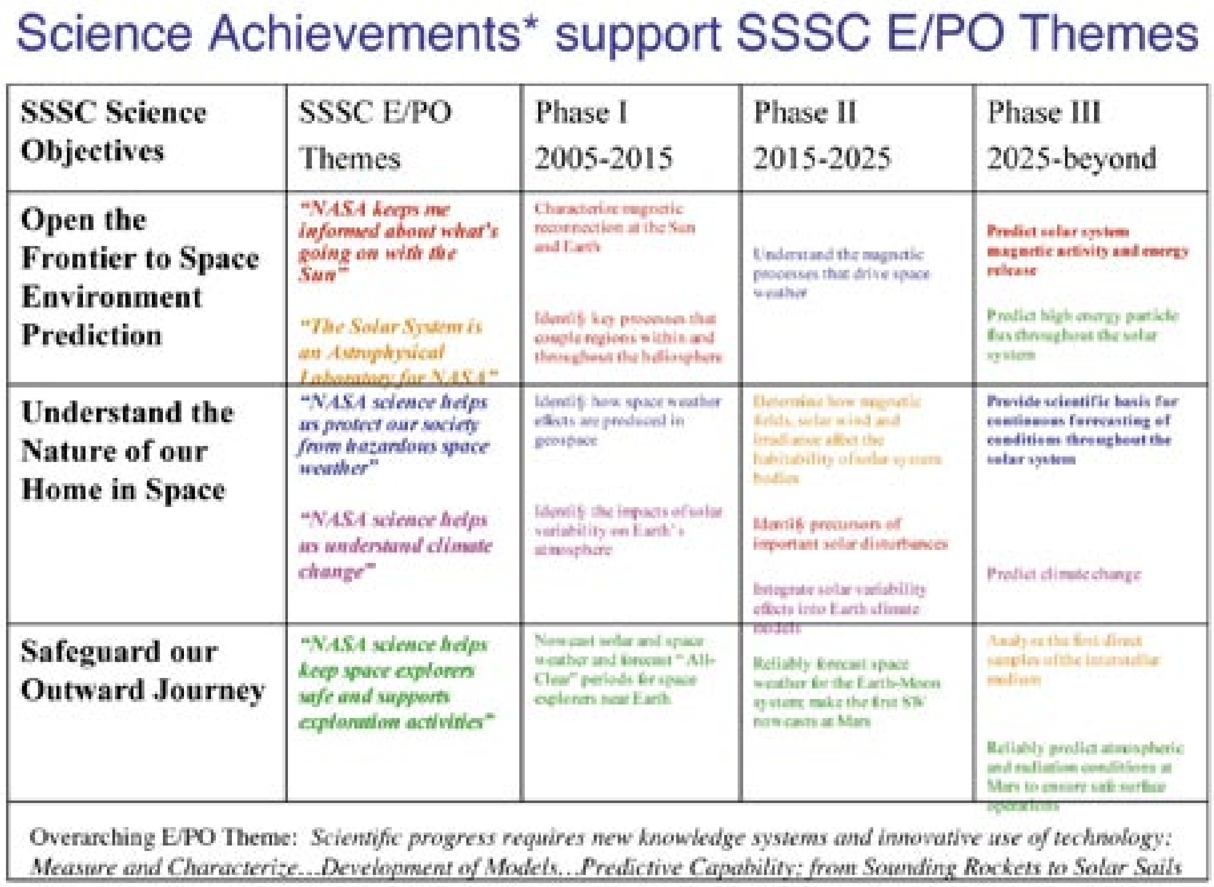


We recommend that E/PO activities stemming from the science achievements or milestones be developed to support the following five messages:

- **"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"**

These themes have been identified by the community because they are of high interest and relevance to the public and they span the range of scientific activity engaged in by the SSSC community, as indicated by the selected achievements articulated in this Roadmap and called out Table B. In addition, as Table C indicates, these themes map to the majority of the missions in the Roadmap.

Table B. Science Achievements from the Roadmap support SSSC E/PO Themes



Science Achievements* support SSSC E/PO Themes

SSSC Science Objectives	SSSC E/PO Themes	Phase I 2005-2015	Phase II 2015-2025	Phase III 2025-beyond
Open the Frontier to Space Environment Prediction	*"NASA keeps me informed about what's going on with the Sun"* *"The Solar System is an Astrophysical Laboratory for NASA"*	Characterize magnetic reconnection at the Sun and Earth Identify key processes that couple regions within and throughout the heliosphere	Understand the magnetic processes that drive space weather	**Predict solar system magnetic activity and energy release** Predict high energy particle flux throughout the solar system
Understand the Nature of our Home in Space	*"NASA science helps us protect our society from hazardous space weather"* *"NASA science helps us understand climate change"*	Identify how space weather effects are produced in geospace Identify the impacts of solar variability on Earth's atmosphere	Determine how magnetic fields, solar wind and irradiance affect the habitability of solar system bodies Identify precursors of important solar disturbances Integrate solar variability effects into Earth climate models	**Provide scientific basis for continuous forecasting of conditions throughout the solar system** Predict climate change
Safeguard our Outward Journey	*"NASA science helps keep space explorers safe and supports exploration activities"*	Nowcast solar and space weather and forecast "All-Clear" periods for space explorers near Earth	Reliably forecast space weather for the Earth-Moon system; make the first SW nowcasts at Mars	Analyze the first direct samples of the interstellar medium Reliably predict atmospheric and radiation conditions at Mars to ensure safe surface operations
Overarching E/PO Theme: *Scientific progress requires new knowledge systems and innovative use of technology: Measure and Characterize…Development of Models…Predictive Capability: from Sounding Rockets to Solar Sails*				

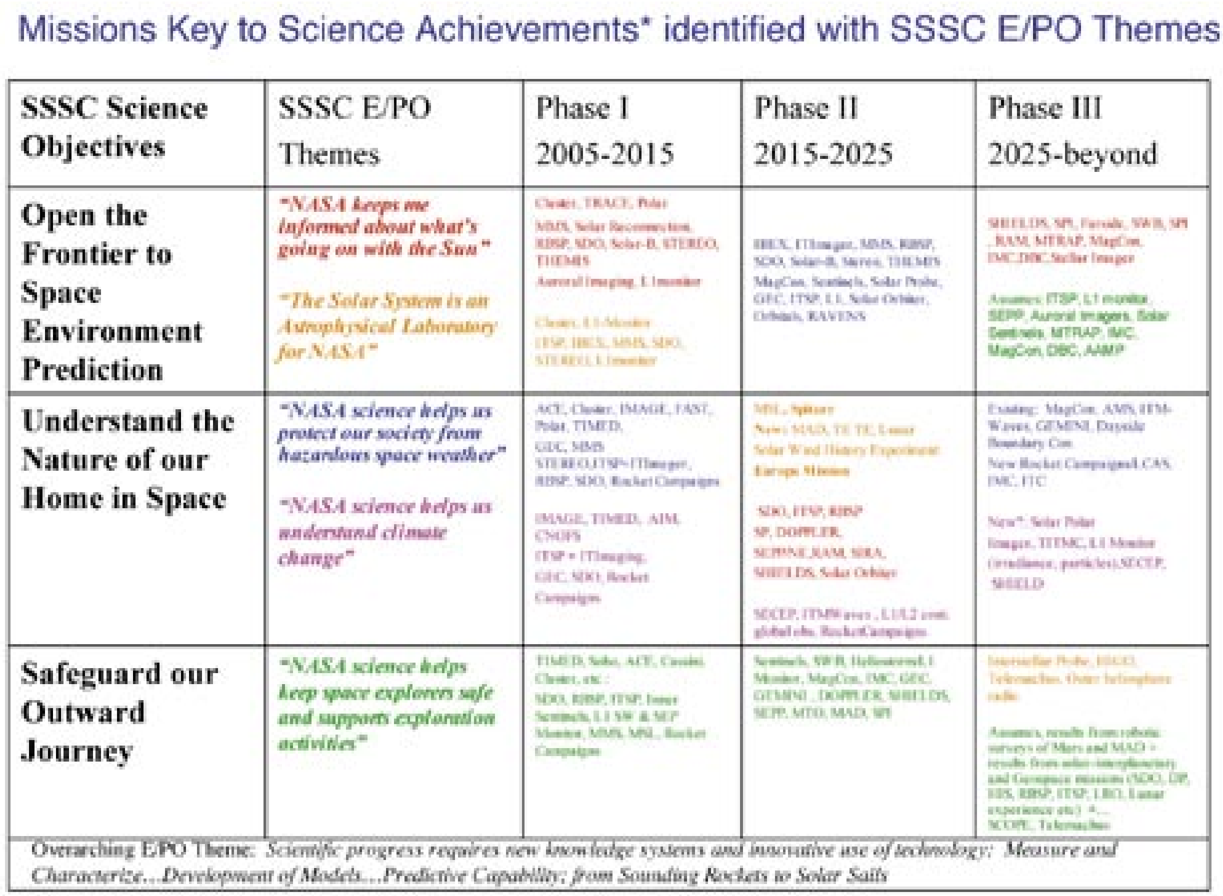
Expanded and Invigorated Education and Public Outreach will be Essential to the Achievement of the Exploration Vision

NASA's Strategic Objective for Education and Public Outreach is to: "Use NASA missions and other activities to inspire and motivate the nation's students and teachers, to engage and educate the public, and to advance the scientific and technological capabilities of the nation". The SSSC community emphasizes the connection between achievement of this strategic objective and the Exploration Vision. The development of the workforce needed to achieve NASA's Exploration Vision, including the scientific objectives described in this roadmap, will require that NASA's E/PO activities engage young people and capture their interest and passion. Furthermore, NASA's E/PO activities need to increase the capacity of our nation's education systems, both in (Formal: K-16) and out of school (Informal), to prepare students for scientific and engineering careers.

The E/PO themes articulated by the SSSC community indicate that their science and mission activities will be valuable hooks for E/PO. For example, the development of the capability to predict the variable radiation hazards and space weather conditions that our astronauts and robots will fly through and encounter on excursions to the Moon and Mars will be very exciting scientific work that the public will want to know about. New advances in the research of our Sun as an astrophysical laboratory will fuel the generation of authentic, science-rich education resources that will increase the capacity of the nation's education systems. Such new capabilities and discoveries can be connected to K-12 science education via appropriate national science education standards.

Developing the workforce to implement the Exploration Vision will require substantial focus on underrepresented communities. Recent estimates of the demographic makeup of the science and engineering workforce in the USA indicate that this population is overwhelmingly white. Population projections to 2025, howev-

Table C. SSSC recommended missions identified with SSSC E/PO Themes



Missions Key to Science Achievements* identified with SSSC E/PO Themes

SSSC Science Objectives	SSSC E/PO Themes	Phase I 2005-2015	Phase II 2015-2025	Phase III 2025-beyond
Open the Frontier to Space Environment Prediction	*"NASA keeps me informed about what's going on with the Sun"* *"The Solar System is an Astrophysical Laboratory for NASA"*	Cluster, TRACE, Polar MMS, Solar Reconnection, RBSP, SDO, Solar-B, STEREO, THEMIS Auroral Imaging, L1monitor Cluster, L1-Monitor ITSP, IBEX, MMS, SDO, STEREO, L1monitor	IBEX, ITImager, MMS, RBSP, SDO, Solar-B, Stereo, THEMIS MagCon, Sentinels, Solar Probe, GEC, ITSP, L1, Solar Orbiter, Orbitals, RAVENS	SHIELDS, SPI, Farside, SWB, SPI, RAM, MTRAP, MagCon, IMC, DBC, Stellar Imager Assumes: ITSP, L1 monitor, SEPP, Auroral imagers, Solar Sentinels, MTRAP, IMC, MagCon, DBC, AAMP
Understand the Nature of our Home in Space	*"NASA science helps us protect our society from hazardous space weather"* *"NASA science helps us understand climate change"*	ACE, Cluster, IMAGE, FAST, Polar, TIMED, GEC, MMS STEREO, ITSP+ITImager, RBSP, SDO, Rocket Campaigns IMAGE, TIMED, AIM, CNOFS ITSP + ITImaging, GEC, SDO, Rocket Campaigns	MSL, [illegible] New: MAD, [illegible], Lunar Solar Wind History Experiment Europa Mission SDO, ITSP, RBSP SP, DOPPLER, SCIPWNE, RAM, SIRA, SHIELDS, Solar Orbiter SECEP, ITMWaves, L1/L2 cont. global obs. RocketCampaigns	Existing: MagCon, AMS, ITM-Waves, GEMINI, Dayside Boundary Con. New Rocket Campaigns, CAS, IMC, ITC New*: Solar Polar Imager, ITTMC, L1 Monitor (irradiance, particles), SECEP, SHIELD
Safeguard our Outward Journey	*"NASA science helps keep space explorers safe and supports exploration activities"*	TIMED, Soho, ACE, Cassini, Cluster, etc.: SDO, RBSP, ITSP, Inner Sentinels, L1 SW & SEP Monitor, MMS, MSL, Rocket Campaigns	Sentinels, SWB, [illegible], L1 Monitor, MagCon, IMC, GEC, GEMINI, DOPPLER, SHIELDS, SEPP, MTO, MAD, SPI	Interstellar Probe, [illegible], Telemachus, Outer heliosphere radio Assumes, results from robotic surveys of Mars and MAD + results from solar-interplanetary and Geospace missions (SDO, DP, [illegible], RBSP, ITSP, LRO, Lunar experience etc.) + ... SCOPE, Telemachus
Overarching E/PO Theme: *Scientific progress requires new knowledge systems and innovative use of technology: Measure and Characterize...Development of Models...Predictive Capability; from Sounding Rockets to Solar Sails*				

er, indicate that the percentage of traditionally underrepresented communities will increase relative to the current majority group. Thus, successful E/PO efforts designed to increase the workforce to achieve the Exploration Vision will benefit substantially by targeting underrepresented groups.

An exciting example of E/PO targeted at underrepresented communities is NASA's Sun-Earth Connection Education Forum's (SECEF) Sun-Earth Day programming for 2005: Ancient Observatories: Timeless Knowledge. This broad program allowed NASA and Native American astrophysicists to share their research into the efforts of ancient cultures to understand the Sun, highlighting the importance of the Sun across the ages. Through programs such as these, SSSC scientists are conveying NASA's solar mission and research program activities to diverse audiences (both English and Spanish language materials have been disseminated).

Integrate messages and utilize best-practice strategies. Unification of NASA's scientific enterprise into the Science Mission Directorate presents opportunities for science education efforts in both the formal and informal arenas, as well as public outreach from across NASA, including the SSSC community. While each Division, mission, and individual scientist and engineer within NASA will have unique content and experiences to contribute to E/PO; integration into a single science directorate has the potential to be more effective in terms of message and approach. Moving forward, it won't matter if it's Space Science, Earth Science, Solar Physics or Biological Research, etc. – the 'brand' will be exciting, relevant NASA science. Furthermore, approaches to bring this content to the broadest possible audiences can take advantage of the best strategies of each of the former enterprises to create the strongest possible suites of products and programs.

SSSC Scientific Community is Vigorously

Engaged in E/PO; and E/PO Efforts Align Well with SMD's Education Goals and Priorities

SSSC E/PO programs currently encourage the scientific community to share the excitement of their discoveries with the public. The programs enhance the quality of science, mathematics, and technology education, and help create our 21st century scientific and technical workforce. Efforts align with NASA's Science Mission Directorate's education goals and priorities to inspire and motivate students to pursue careers in science, technology, engineering and mathematics (STEM), and to engage the public in shaping and sharing the experience of exploration and discovery. In addition, E/PO programs include the development of tools for evaluating quality and impact, in order to identify and disseminate best practices in E/PO.

E/PO activities are currently integrated throughout the SSSC flight missions and research programs that support the SSSC scientific community. As the result a significant fraction of the Sun-Solar system scientific community contributes to a broad public understanding of the science and is directly involved in education at the pre-college and college level. Graduate student participation in SSSC research programs are enhanced by the Graduate Student Research Program, a cooperative program between NASA Education and the Science Mission Directorate.

Centralized efforts such as the Sun-Earth Connection Education Forum (SECEF; a partnership between NASA Goddard Space Flight Center and the University of Berkeley) strive to establish strong and lasting partnerships between the SSSC science and formal and informal education communities. These centralized efforts seek to

facilitate the involvement of SSSC scientists in E/PO activities; to develop a national network to identify high-leverage education and outreach opportunities and to support long-term partnerships, to

provide ready access to the products of SSSC science education and outreach programs, and to

promote the participation of underserved and under-utilized groups in the SSSC science program by providing new opportunities for minorities and minority universities to compete for and participate in SSSC science missions, research, and education programs.

Vigorous E/PO programs also stem directly from various science programs within the SSSC community that effectively connect with and serve the E/PO needs of local communities.

Sun-Earth Day

Sun-Earth Day is an annual national program supported by SECEF. Since 2001 the SSSC community has shared the science of the Sun with educators, students, and the general public via informal learning centers, the Web, TV, and other media outlets through high-profile, well supported annual events. NASA science is connected to classrooms and museums in real time, and educational resources are disseminated via the Web and through NASA centers. In the context of an overarching emphasis on the Sun-Earth connection, a specific theme is created each year to continue to engage the public.

2001 - Having a Solar Blast

2002 - Celebrating the Spring Equinox

2003 - Live from the Aurora

2004 - Venus Transit

2005 - Ancient Observatories: Timeless Knowledge

2006 – Eclipse In a Different Light

Sun-Earth Day activities have broad reach. For example, the 2004 Sun-Earth Day website received 40 million hits in 40 hours. There were 1000 news reports on various TV channels, including 40 interviews with NASA scientists. More than 12,000 packets of educational materials were distributed to teachers, museums, and amateur astronomers in support of the 2004 Sun-Earth day programming.

As part of the 2005 Sun-Earth Day programming, in fall 2004, the Ancient Observatories: Timeless Knowledge website (sunearthday.nasa.gov) and the Traditions of the Sun website (www.traditionsofthesun.org) were launched to allow users to explore Chaco Canyon and other areas. Visited 500,000 times, these websites also highlight NASA research on the Sun and Native American solar practices within a larger historical and cultural context. Formal education programs engaged 75,000 teachers and 225,000 students, with all 10 NASA Centers hosting events. 100 NASA Explorer Schools also participated. Informal education efforts included programs hosted by 24 museums across the country; and training for Girl Scout Master Leaders who ultimately engaged some 10,000 girl scouts in Sun-Earth Day activities. The culminating event for Sun-Earth Day 2005 was a bilingual webcast live from Chichen Itza, which reached thousands of Hispanics and Native American participants.

The Solar and Heliospheric Observatory (SoHO)

The SoHO mission has a vigorous dissemination program of images for informal audiences and media outreach, regularly distributing near-real time images of the Sun (LASCO and EIT images) on the Web, Weekly to the American Museum of Natural History's AstroBulletin, and to a variety of media publishers, including National Geographic. Lenticulars (3-D Sun and space weather motion cards) are a very popular tool for engaging students and the general public. Over 180,000 Lenticulars have been distributed.

The SoHO mission also has two model collaborations that target educators and students: FiMS (Fellowships in Mathematics and Science), a partnership grant with the Pennsylvania Department of Education (in 3 school systems), is a strong example of the power of working directly with the local formal education system. SoHO educators and scientists work with their local teachers to increase content knowledge and support their ability to develop and implement inquiry-based lessons that are tied to state standards and the current curriculum. The Endeavour program, a collaboration between SoHO/NASA and 18 school systems, gives teams of students real-life NASA problems to research. Students are supported by teacher team leaders that have been exposed to the content and training through professional development.

Efforts to broaden the reach of SoHO's E/PO efforts, English and Spanish presentations on the Dynamic Sun CD, and building your own spectroscope poster have been very effective. In addition, SoHO is bringing the science and exploration of our Sun to the visually impaired through their ground-breaking "Touch the Sun" book.

E/PO Challenges and Recommendations

Strong opportunities exist to further extend the power of SSSC science and related mission activities to engage and inspire students in formal education settings, audiences at informal learning centers (Museums, Science Centers, etc.), and general public audiences across the nation via the press and other communication outlets. Table D presents a summary of challenges to effective E/PO, and articulates a series of recommendations to expand and enhance NASA's E/PO activities.

Table D. Challenges and recommendations to effective E/PO

Challenge	Recommendation
E/PO efforts vary widely across NASA. This is a disadvantage for both PIs and for audiences. PIs are often in the position of inventing their own E/PO programs, products and activities; and audiences need to constantly learn anew how to take advantage of these efforts.	Generate uniform, standards-based product lines with themed content for schools, museums, and science centers, and the press and media outlets. Invest production resources in development of core products that can be used appropriately by range of E/PO partners.
The formal, K-12 science education system needs strong connections with NASA's scientific, engineering and technological enterprises if it is going to play sufficient role in preparing the science and engineering workforce required to implement and achieve the Exploration Vision.	Correlate NASA's activities, enterprise-wide, with National Science Standards (e.g. National Science Education Standards of the NRC, and Benchmarks for Scientific Literacy, Project 2061) to develop a roadmap for infusing NASA resources into the formal K-12 system. Middle School presents a particular opportunity due to level of concepts mastered and more flexible curricula relative to High School. Develop templates for products, programs and professional development that, combined with the roadmap, effectively connect NASA's ongoing, authentic activities to classrooms for educators and learners.
Not enough undergraduates are opting for physics-based careers in particular and science and engineering careers in general. Extend focus from K-12 to K-16 to integrate cutting edge SSSC topics (in addition to other relevant NASA content) into undergraduate physics courses.	Broad dissemination is required to achieve impact. Requiring individual PIs and Missions to create their own dissemination channels can be burdensome and lessen impact. Expand existing, and develop new centrally supported channels for dissemination that mission and research-based E/PO can use to reach full range of audiences.
E/PO investments are not maximized due to lack of sustained support and dissemination.	Make sustained investment over time in Web-based dissemination of NASA materials: use of best-practice templates to create the materials will facilitate maintaining currency.
Outreach, not advertisement, is required in order to keep the public informed and engaged at the level required if NASA is to make progress towards achieving the Exploration Vision, particularly over the longer term.	Improve coordination between Public Affairs and Outreach and Education to conduct timely outreach that educates the public about NASA's activities and achievements, with appropriate emphasis on risk.

Provide a consistent and coherent set of education resources and professional development for formal and informal science education that derives from across the NASA enterprise. NASA needs to centralize its educational outreach to better support the capacity of education and public outreach partners to take advantage of SSSC science to engage their audiences. Educators in the K-12 arena require standards-based educational resources coupled with high-quality professional development offerings in order to tap ongoing NASA missions and take advantage of the constant stream of fresh, current, authentic scientific discovery and engineering activities. The creation of such resources (e.g. an informational website, an animated simulation, a set of data visualizations, a teaching guide, a set of standards-based curriculum activities, a professional development seminar, online course or videoconference, an interactive module, a poster, a set of opportunities to interact online and by video with scientists, engineers and technicians, an opportunity for student research, regular updates, etc.), coupled with appropriate professional development, will ensure that educators always have NASA in their tool-kit for effective science education. Partnership with professional organizations such as the National Science Teachers Association has proven effective for NASA, and should be expanded.

SSSC and other NASA missions and activities likewise provide wonderful springboards for learning in the informal setting. But educators and exhibit planners in the informal settings typically find each NASA opportunity requires a significant effort, simply to ramp up, since there is little consistency in what NASA produces, from center to center, from mission to mission. It would be tremendously helpful to know that for each NASA activity, there will be a standard set of resources (e.g., an informational website, an annotated simulation, a set of opportunities to interact online and by video conferencing with scientists, engineers and technicians, activities for out-of-school settings, regular updates, etc.) with common interfaces and similar formats that are fairly constant from activity to activity. Professional development is also required for informal educators; and current partnership efforts with professional organizations such as the Association of Science and Technology Centers have proven effective, and should be expanded.

It is understood that flexibility is essential - unique opportunities and requirements of each activity should be exploited, technologies will evolve, and evaluation inform revision – however, the ability to count on a standard package would likely reduce the learning curve for users and increase the usability and use of the resources. SECEF is a good example of the value of a coordinated national effort to develop and support E/PO activities; emphasis on standardized packages will strengthen this approach.

Promote and support the integration of the SSSC-related content more fully into standards-based K-12 science curricula. National science education standards provide direct opportunity to take advantage of SSSC science specifically and NASA science in general to improve science education on a national level. In this era of standards-based curriculum and high stakes testing, what gets taught is what is required in the curriculum and thus assessed on tests. State science curriculum standards generally map to these national standards, and thus tremendous opportunity exists for current SSSC science content to enrich and infuse these curricula. Influential science education standards such as the National Science Education Standards (National Research Council) and the 2061 Benchmarks for Science Literacy (AAAS) place substantial emphasis on SSSC related science concepts from the earliest grades through high school. The 2061 Benchmarks, for example, posit that in order to achieve scientific literacy students in grades K-2 master concepts such as ‘The Sun can be seen only in the daytime, but the moon can be seen sometimes in day and sometimes in night’ (4A/2); students in grades 3-5 further expand this understanding to ‘Stars are like the sun, some being smaller and some larger, but so far away they look like points of light’ (4A/5); in grades 6-8 they learn that ‘The Sun is a medium-sized star located near the edge of a disc-shaped galaxy of stars, ….’ (4A/1), and that ‘Telescopes reveal that the Sun has dark spots’ (10A/2); and by high school, that ‘Increasingly sophisticated technology is used to learn about the universe. Visual, radio, and X-ray telescopes collect information from across the entire spectrum of electromagnetic waves; ….' (4A/3). This progression of understanding highlights the role of understanding the Sun at many levels in developing scientific literacy. SSSC scientific research provides vivid, authentic examples to promote student mastery of these concepts.

The entire NASA enterprise could, for example, be mapped to the Benchmarks for Scientific Literacy, and/or the National Science Education Standards. The result would be a roadmap in itself for integrating NASA science and engineering activities into science curricula across the nation.

Extend focus to higher education in order to ensure adequate numbers of trained scientists and engineers for the SSSC community (and the rest of NASA) to achieve the Exploration Vision. The field of solar and space physics is in need of a national effort that relates the exciting applications in our field to specific curricular needs of introductory physics and astronomy (of which there are substantial enrollments at just about every college in the nation). And, in general, the excitement of space science should be utilized to entrain and encourage more undergraduates through physics, math and engineering programs at the university level. This will compliment current programs that are geared towards providing early research experiences (NSF's REU program, for example) which are very important for attracting non-traditional students into the workforce. Attention needs to be paid to how the space physics workforce is developed – where do students come from and why – in order to ensure sufficient numbers for a healthy scientific community able to achieve NASA's goals.

Enhance existing and create new distribution channels for E/PO efforts: products, programs, and messages. It is not realistic to make individual SSSC PIs responsible for building and/or sustaining their own dissemination relationships. This is not to say that individual PIs should not be encouraged to go into classrooms, make public presentations, appear in the media, etc. We recommend that NASA develop a spectrum of dissemination options that are supported and sustained centrally. In addition, NASA should support best practice use of World Wide Web for keeping products current and leveraging development efforts over time.

Emphasize unique learning opportunities that SSSC-related content can provide, in particular, focused on the visualization of data, essential for advancing science learning and the nation's scientific capacity. Expand efforts already underway to create high-production value media programs around the scientific assets of NASA, including Sun-Earth System. Fully digital space shows; large-format media projections, television productions, etc. are powerful vehicles for promoting public understanding of complex phenomena and teaching students of all ages critical skills for 21st century science involving collecting, analyzing, visualizing and communicating data and constructing, manipulating and interpreting scientific models and simulations. Increased efforts, taking advantage of partnerships with media production groups and distributers, will contribute substantially to achieving greater impact for E/PO programs.

Focus on innovative external partnerships to create programs that reach broadest range of public. Through leveraging partnerships with informal science learning centers (museums, planetaria, science centers, zoos); national parks; community groups (Girl Scouts), publishers and the media, SSSC science can be more widely disseminated by taking advantage of existing channels. For example, NASA has connected very effectively with the National Parks to support content on the aurora and noctilucent clouds for summer programs in Alaska to information about the Sun supporting educational programs at National Parks in the southwest. Programs such as these provide amplified impact by enhancing the capacity of established channels to engage, excite and educate the public around science and engineering content. New avenues should also be explored, for example, products developed with the gaming industry could engage the public, young and old, in the Exploration Vision.

To maximize impact of SSSC science for E/PO, efforts should take advantage of opportunities that exist at the intersection of the "formal" education and "informal" education sectors. Too often in education policy and strategy, schools and museums are viewed independent of one another with isolated objectives and strands of efforts. While there are clear differences between the two, substantial connections and overlaps exist. Many informal science education institutions already operate at the intersection of the two sectors – offering substantive professional development for teachers, providing learning experiences and field trips for classes, delivering afterschool services and developing and distributing curriculum materials and resources. A key strength of these institutions is local knowledge. The formal education landscape is highly variable, and this local knowledge is key to successful connections between science and engineering-rich agencies, such as NASA, and science and engineering education efforts in the formal setting. NASA Education and Public Outreach should take advantage of the existing connections and overlap between the formal and informal education arenas.

Develop better coordination with Public Affairs is required to maximize E/PO efforts. Consistent messaging is essential to effective communication, and effective communication is key to strong E/PO. More substantial overlap should occur between Public Outreach and Public Affairs (PA). The activities are distinct: Public Outreach from SSSC covers a broad range of topics and targets the public directly, and Public Affairs communicates specifically new and current discoveries to the media for dissemination to the public. However the visual and editorial resources required by both are very similar, and thus we recommend that Public Affairs team up with the E/PO group early in order to develop the same core messages and visual assets. This will facilitate getting better media coverage of scientific results and publicizing exciting E/PO events. It will also strengthen education programs because they can also take advantage of the visual and editorial assets developed for Public Affairs and Public Outreach.

E/PO efforts need to focus on outreach, not advertisement. While it is important to raise public awareness of SSSC missions and activities, it is essential to invest E/PO funds in products and programs that go beyond advertisement and truly engage and inform. Thus we strongly discourage the use of E/PO funds for lanyards, pins, etc., that are solely designed to advertise a mission.

Educate the public via outreach through informal and formal channels about the risks inherent in the exploration of space. As NASA pursues Return to Flight and the Exploration Vision, it will be very important for the public to be aware of the risks associated with these activities. In the event that accidents occur that result in tragic loss of life or even setbacks in mission activities, the public will be best able to respond appropriately if they were aware up front of the risks involved.

Shift in Management and Implementation of SMD E/PO Efforts

It can't be stressed too highly the impact NASA has had through commitment of substantial funds for E/PO efforts over the past decade or so. In addition, the value of having the scientific community intimately involved in the development and implementation of E/PO products and programs can't be over emphasized. Thus we strongly advocate maintaining the established commitment of funds for E/PO.

At the smaller scale NASA should continue to use the model of supplements for which individual PIs can apply to support E/PO activities that stem from their scientific research and mission activities. Rather than rely on the PIs to invent their own E/PO activities, however, we recommend that the allocation of E/PO funds be linked to a portfolio of approved E/PO program and product templates from which the PI can select; and require dissemination activities through one or more of NASA's approved and maintained channels as appropriate. In addition, E/PO activities in the near term should map to one of the 5 themes articulated above. Themes will be modified and new themes developed as part of future SSSC strategic planning activities.

At the mission scale – we recommend that each mission select from a range of approved product and program suites, and identify E/PO theme(s) that their activities map to. In addition, mission PIs should be required to utilize appropriate dissemination strategies and channels. While individual PIs with particular interest and commitment to developing new types of E/PO should be encouraged and supported, as a general case, do not burden PIs with inventing E/PO programs as they are putting their mission proposals together. In essence, science proposals funded by the Science Mission Directorate should be selected on the basis of their scientific merit. Funding for E/PO derived from these scientific missions and programs should then be set at agency approved levels. The E/PO funds should then be allocated to selections from the portfolio of approved program and product templates and/or competed, if existing program and product templates are not sufficient.

The portfolio of approved product and program suites should be developed using existing successful E/PO efforts as models, as well as taking advantage of best practices in formal and informal education. It is very important that these be developed through collaboration between the Science Directorate and the Office of Education. It also very important that PIs funded by the Science Directorate play a significant role in the choice of allocation of their E/PO funds to the products and program suites approved by the Science Mission Directorate and developed in collaboration with the Office of Education.

Sustained public engagement with, and support of, the Exploration Vision will be essential to NASA's success over the next 30 years. The SSSC community is excited to collaborate in the E/PO efforts designed to bring the public along on the Vision for Space Exploration. Progress in SSSC science will not only enable the safe and productive transit and landing of human and robotic explorers on other planets and planetary bodies in our Solar System; but will also advance our capacity to mitigate hazardous space weather impacts and global climate change at Earth; and, continue to open new frontiers of scientific discovery about the Earth, the Solar System and the Universe.

Chapter 3

Sun-Solar System Connection: The Missions

Candidate Mission Reference List

SSSC utilizes several mission resources. Strategic fundamental science missions are executed as Solar-Terrestrial Probes (STP), The Living With A Star (LWS) mission line is also strategic, dedicated to research on understanding and mitigating effects of space weather. Flagship Missions (FLG) are grand challenge missions that require separate new starts outside the STP or LWS programs. Explorer (EXP) missions are smaller than the others and present opportunities for open competition to address scientific investigations that are relevant and timely. Some missions receive external (EXT) funding, either from other parts of NASA, other agencies, or other national entities. Below, we list & define acronyms for SSSC mission candidates, and categorize them, to the degree possible at this time, according to these mission lines. Missions labeled P4 have been deferred into Phase 4 - past the end of this roadmap.

Acronym	Mission Name	Program Line
AAMP	Auroral Acceleration Multi-Probe	STP
ADAM	Aeronomy and Dynamics At Mars	EXT
AIM	Aeronomy of Ice in the Mesosphere	EXP
DBC	Dayside Boundary Constellation	LWS
DOPPLER	Doppler	STP
FS	Far-Side Sentinels	LWS
GEC	Geospace Electrodynamic Connections	STP
GEMINI	GEospace Magnetosphere-Ionosphere Neutral Imagers	LWS
HS	Heliostorm	LWS
HIGO	Heliospheric Imager and Galactic Onserver	STP
IE	Io Electrodynamics	P4
IHS	Inner Heliospheric Sentinels	LWS
IBEX	Interstellar Boundary Explorer	EXP
IMC	Inner Magnetospheric Constellation	LWS
ISP	Interstellar Probe	FLG
ITMC	Ionosphere-Thermosphere-Mesosphere Coupler	STP
ITMW	Ionosphere-Thermosphere-Mesosphere Waves	STP
ITSP	Ionosphere-Thermosphere Storm Probes plus Imager	LWS

Acronym	Mission Name	Program Line
JPO/JUNO	Jupiter Polar Orbiter	EXT
L1SCE	L1 Solar-Climate Explorer	EXT
L1M	L1 Mission	EXT
LRO	Lunar Reconnaissance Orbiter	EXT
MARS	Mars Atmospheric Reconnaissance Survey	EXT
MC	Magnetospheric Constellation	STP
MSL	Mars Science Laboratory	EXT
MMS	Magnetospheric MultiScale	STP
MTRAP	Magnetic TRAnsition Region Probe	P4
NO	Neptune Orbiter	EXT
PK	Pluto/Kuiper	TBD
RAM	Reconnection and Microscale Probe	STP
RBSP	Radiation Belt Storm Probes	LWS
SCOPE	Solar Connection Observatory for Planetary Environments	P4
SECEP	Sun-Earth Coupling by Energetic Particles	LWS
SEPM	Solar Energetic Particles Mission	LWS
SHIELDS	Solar Heliospheric & Interplanetary Environment Lookout for Deep Space	LWS
SI	Stellar Imager	FLG
SDO	Solar Dynamics Observatory	LWS
SP	Solar Probe	FLG
SSD	Solar Sail Demo	EXT
SPI	Solar Polar Imager	LWS
STEREO	Solar-TEresstrial RElations Observatory	STEREO
SWB	Solar Wind Buoys	LWS
TE	Titan Explorer	P4
TLM	Telemachus	LWS
THEMIS	Time History of Events and Macroscale Interactions during Substorms	EXP
TWINS	Two Wide-Angle Imaging Neutral Atom Spectrometers	MOO
VAP	Venus Aeronomy Probe	P4

Near-Term Missions:

Aeronomy of Ice in the Mesosphere (AIM)

The primary goal of the Aeronomy of Ice in the Mesosphere (AIM) mission is to resolve why Polar Mesospheric Clouds (PMCs) form and why they vary. In addition, AIM will determine the mesospheric response to solar energy deposition and coupling among atmospheric regions.

AIM will examine the relative contributions of solar and anthropogenic effects that cause change in the upper atmosphere and it will examine long term change. AIM will also make key observations of solar energetic particle induced effects on upper atmospheric composition, in particular of odd-nitrogen compounds and ozone.

AIM is a top priority in view of current heightened scientific and public interest in PMCs and the immediate need to understand how the upper atmosphere responds to variable solar energy inputs such as solar storm events.

Geospace Electrodynamic Connections (GEC)

GEC will determine the fundamental processes coupling the ionosphere and magnetosphere. The upper atmosphere is the final destination of the chains of fields, particles and energy that start at the Sun, transit the heliosphere, and are modified by the magnetosphere and upper atmosphere. To transform and inform our understanding of this fundamental question a formation of 3-4 spacecraft must be sent to resolve the spatial structures and time variations, repeatedly and systematically, into the depths of the atmosphere to this transition region: 130 to 180 km. The spacecraft will have complete instrument packages that measure both the magnetosphere energy/momentum inputs at high latitudes and the atmosphere-ionosphere responses.

GEC will transform our understanding of the chain of events from the sun to the atmosphere by providing for the first time, comprehensive, collocated, simultaneous atmospheric measurements, the models with which to interpret them, and context setting measurements of the Sun, heliosphere, and magnetosphere. These questions cannot be addressed without actually making the in situ observations. GEC does this using proven technologies, such as formation flying, to unravel the spatial and temporal coupling of the transition region phenomena in a reconfigurable observatory.

GEC will transform our understanding of fundamental processes in the upper atmosphere. It will also enable practical applications relevant to Protecting our Home in Space, and the Outward Journey. Dipping the spacecraft from the collisionless to the collisional regime provides an analog for aerobraking and aerocapture operations at Mars.

Under current NASA funding guidelines, GEC is planned for launch in 2017, with a two -year prime mission lifetime. It is possible that GEC will overlap with the ITSP mission, with corresponding synergies that are discussed under the ITSP description. However, each mission provides unique measurements and insights, and neither one should be delayed for the sake of overlap.

Inner Heliospheric Sentinels

The four Inner Heliospheric Sentinel spacecraft flying in various formations will detect how structures change in space and time during the transit. IHS investigations will discover, model, and understand the connection between solar phenomena and geospace disturbances.

Interactions in interplanetary space make the linkage between point sampled 1 AU measurements and their solar sources difficult or impossible. IHS science is important to understanding which disturbance will be geoeffective and for developing predictive capability. The interactions relate to particle acceleration, the drivers of space weather and characterization of the extreme conditions near Earth and throughout the heliosphere. Most space weather evolves as it passes through the inner heliosphere. Understanding this influential region of space is required for safe and productive use of space.IHS should fly in conjunction with SDO and will contribute to understanding gained by the Geospace Storm Probe missions. In an extended mission they will provide essential information about material that eventually reaches SWB or other spacecraft at 1 AU and beyond

Interstellar Boundary Explorer

IBEX will remotely sense the global interaction between the solar wind and the interstellar medium, complementing the single point direct measurements now being obtained by Voyager

IBEX places a spinning, sun-pointing spacecraft in a highly elliptical equatorial orbit with an apogee of 35 RE so that it spends most of its time outside the magnetosphere. The payload includes tightly integrated high and low energy single-pixel neutral atom cameras of very high sensitivity needed to observe the relatively weak but telltale fluxes emitted from the heliospheric boundary region. During the course of a year, the cameras will sweep out the entire sky to form a complete map of the interstellar boundary.IBEX began development in May 2005 for launch in 2008, which may be in time for correlative operations with Voyager. Voyager 1 recently passed through the solar wind termination shock and into the heliosheath region.

Ionosphere-Thermosphere Storm Probes (ITSP)

The ITSP mission investigates the spatial and temporal variability of the ionosphere at mid-latitudes. ITSP combines imaging and in-situ measurements of the I-T system, and physics based models to inform our understanding. Two LEO satellites, in different local time orbits are required to determine how electric fields, thermospheric winds, and composition vary with local time, and generate dramatic changes of electron density in the main ionospheric layer during storms. An IT imager will fly as a Mission Of Opportunity on another spacecraft to support the LEO measurements by observing global composition changes.

To meet the needs of tomorrow and to go beyond an understanding of the climatalogical behavior of the ionosphere we need to make simultaneous, collocated comprehensive measurements of the global behavior of the IT system. The scientific questions addressed by ITSP have direct relevance to the Vision for Space Exploration and to the needs of society. When we prepare to go to Mars, we must be able to land with precision and communicate with assurance. ITSP informs the design of systems for precision navigation and communication without requiring that we build at Mars the equivalent of the Earth's network of ionospheric observatories. ITSP will allow us to characterize, understand, and predict plasma density gradients that degrade augmented GPS systems, and lead to the mid-latitude ionospheric irregularities which produce scintillation of radio signals.

ITSP was designed to overlap with the SDO and RBSP missions flying in the 2008-2015 timeframe. The current schedule places ITSP at solar maximum and in the declining phase of the solar cycle – times when the ionosphere is both enhanced and disturbed. ITSP will fly during the phase of the solar cycle that is the most stressing both from the standpoint of technical systems and models. ITSP results will be available in time to guide the concept of operations for precision landing on Mars and communications (surface-surface and surface-space).

Under current NASA funding guidelines, GEC would launch in a similar timeframe (2017 with a two year lifetime) to ITSP, so the missions would potentially overlap. The GEC mission is focused on very different scientific objectives in a different altitude and latitude regime from ITSP. Each mission provides scientific insight that is unique. An overlap in the mission timeframes provides synergistic opportunities because GEC measures the high latitude drivers that contribute to the middle and low latitude response measured by ITSP. However, because of the urgency of each of these missions, each should fly as early as funding permits, regardless of any loss of overlap with the other.

L1-Earth-Sun

The L1 Earth-Sun mission will provide the first comprehensive and continuous observation of the Earth's whole day side atmosphere, together with measurements of the contributions to the critical solar spectral irradiance that drive the upper atmosphere.

The Earth-viewing portion of the mission consists of a combination of spectrometers in an extended wavelength range (58 nm to 2.4 mm), with high spatial resolution on the entire sunlit Earth disk. The solar portion of the mission consists of a UV/soft x-ray irradiance spectrometer, an imaging bolometer, and a UV/EUV imaging spectrograph to explain the irradiance phenomena that affect Earth's atmosphere by providing identification and realistic assessment of the contributions of evolving solar activity features to total spectral irradiance. The mission also includes magnetometer capable of high time resolution measurement of magnetic field fluctuations and shocks, and two energetic particle analyzers capable of measuring energy resolved charged particle spectra.

By observing simultaneously the Earth, the Sun, and the solar wind, the L1-Earth-Sun mission will enable the first detailed exploration of the couplings within the Earth-Sun system. It fulfills a fundamental and critical need in the S3C Strategic plan with cross-cutting synergistic objectives relevant to understanding fundamental processes which influence Earth's climate as well as strong relevance to the Vision for Exploration by improving our understanding necessary for solar activity prediction and its impact on the Earth.

The L1-Earth-Sun mission should fly in the early part of Phase 2 in order to maximize overlap with SDO and GEC. SDO provides complimentary information regarding solar energy deposition while GEC provides in situ observations of the Earth's upper atmosphere that strongly compliment and partially validate the L1-Earth-Sun remote observations. Flying L1-Earth-Sun in early Phase 2 also permits the timely replacement of key existing assets at L1.

L1-Mission

In situ observations from the Earth-Sun L1 point are essential to understanding geospace and provide about one hour of warning of disturbances traveling toward Earth in the solar wind. The essential quantities are plasma, particles and fields measurements. Enhancing capabilities include radio sensing, composition and high-energy particle detection, and even solar observations, though these can often be accomplished from other vantage points.

Without upstream information the state of the magnetosphere cannot be understood. Models of propagation in the inner heliosphere need a reference at 1 AU against which to test their models. Spatial variations in structures around L1 is not well understood. Data from L1 is needed at at all times to provide adequate warning for many operational users in addition to NASA scientists.

The timing of this mission depends upon future assets launched by NASA and other agencies and the continued functioning of existing spacecraft. The existing Great Observatory provides L1 observations and some future mission must do the same. Partnerships may be the preferred method for satisfying the need for observations from L1. The possible flight of Heliostorm, an Earth Science L1 mission, or collaboration with the IH Sentinels or SWB missions may provide additional options.

Lunar Reconnaissance Orbiter

LRO is conceived as an advance exploration of the moon to prepare for a human return there with longer duration visits than previously achieved. It will contain an investigation for monitoring the radiation environment that will be encountered by astronaut-explorers.

LRO measurements will provide important information about the practical consequences of cosmic ray, solar energetic particles, and magnetotail particle acceleration for long term human presence on the moon.

LRO is needed in the near term to refresh and update our knowledge of the moon and its environments. The radiation environment in particular needs to be better documented, particularly for storm events in which potentially lethal radiation levels are expected.

Magnetospheric Multi-Scale

MMS is the first mission designed from the bottom up to separate space from time at the fine scales needed to understand the reconnection diffusion region. MMS will determine the fundamental physical properties of magnetic reconnection.

MMS is a four spacecraft mission designed to study magnetic reconnection, charged particle acceleration, and turbulence (cross-scale coupling) in key boundary regions of the Earth's magnetosphere. The primary goal of the mission is to use high time resolution, in situ plasma and fields measurements to determine the micro-scale processes in the exceedingly small (perhaps <100 km thick) diffusion region, where the electrons in a plasma become decoupled from the magnetic field, and the field reconnects. The close spacecraft spacing will also enable exploration of the cross-scale coupling of plasma turbulence in the Earth's magnetosheath, at the magnetopause, and in the magnetotail. Finally, charged particle acceleration processes associated with magnetic reconnection, turbulence, and electric fields in the outer magnetosphere will be determined using direct measure of the plasma and waves that cause the acceleration. MMS will resolve rapidly moving narrow structures, to yield a full understanding of the factors controlling the rate of reconnection. This will enable a predictive science of space weather, which in turn will allow us to understand energetic processes throughout the solar system.

MMS has recently entered development and its results will be needed as soon as possible as a basis for the predictive models of space weather needed to undertake heliospheric weather prediction in support of Exploration. Magnetic reconnection is a primary source of energy release and particle acceleration in plasmas. No mission has ever been properly instrumented and configured to measure the small-scale features of reconnection in space. Thus, we know little about this fundamental process that drives much of the activity on the Sun, near Earth, and throughout the Solar System.

Pluto/Kuiper

New Horizons is designed to help us understand worlds at the edge of our solar system by making the first reconnaissance of Pluto and Charon - a "double planet" and the last planet in our solar system to be visited by spacecraft. The mission would then visit one or more objects in the Kuiper Belt region beyond Neptune.

New Horizons is scheduled to launch in January 2006, swing past Jupiter for a gravity boost and scientific studies in February or March 2007, and reach Pluto and its moon, Charon, in July 2015. Then, as part of an extended mission, the spacecraft would head deeper into the Kuiper Belt to study one or more of the icy mini-worlds in that vast region, at least a billion miles beyond Neptune's orbit. Sending a spacecraft on this long journey could help us answer basic questions about the surface properties, geology, interior makeup and atmospheres on these bodies.

The relation to the Sun-Solar System Connection presented by New Horizons is the opportunity to obtain in-situ measurements of the solar wind interaction with Pluto. Ionization of Pluto's escaping atmosphere suggests the interaction with the solar wind will be similar to that of a comet. In contrast to cometary interactions that have been measured relatively close to the Sun, the weak magnetic field and tenuous density of the solar wind in the outer heliosphere imply that the interaction with Pluto's atmosphere will include significant kinetic effects and be highly asymmetric. Understanding these interactions will expand our knowledge of the astrophysical processes affecting these bodies and that part of the solar system. The SWAP instrument on New Horizons will make measurements of the solar wind deceleration and deflection due to the interaction with Pluto. The PEPPSI instrument will measure energetic particles produced in the interaction region. SWAP will also measure solar wind conditions at large distances from the Sun and measure the effects of pickup protons from the interstellar medium in the distant heliosphere.

Radiation Belt Storm Probes (RBSP)

RBSP will focus on the variability and extremes of energetic radiation belt ions and electrons by identifying and evaluating their acceleration processes and transport mechanisms and identifying and characterizing their sources and losses. The RBSP instruments provide comprehensive measurements of the particle phase space densities plus the local AC/DC magnetic and electric fields in the inner magnetosphere where the intense radiation belts reside.

RBSP consist of two small satellites in "chasing" elliptical orbits with low perigees, ~ 5.5 RE , geocentric, apogees and slightly different orbital periods. The different periods generate an orbital evolution that provides both variable radial separations in the same local time frame and local time separations at a range of constant radial distances to separate space-time effects in the radial transport and azimuthal drifts of the particles.

RBSP provides one link in the chain of evidence that tracks the Geospace response to solar and interplanetary sources and variability. ACE, TWINS, SDO, MMS, ITSP and IHSentinels will fill in many of the other links. Flying together, they would provide a nearly complete picture of geospace, its the external environment and the its responses to solar variability and evolving interplanetary plasma and field structures. RBSP is important to objectives H and J because it provides the observations needed to characterize and develop models of the near Earth space weather. Its data will form the basis for specification of the near Earth radiation environment and its variability on a time scale that meets the needs of the Exploration Visions early operations near Earth.

RBSP data will provide a measure of the magnetospheric energy inputs to the ionosphere and atmosphere important to space station and crew vehicle communications, reentry and atmospheric drag induced orbit variations. In addition, RBSP observations will also provide new knowledge on the dynamics and extremes of the radiation belts that are important to all technological systems that fly in and through geospace. This includes many platforms that are important to life and society as we rely ever more on space platforms to link us together through communications, to provide Earth resource data and to provide entertainment streams. It is also very important that we understand the space weather in geospace as we resume human exploration because it can impact the many US space assets that play a role in our national security and support human exploration.

Solar-B

Solar-B will reveal the mechanisms of solar variability and study the origins of space weather and global change. NASA is a 1/3 partner with the Japanese space agency (JAXA) on this mission to investigate the detailed interactions between the Sun's magnetic field and the corona. High resolution observations of active region on the photosphere together with an X-ray telescope and imaging spectrograph will help understand the creation and destruction of magnetic fields, variations in solar luminosity, generation of UV and X-radiation, and the dynamics of the solar atmosphere.

Solar B addresses most of the expected achievements in Phase 1: reconnection, the mechanisms of particle acceleration near the Sun, the origins of solar disturbances, understanding of the sources of irradiance variations, causes of the extremes in the local environment, and prediction of space weather. Many Phase 2 topics are also covered.

Solar B complements SDO, STEREO, and SOHO by providing high resolution imaging and understanding of detailed mechanisms of variability. The essential next step in understanding the origins of solar activity requires the high resolution data from Solar B.

Solar Dynamics Observatory (SDO)

SDO will help us to understand the mechanisms of solar variability by observing how the Sun's magnetic field is generated and structured and how this stored magnetic energy is released into the heliosphere and geospace. SDO's goals are to understand the solar cycle, the transfer of energy through the solar atmosphere, and the variable radiation output of the Sun. SDO measures subsurface flows, photospheric magnetic fields, high-temperature solar atmospheric structures, and the extreme ultraviolet spectral irradiance that affects Earth's atmosphere.

Solar magnetism drives the variability that causes most space weather. Helioseismology measures the internal causes of activity. Photospheric and coronal observations trace the evolution of magnetic field structures and the origins of disturbances. The upper atmosphere is highly sensitive to solar EUV variability. SDO's investigations are essential to many phase 1 and 2 achievements relevant to all three SSSC Objectives.

SDO needs to fly immediately to provide crucial understanding of solar activity, the solar cycle, and the inputs to geospace. Predictive modeling cannot improve without the improved data SDO will provide. SDO is an essential replacement for the aging SOHO spacecraft.

Solar Sail Demo

Because of the inability to fully validate this technology on the ground, the application of solar sails to a strategic science mission absolutely requires a prior successful flight validation. Such a Sail Demo (40-m edge length, 25 g/m^2) could be readily scaled then to fit the needs of the Heliostorm mission (100-m edge length, 14 g/m^2). Once a mission in the class of Heliostorm has flown, further scale-up could be accomplished for Solar Polar Imager (160-m edge length, 12 g/m^2). A further, third generation solar sail would be required for a visionary mission such as Interstellar Probe.

The flight of a Sail Demo must precede the first strategic launch by 5-6 years. A Sail Demo mission in mid-2010 would permit the flight of Heliostorm in 2016 or thereafter. Approximately 5 years would then be needed after Heliostorm to enable the scale-up to Solar Polar Imager.

Solar Orbiter

Solar orbiter is a European Space Agency (ESA) mission with U.S. participation that will fly as close as 45 solar radii to the Sun in order to study the solar atmosphere with unprecedented spatial resolution (~100 km pixel size).

Its science goals are to characterize the properties and dynamics of the inner solar wind, to understand the polar magnetic fields using helioseismology, to identify links between activity on the Sun's surface and coronal disturbances using co-rotating passes, and to fully characterize coronal regions from high inclination orbits. Using Venus gravity assists, the orbital inclination will shift over time providing the first high latitude views of the solar poles. Solar Orbiter will provide key components to NASA's LWS program by understanding the causes of Space Weather and thus will answer science questions of Objective H. It will also provide data to increase our fundamental understanding of particle acceleration and the role of the solar dynamo in structuring the solar magnetic field (Objective F).

Both science areas are essential in developing a short and long term predictive capability for the Exploration Vision (Objective J). Solar Orbiter is positioned to fly in the 2015-2025 (Phase 2) time frame which will coincide with Inner Helisopheric Sentinels to continue the system science of our Great Solar Observatory.

Solar Probe

Solar Probe is the first flight into the Sun's corona, only 3 solar radii above the solar surface. Solar Probe's instruments measure plasma, magnetic fields and waves, energetic particles, and dust that it encounters. They also image coronal structure surrounding Probe's orbit and in polar structures at the coronal base. Probe makes two passes into the corona, separated by 4.5 years, exploring why the corona changes its whole form over the solar cycle.

The corona is heated to millions of degrees by poorly understood processes governed by its magnetic field. The UV radiation from the hot solar atmosphere affects the chemistry of the atmospheres of the Earth and other planets. The boundary where the corona accelerates to the solar wind governs the heliosphere and its interactions with the planets and the interstellar medium. That boundary is also critical to the release of solar disturbances that travel throughout the solar system, to the Earth and other planets, producing energetic particle events and magnetospheric storms. Probe will transform our understanding of the physical processes that control the heating of the solar corona, the acceleration of the solar wind, and the release of eruptive activity. Accurate prediction of events that disturb the Earth's human systems and deepspace explorers require this understanding.

One factor sets the placement of Solar Probe in the Roadmap: Probe is the most technically challenging mission attempted. It must function in the cold and intense particle radiation of its orbit-shaping flyby at Jupiter, and in the heat and high-speed dust impacts of the solar corona. The path to meet the technical challenges is now well defined and Solar Probe is ready for a mission start. Probe can only be achieved with specific budget augmentation because the work to ensure surviving its difficult environment keeps it more costly than any line mission.

Solar TErestrial RElations Observatory

The Solar-Terrestrial Relations Observatory (STEREO) will determine the 3-D structure and evolution of coronal mass ejections (CMEs) from their eruption on the Sun through the inner heliosphere to Earth's orbit. The mission will employ remote sensing and in situ measurements from two spacecraft drifting in opposite directions away from the Earth at 1 AU to triangulate CME-driven shocks, detect preceding shock-accelerated particles, and analyze in situ CME and solar ejecta signatures, including heavy ion mass and charge states. In addition, as the spacecraft reach large separations, one spacecraft will observe the propagation of CMEs that will be directly sampled by the second spacecraft to provide a definitive determination of the relation between the white light and in situ features of a CME. The instrumentation package on each spacecraft includes a coronal and heliospheric imaging package (with an EUV imager, two coronagraphs, and heliospheric imagers), a set of radio wave receivers, and an array of in situ measurements for measuring the solar wind, energetic particles, and interplanetary magnetic fields.

This mission will provide not only fundamental knowledge about the 3D structure and propagation of CMEs, but also provide important information on CME-shock-accelerated particles, constributing to the characterization of the space environment. This mission is a high priority for SSSC science because of the central role of CMEs in determining "space weather."

The Solar-Terrestrial Relations Observatory (STEREO) is nearly complete and ready to be launched in 2006.

Time History of Events and Macroscale Interactions for Substorms (THEMIS)

THEMIS is a MIDEX Explorer mission that addresses the spatial and temporal development of magnetospheric substorms. The mission consists of 5 identical spacecraft and a array of ground-based all-sky cameras. The cameras are a mission-critical element of THEMIS, providing a global context for the in situ measurements and also detecting auroral substorm onset for mission operations decisions. When the spacecraft are on the day side, it will address the question of solar wind control of the magnetosphere and the coupling of energy across the various dayside boundaries.

THEMIS addresses the issue of onset and evolution of the substorm instability, an explosive yet fundamental mode of the magnetosphere. This was identified by the National Research Council as one of five main strategic questions in space physics.

The mission was selected in the last MIDEX proposal solicitation and is currently in Phase C/D development.

The Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS)

TWINS provides stereoscopic viewing of the magnetosphere by imaging charge exchanged energetic neutral atoms (ENAs) over a broad energy range (~1-100 keV) using identical instruments on two widely spaced high-altitude, high-inclination spacecraft. TWINS will enable a 3-dimensional visualization of large scale structures and ion dynamics within the magnetosphere. The TWINS instrumentation is essentially the same as the MENA instrument on the IMAGE mission and provides a 4°x 4° angular resolution and 1-minute time resolution ENA image. In addition, a simple Lyman-alpha imager is used to monitor the geocorona.

The first TWINS spacecraft may overlap with the IMAGE mission, providing an early (2005-2006) opportunity for magnetospheric stereo imaging that could evolve into three spacecraft imaging with the launch of the second TWINS in 2006.

TWINS will provide a 3D view of the ring current ions in the magnetosphere. These ions carry much of the energy and most of the mass into and through geospace. Different from in situ observations, TWINS will provide a dynamic picture of the whole geospace system with a cadence that resolves the radial and azimuthal ion motions. The in situ measurements provided by RBSP, MMS and ITSP, are truth data that can be used to further validate the necessary inversion process that will be applied to the TWINS data to obtain 3D ion flux distributions. These TWINS distributions will provide a global geospace input for space weather models. The 3D ion distributions will enable inferring the inner geospace currents and electric fields which penetrate to low altitudes and high latitudes where they couple energy into the ionosphere-thermosphere system partially driving its space weather.

While TWINS is not a subject of the current roadmap, except as a mission of opportunity element of the Great Observatory, it does support many of the objectives H and J, as can be seen in the discussion above. TWINS value is greatly enhanced if it is flying simultaneously with RBSP, ITSP and MMS. While those missions are to be launched in the next decade, it should be noted that the first of the current sister platforms in the TWINS orbits have been flying since 1994 and will probably be operated for years to come. Thus we expect the TWINS instruments, if they survive, could be operating out through 2015 or so.

Candidate Missions for Phase 2 and Phase 3:

Aeronomy and Dynamics at Mars (ADAM)

Aeronomy and Dynamics at Mars (ADAM) will determine the direct, dynamic coupling of a dusty atmosphere with the solar wind. It is a single spacecraft that will orbit Mars, taking in situ and remote sensing data of the upper atmosphere, ionosphere, and solar wind. Instruments will measure the composition, thermal profile, and circulation in the Martian upper atmosphere. Mars Aeronomy will determine the sources and sinks of ionospheric plasma, its coupling to other regions of the atmosphere, and its to the solar wind.

The dynamics, evolution, and fate of the Mars upper atmosphere addresses fundamental science questions as well as providing pertinent information for manned flights to Mars. Aerobraking and aerocapture require a detailed knowledge of the Martian upper atmosphere, as well as an understanding of how and why the atmosphere varies, for hazard prediction and risk mitigation.

This is a high priority mission with direct relevance to the manned flight component of the Vision for Space Exploration. It should be flown as soon as possible in order to allow time for the scientific investigations of the Mars upper atmosphere to progress to a point of transferring the lessons learned from ADAM to the manned flight program with sufficient lead time to impact mission development. Therefore, it should be a Phase 1 or early Phase 2 mission.

Auroral Acceleration Multi-Probe

The Auroral Acceleration Multi-Probe (AAMP) mission is designed for extremely high time resolution measurements of particle distributions and three-dimensional electric and magnetic fields in situ within the Earth's auroral acceleration region. The auroral acceleration region provides a unique laboratory for the study of acceleration processes, both because it reveals many of the critical processes and because it is readily accessible to measurement. Our basic understanding of particle acceleration in parallel electric fields and kinetic Alfven waves, as well as the structures that support parallel fields, have come from in situ auroral observations. To make the progress required for a predictive understanding requires simultaneous measurements both along and perpendicular to magnetic fields. The AAMP four satellite mission is designed to provide the needed conjunctions through a careful orbit strategy.

One of the key goals of Objective F is providing the detailed understanding of the processes that accelerate particles to high energies that will be necessary to predict fluxes of high energy particles throughout the solar system. This predictive capability is the goal of RFA J.3. In addition, by providing a better understanding of energetic particles in the Earth's space environment, AAMP is also important to Objective H because it will enable mitigation of impacts on space assets, and, by quantifying the auroral input to the ionosphere/thermosphere, it will improve models of lower latitude composition and variability of the ionosphere, which affect communications/navigation activities.

The fundamental understanding of acceleration processes is critical to the NASA SSSC goals and, thus, the mission should be flown as soon as possible. Its placement in the mission queue indicates the need to inform activities that occur in the intermediate time frame.

Dayside Boundary Constellation

DBC will determine the global topology of magnetic reconnection at the magnetopause. It is a network of ~30 Sun-pointing, spinning, small spacecraft, separated by ~1 RE, that skim both the dawn and dusk sides of the dayside magnetopause. The multi-spacecraft provide simultaneous comprehensive observations of boundary phenomena including turbulence over a wide range of latitudes and local times. Three spacecraft are boosted to have apogee outside the bow shock to provide continuous monitoring of the foreshock-preconditioned solar wind input.

This mission addresses critical unresolved questions about the transfer of energy across the magnetopause boundary. It also will robustly measure the global magnetic field topology on the Earth's dayside magnetopause, something which has not been done before.

MagCon is a precursor mission to DBC, as it will have a constellation of spacecraft in the magnetospheric equatorial plane. Therefore, DBC should be in the Phase 3 mission queue.

Doppler

Doppler consists of a suite of small, lightweight, moderate resolution spectral imagers (UV/EUV imaging spectrograph, 2 EUV imagers, and a Magnetograph) to detect, observe and study remotely all of the relevant signatures of solar activity responsible for space weather events and disturbances.

Doppler addresses issues directly relevant to supporting the Vision for Exploration by enabling improved nowcasting and future forecasting of solar activity by identifying and developing new precursor signatures of CME initiation and onset, flare eruption, and flare initiated SPEs. The DOPPLER mission enables improved nowcasting and forecasting of solar activity by providing improved understanding of the physical processes and mechanisms of energy storage and release on the Sun. Measurements of motions and changes in nonthermal velocity distributions in the lower corona and chromosphere are crucial to understanding and separating various models of CME initiation and onset. Depending upon the specific physical process, Dopplergrams and other derived data products are likely to be the most reliable indicators that a specific region is about to erupt.

The DOPPLER mission should fly in the early part of Phase 2 (2015-2020), with overlap with SDO to identify and develop new solar activity precursor signatures necessary to protect astronauts during surface EVAs on the Moon (late Phase 2). The small, lightweight instrumentation developed by DOPPLER would then be available for Phase 3 missions required to provide nowcasting and forecasting capability at Mars and beyond.

Farside Solar Observer

Farside Solar Observer is a mission with a spacecraft placed at 1 AU viewing the far side of the Sun. It will provide new knowledge about the solar dynamo, solar activity, and the dynamic space environment in general. It contains both remote sensing and in situ instruments. Remote sensing instruments include a magnetograph-Doppler imager and a radio science package for coronal sounding. Its location at about 180 degrees from Earth allows, in conjunction with similar observations from near Earth, helioseismological measurements of the deep interior flows that are thought to drive the dynamo. The magnetograph will provide more longitudinal coverage of the Sun so that the evolution of solar magnetic fields and active regions can be observed for longer times. Farside Solar Observer also provides an additional in situ observation post for the space environment. The in situ instrument package would be similar to that on the STEREO spacecraft.

Farside Solar Observer provides information crucial for understanding fundamental processes (Objective F) and for developing the capability to predict the space environment. Farside will aid predictions of space weather and provide inputs for SWB, MARS, and high-latitude solar observatories.

While it would be advantages to have this (or the SHIELDS) mission earlier, it was placed in Phase 3 because it was considered lower priority.

Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)

GEMINI is a mission that will provide the first 3-dimensional observations of the global Geospace dynamics in response to external solar drivers and internal coupling. Stereoscopic views of the radiation belt associated ring current and thermal ions of the plasmasphere, simultaneous images of the aurora in both hemispheres, and coordinated ground based observations are used to determine the coupling dynamics between the ionosphere, ring current, and plasmasphere and to discover the important feedback and dissipative mechanisms between these regions.

The power of GEMINI is that imaging this complex coupled system to unravel its macro-scale interactions simultaneously provides the global context for correct interpretation of in-situ observations. It is to magnetospheric space-weather what the Solar Terrestrial Relations Observatory is to the solar-wind observations. The discoveries from this mission are applicable to understanding fundamental processes at work not only in Geospace but other magnetized planetary systems and thus are important to Objective F. Global Geospace observations are needed to provide the system level context for nowcasting and prediction of the plasma environment where exploration activities are occurring within Geospace. In addition, these results are significantly augmented when coupled with inner heliospheric and solar disk observations. The conjugate auroral observations are essentially the “footprints” of the magnetosphere and therefore provide the magnetospheric configuration to distances beyond the lunar orbit. For these reasons GEMINI is important to Objective J.

Operating GEMINI in conjunction with the RBSP and ITSP missions is ideal as documented in the LWS Geospace definition report. However, even without mission overlap, the system level understanding of the coupling between regions in Geospace that creates, evolves and annihilates radiation belts and how that induces and impacts ionospheric variability is extremely significant to operational space based assets that society has become so dependent on. As such, GEMINI is important to objective H.

Heliostorm

The Heliostorm mission would measure the solar wind and heliosphere state “upstream” of the Earth and Moon. Through the use of breakthrough solar sail technology, it would fly 50% further from the Earth (farther upstream) than the current ACE measurement at the Earth-Sun L1. A set of in-situ measurements then would provide 50% greater warning time (compared to ACE) of CMEs and shock-accelerated energetic particles. In conjunction with other assets outside the Earth’s magnetosphere, the mission would determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes.

Heliostorm safeguards our outward journey by providing an input that is absolutely vital to the prediction of space weather in cislunar space. Astronauts on the lunar surface will benefit greatly as the enhanced warning time will permit reaction to actual upstream conditions measured remotely by Heliostorm. The solar wind input to the Earth is required by all models of the Earth's magnetosphere, and would be provided by Heliostorm or a conventional L1 monitor.

Heliostorm could be flown 5-6 years after a successful Solar Sail Flight Validation (Sail Demo). Heliostorm (or a conventional L1 monitor) must be flown in time to replace the current ACE/Wind configuration. This suggests a launch in the 2016-2020 time frame.

Inner Magnetospheric Constellation

IMC will determine the interaction among the radiation belts, ring current, plasmasphere, and outer magnetosphere. It is multiple spacecraft in at least two ecliptic plane "petal" orbits. Large day/night and dawn/dusk asymmetries exist in the inner magnetosphere and complicate the global specification of particles and fields. Through simultaneous measure of radial and longitudinal variations in the radiation belts, the temporal and spatial asymmetries will be resolved.

The in-situ measurements from these multiple positions allow the construction of comprehensive "weather maps" of the inner magnetosphere (1.5-12 Earth radii) that evolve in response to Sun-induced disturbances. This spacecraft fleet focuses on detailed specification of the orbital environment of most spacecraft and manned missions, to determine in detail the origin and evolution of particle populations and their interaction with the evolving electro-magnetic field during magnetic storms.

These observations extend the radiation belt storm probe results by making simultaneous maps of the radial as well as the longitudinal variations in the radiation belts. It should fly after RBSP, and probably after GEMINI, putting it into Phase 3 of the mission queue.

Ionosphere Thermosphere Mesosphere (ITM) Waves

ITM Waves is designed to observe the sources and sinks of gravity waves, including modes of interaction between multiple wave sources, as well as modes of interaction with the neutral and ionized constituents of the atmosphere, and with tides and the zonal mean circulation.

The wave processes studied by ITM Waves are fundamental to the coupling between distinct altitude regions, and to the overall dynamics of the Earth's atmosphere. These processes play a key role in the response of the atmosphere to solar storms. Gravity waves are also thought to be a critical factor in preconditioning the ionosphere by contributing to the initial conditions necessary for plasma instabilities to form near the magnetic equator, and perhaps also at mid-latitudes. These unstable conditions can result in the formation of large-scale depletions in the plasma density, coupled with small-scale irregularity formation and severe radio wave disruptions. The ITM-Waves mission will thereby enable further development of the theory and models necessary for comprehensive understanding of the phenomena. Insight into these phenomena in geospace may help to mitigate issues related to aero-braking and aero-capture in the Martian atmosphere, so ITM-Waves is pertinent to exploration mission requirements.

ITM-Waves should follow GEC and ITSP as closely as possible in time because these two missions provide key information on how the atmosphere responds to solar energy, storms, and substorms. Together the three missions are synergistic in that they address the overall goal of understanding the Earth's response to solar energy. If possible, ITM-Waves should overlap in time with the Mars Dynamics mission because additional synergies would be created by studying the responses of both atmospheres to simultaneous solar forcing.

Interstellar Probe

Interstellar Probe is the first mission that will leave our heliosphere and directly sample and analyze the interstellar medium. It is a single spacecraft that will use an advanced in-space propulsion system such as a solar sail or nuclear electric propulsion to reach the upstream interstellar medium at a distance of 200 AU within about 15-20 years. This spacecraft will carry the first payload specifically designed to directly determine the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields.

On its way, it will provide only the second opportunity after Voyager to directly observe the thick region of interaction between the solar wind and the interstellar medium, from the termination shock to the heliopause and beyond. This region plays a central role modulating the Galactic Cosmic Ray flux and in the creation of the anomalous component and understanding this modulation will help increase the productive and safety of human explorers. Additional advanced instrumentation used en route could determine the nature and chemical evolution of organic molecules in the outer solar system and interstellar medium and measure the cosmic infrared background (CIRB) radiation normally hidden by the Zodiacal dust.

Because this mission is enabled by advanced propulsion, it has been place in Phase 3. The Solar Polar Imager mission would provide a technology demonstration of the solar sail propulsion system needed for Interstellar Probe. It is expected that additional resources would be needed for this mission because of its 15+ year lifetime coupled with the need for advanced propulsion.

Io Electrodynamics

Io Electrodynamics uses a spinning spacecraft, placed in an elliptical Io-resonant orbit that provides repeated encounters with the Io flux tubes. A radiation hardened payload of fields and particles instrumentation will complement a UV imager for context observations.

IE will investigate the magnetic coupling and energy conversion process in a unique magnetized plasma situation, while determining the role of Io in Jovian radio emissions.

The timing of IE is non-critical relative to the other SSSC missions, but the mission is complementary to other missions that support Exploration of the terrestrial planets, for comparative purposes.

Jupiter Polar Orbiter

JPO places a spinning radiation hardened spacecraft in polar elliptical orbit around Jupiter at 75° inclination. The payload includes fields and particles instruments, planetary imagery and radio science. Measurements will be made of the Jovian auroral acceleration regions and radiation belts, the polar magnetic field and plasma waves. Radio occultations of the ionosphere and atmosphere will determine their characteristics.

JPO will conduct a comparative test of magnetospheric models in a case where planetary rotation is dominant over the solar wind interaction in powering the system.

JPO timing relative to other missions is non-critical but the mission is highly complementary to other missions that support Exploration of the terrestrial planets, for comparative purposes.

L1 Solar-Climate Explorer

L1SCE examines the mechanisms that potentially link solar variability to changes in Earth's climate via solar irradiance or Earth albedo variations, energetic particle precipitation.

L1SCE measures the spatial, spectral, and temporal variation in the Earth's albedo, while simultaneously measuring the solar photon, electromagnetic, and particle flux incident upon Earth. A platform in Earth-Sun L1 halo orbit provides continuous viewing in both directions for >3 yrs. The payload includes multi-wavelength imaging spectro-radiometer, solar irradiance, in-situ plasma, magnetic field, and energetic particles instruments.

This mission is needed as soon as possible to complement other missions. It represents an interdisciplinary partnership between Sun-Solar System Connections and Earth Science.

Magnetospheric Constellation

MC will employ a sensor web of ~36 spacecraft to describe the temporal and spatial structure of complex processes occurring throughout vast regions of the Earth's magnetosphere, including most of cislunar space between the Earth and its Moon. In situ plasma, magnetic field, and energetic particle observations, and possibly imaging, will be used to distinguish between nonlinear internal dynamics of the magnetosphere and global responses to varying solar wind conditions. The data will be provided on spatial and temporal scales sufficient to enable close cooperation with state-of-the-art numerical simulations capable of describing where magnetic flux, mass transport, energy conversion, and dissipation occur. By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

MC is the first sensor web for space weather in geospace and is focused on Earth's dynamic magnetotail, the origin of severe storms in geospace. By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

Understanding the mass and energy flow in the magnetotail and throughout the rest of the magnetosphere is an unresolved issue of fundamental importance. With the flight of the New Millennium ST-5 mission, many of the technological obstacles of this mission have been addressed. It should be the next STP mission after GEC, which puts it in the Phase 2 mission queue.

Magnetosphere-Ionosphere Observatory (MIO)

MIO will determine the processes that drive auroral arcs. It is a tight cluster of satellites in geosynchronous orbit that are magnetically connected to a ground-based observatory, with a satellite-based electron beam establishing the precise connection to the ionosphere. One of the longest standing problems in magnetosphere-ionosphere coupling is the fundamental question how large-scale processes in the magnetosphere (with spatial scales of many thousands of kilometers) effectively couple to the ionosphere to produce very narrow auroral arcs (with scales less than 1 km). The MIO spacecraft cluster will perform the local gradient measurements required to identify the causal mechanism for generating auroral arcs.

The MIO mission examines the still unresolved relationship between magnetospheric dynamics and auroral arc features. The electron beam explicitly addresses the ambiguities of ionosphere-magnetosphere connectivity. It addresses fundamental scientific questions that are of direct relevance to life and society.

Conceivably, MIO could fly at any time. However, it did not make it in to the mission phasing diagram within the available resources. Therefore, it is part of the Phase 4 mission queue.

Mars Atmospheric Reconaissance Survey (MARS)

The Mars Atmospheric Reconaissance Survey (MARS) mission will provide a robust assessment of the upper atmosphere of Mars to enable safe human space flight to that planet. It will consist of a comprehensive package of in situ and remote sensing instruments to quantify the dynamics and chemistry throughout the Mars atmosphere. It could be one or several spacecraft, depending on what is thought to be needed to resolve the remaining questions about the Mars space environment.

This mission will provide as complete a set of measurements as possible to answer any remaining questions about the Mars upper atmosphere and its interaction with the solar wind before manned flights to Mars begin.

It should fly after ADAM, but before astronauts go to Mars. Therefore, it is part of the Phase 3 mission queue.

Magnetic TRAnsition region Probe

The primary objective of MTRAP is to measure the build up and release of magnetic energy in the solar atmosphere. MTRAP will measure the vector magnetic field from the photosphere to the magnetic transition region, where the solar atmosphere changes from being plasma to magnetic field dominated. MTRAP will also obtain simultaneous plasma diagnostics of the magnetic transition region with UV/EUV imaging spectrograph neasurements. MTRAP has two orders of magnitude greater collecting area and one order of magnitude improvement in angular resolution over Solar-B and will greatly improve our ability to follow rapid changes in the magnetic field geometry. MTRAP is centered around a very large solar optical telescope with a 6m aperture, providing over 100 times the collecting area and 10 times the angular resolution (0.05 arcseconds) of Solar-B.

MTRAP addresses fundamentally important questions and issues related understanding magnetic reconnection and micro-scale instabilities in the chromosphere/corona interface on the Sun.

MTRAP should fly early in Phase 3 of the STP line (2025-2035), benefiting from knowledge learned from Solar-B and SDO.

RAM

The Reconnection and Microscale (RAM) mission is a next generation, high resolution solar mission focused on understanding the basic small-scale processes in hot magnetized plasmas that are ubiquitous throughout the universe. In hot magnetized plasmas the physical processes governing the dynamics take place on remarkably small spatial and temporal scales. RAM addresses several fundamental questions such as what are the mechanisms and magnetic topology that lead to reconnection, what micro-scale instabilities lead to global effects and how do magnetic stresses form and release in the solar corona? RAM includes a 0.02 arcsec/pixel EUV imaging telescope, a 0.1 arcsec/pixel UV/EUV imaging spectrograph, and a small x-ray calorimeter to perform simultaneous high resolution imaging and imaging spectroscopy to understand the small scale dynamic processes and mechanisms of reconnection on the Sun.

RAM addresses fundamentally important questions and issues related understanding magnetic reconnection and micro-scale instabilities on the Sun.

RAM should fly as one of the first missions in Phase 3 of the STP line (2020-2025), benefiting from knowledge learned from Solar-B and SDO.

SHIELDS

Solar Heliospheric and Interplanetary Environment Lookout in Deep Space (SHIELDS) is a new mission concept developed specifically in response to the Vision for Exploration to help ensure the safety and productivity of human and robotic explorers.

SHIELDS places two spacecraft in fixed locations 120° from Earth in order to view the entire solar surface and to determine the direction of propagation of CMEs anywhere in the inner heliosphere. Remote sensing instruments include coronagraphs (for observing CME onset and propagation), magnetographs (to observes evolution of the surface magnetic fields and active regions) and EUV telescopes (to observe flare activity). Observations of the entire solar surface should help enable the predictability of longer periods that are “all clear”of solar activity (Objective J). The spacecraft would also carry in situ instruments similar to those on STEREO and FARSIDE to observe the CMEs and associated solar energetic particles, also in support of Objective J.

This mission could replace the Farside Sentinel by providing the farside views of the Sun. To provide the helioseismology needed to understand the dynamo and origins of solar activity (Objective F), a Doppler-magnetograph would also be needed. This would be a more costly mission than Farside since it uses two spacecraft, and, at some point the community will decide which of the two to pursue. Like Farside, this mission has been place in Phase 3. It will support RAM, SWB, MARS, high latitude solar observations, and provide inputs for studies of impacts on planets other than Earth.

Solar Connection Observatory for Planetary Environments (SCOPE)

SCOPE measurements will be made using dual meter-class telescopes (EUV & UV) covering bandpasses from 55 – 31 nm. The instruments will provide Hubble Space Telescope (HST) - class performance for UV observations and the highest sensitivity and spatial resolution yet achieved below 120 nm. High spectral resolution (R<105) measurements of diffuse emissions will be made with 50 times the etendue of HST-STIS permitting inner solar system observations of Venus, Mercury, and comets to within ~0.35 AU of the Sun, L1-halo orbit for observations for uninterrupted measurements of the Earth's North or South polar regions and a remote perspective on planets giving full hemisphere studies up to rotational poles. The potential operational lifetime is 5+ years.

The SCOPE mission will compare the global effects of external and internal driving mechanisms on planet and comet near-space environments through observations of auroral, airglow, coronal, and/or internal plasma emissions. It will differentiate features of Jupiter's (and other giant planets') auroral emissions due to internal processes (rotation and internal plasma sources) from those due to solar wind interactions and will measure the response of ionosphere-solar wind coupling to changes in solar activity in planetary systems without magnetospheres (Mars, Venus, Comets). The mission will also refine and expand our knowledge of Earth's global geospace response by extending auroral observations into new domains of spatial and spectral resolution. A key result will be a data base that can be used to directly compare the terrestrial solar interaction with those of superior (Mars-Neptune) planets from opposition campaigns that monitor both systems along the same Sun-planet line.

SCOPE will provide fundamental science observations and understanding of key planetary and interplanetary processes that are critical to the exploration vision and the overarching goals of the SSSC program. SCOPE should be launched as soon as possible in Phase 4 when our understanding of more basic planetary processes has matured.

Solar Energetic Particle Mission (SEPM)

SEPM – the Solar Energetic Particle Mission will determine how, when, and where solar energetic particles (SEPs) are accelerated and help determine how the solar wind is accelerated. A large aperture UV coronagraph-spectrometer and a large aperture visible light coronagraph-polarimeter will observe the corona from 1.15 to 10 solar radii. SEPM instrumentation will be about 100 times more sensitive than current coronagraphs. New diagnostics will determine velocity distributions for electrons and minor ions and derive magnetic field strengths in coronal streamers and coronal mass ejections (CMEs). SEPM will measure critical plasma parameters in pre- and post-shock CME plasmas including suprathermal seed particle populations and it will characterize upstream turbulence which is believed to play a critical role in particle acceleration.

When combined with an integrated theory and modeling program, SEPM measurements will be used to significantly advance our fundamental understanding of energetic particle acceleration (Objective F). Ultimately this understanding will be used to develop a predictive capability for the flux, energy spectrum, and composition of SEP's – thus enabling the Exploration Vision (Objective J) and providing information about the solar sources of Space Weather that affect our home planet (Objective H).

Ideally the remote sensing SEPM spacecraft should fly in concert with a near-Sun spacecraft (e.g. Inner Heliospheric Sentinels or Solar Orbiter) that will detect energetic particles before significant scattering in the interplanetary medium. SEPM should start as early as possible during a period of high solar activity to inform the development of SEP hazard prediction before human explorers return to the moon.

The possible combination of the SEPM and Doppler missions promises a powerful tool for understanding the physical processes of solar energetic particle acceleration and relating SEPs to flares on the disk and to coronal mass ejections that propagate out into interplanetary space.

Solar Polar Imager

Solar Polar Imager will provide critical missing observations need to understand the solar cycle and the origins of solar activity. It is a single spacecraft mission that uses a solar sail to achieve a final 0.48 AU circular orbit with a 75∞ inclination to the ecliptic. The spacecraft carries a magnetograph -Doppler imager for high-resolution helioseismology and surface magnetic field measurements of the polar regions, a coronagraph for polar views of the corona and CMEs, and in situ particles and fields instrumentation for solar wind and energetic particle observations.

This mission is necessary to understand the solar dynamo because the polar orbit enables us to measure the convective surface, subsurface and deep interior flows that control the solar dynamo and to observe the correlation between the flows and solar magnetic field activity and evolution. The rapid four-month polar orbit also allows us to observe the relationship between solar activity and solar wind structure and energetic particles at all latitudes, crucial for characterizing the near-Sun source region of the space environment. In addition, the polar magnetic field measurements are needed to provide the solar surface boundary conditions for the global MHD models used for space weather prediction.

Because this mission requires a solar sail to achieve the near-polar orbit, it has been placed after the Heliostorm mission that will be the first science mission utilizing solar sail propulsion. The Telemachus mission can also address the goal of characterizing the space environment at all latitudes and give some information on the magnetic fields and flows in thepolar regions. Thus at some point, the community may choose between Solar Polar Imager and Telemachus, based in part on the maturity of the solar sail propulsion technology.

Solar Weather Buoys (SWBs)

SWBs are ~15 small spacecraft distributed every ~20∞ in ecliptic longitude around the Sun at 0.9 AU, identically instrumented with plasma, magnetic field, energetic particle, and hard xray detectors.

The initial function of SWBs is to answer definitively the yet un-resolved basic scientific question: what is the spatial longitudinal extent and evolution of the major Solar Energetic Particle (SEP) and Coronal Mass Ejection events that occur during the maximum of the solar cycle? Their complementary function is to give prompt and unambiguous warning of the injection of biologically damaging doses of high-energy particle radiation for astronauts exposed on the surface of the Moon or in transit to the surface of Mars.

SWBs will attack the fundamental problem (F.2) of bringing our understanding of the acceleration and propagation of SEPs and CMEs from the Sun to 1 AU up to the level of prediction. In its complementary role, it will safeguard our outward journey (J.2) to the surfaces of the Moon and Mars.

By launching in 2022, the 5-year deployment phase will be completed in time to catch the rise-to-maximum phase of the solar cycle (2027-2030). During the remainder of the solar cycle (2031-2036), SWBs will paint a definitive scientific picture of how large SEPs and CMEs propagate from the inner heliosphere (being simultaneously observed by IHSentinels, Solar Orbiter, and solar imagers) to 1 AU and beyond towards Mars orbit at 1.4 AU. During this time SWBs' prompt warning capability will be honed and perfected so that they will function with high reliability at the anticipated launch time for the manned mission to Mars (2035).

Sun Earth Coupling by Energetic Particles (SECEP)

SECEP seeks to understand and quantify the impact on atmospheric composition, in particular of odd nitrogen, odd hydrogen, and ozone, by solar energetic particle precipitation (EPP). EPP is thought to be a significant source of ozone destruction through production of high altitude odd nitrogen and odd hydrogen compounds which can be transported lower in altitude where they will catalytically destroy ozone. In order to understand these processes SECEP will measure the precipitating energetic particle influx as well as the descending odd nitrogen and odd hydrogen compounds and ozone densities. Other relevant parameters which affect these processes such as temperature and winds will also be observed.

SECEP is crucial to SSSC goals because it studies a key link between solar energy and its impact on the habitability of Earth. Dramatic effects of EPP on stratospheric and mesospheric ozone have been demonstrated by recent observations. The impact is greatly magnified by the long lifetime of odd nitrogen compounds at stratospheric altitudes. The decent of the odd nitrogen compounds from the ionosphere where it is created to the mesosphere and stratosphere occurs primarily in the polar night where destruction by photolysis can not occur. Therefore SECEP provides valuable fundamental science on how atmospheric regions are coupled.

Because ozone plays a key role in Earth's habitability by shielding the population from harmful UV radiation, SECEP is a high priority mission. SECEP should follow GEC and ITSP closely in time because these two missions provide key information on how the atmosphere responds to solar energy and the three missions together are synergistic for the overall goal of understanding the Earth's response to solar energy and the effect on the human population.

Stellar Imager (SI)

Stellar Imager (SI) is a mission that will obtain the first direct images of surface magnetic structures in sun-like stars. It will image the evolving dynamo patterns on nearby stars by repeatedly observing them with ~1,000 resolution elements on their surface using UV emission to map the magnetic field. SI will achieve at least 30 resolution elements on stellar disks with 1-min. time resolution in one or more broad optical pass bands.

The power of SI lies in its ability to provide information on the dependence of the dynamo on stellar properties, and enable by its population study dynamo model validation within years rather than many decades. It therefore gives solar physicists a unique 'laboratory environment' within which to test predictive models of stellar activity. SI thus addresses the goals of the Exploration Initiative under Objective J by improving long-term space weather forecasts throughout the heliosphere to guide vehicle design and mission planning, and forecasts of extended periods for safe construction at Moon, Mars, Earth-Moon L1, Sun-Earth L2, and LEO staging orbits. By observing planet harboring stars and their evolving environments it will also provide an improved understanding of formation of planetary systems and habitability zones of extra-solar planets. Stellar Imager provides crucially needed information for several of the SSSC Objectives by observing patterns of magnetic activity and underlying atmospheric structure of a population of stars to compare with the sun. It supports Objective F by enabling an understanding of the creation and variability of magnetic dynamos, Objective H by promoting an understanding of the causes and subsequent evolution of activity that affects Earth's space climate and environment and how the habitability of planets are affected by solar variability.

SI should fly early in the Phase 3 mission window (near 2025) to provide the information critical to our planned exploration activities as humans head out through the potentially dangerous interplanetary environment whose character is controlled by the sun.

Tropical ITM Coupler (T-ITMC)

T-ITMC will explore how neutral and plasma interactions distribute energy within and between Earth's low-latitude mesosphere, thermosphere, ionosphere, and inner plasmasphere.

T-ITMC will improve our understanding of the influence of geospace on Earth (Objective H), explore the fundamental interactions between atmospheric plasmas and neutrals across scales from 1 cm to 1000 km (Objective F), and provide a fundamental database of atmospheric dynamics (winds, gravity waves, and ion drifts) that can be applied to exploration of other planets (Objective J).

It should be flown after the GEC and ITSP missions and should be reconfigured as necessary to address unanswered questions from those missions. In the event of limited flight opportunities, the importance of T-ITMC can be evaluated in light of the GEC and ITSP results.

Venus Aeronomy Probe

Venus Aeronomy Probe will study the robust upper atmosphere and solar-wind atmosphere interaction of a planet with essentially no intrinsic magnetic field. This mission will determine the processes by which solar wind energy is transmitted to the ionosphere and upper atmosphere. It will also study how charged particles are accelerated to create auroral-type emissions, how magnetic field ropes form and dissipate, how ionospheric plasma is lost, as well as other electrodynamic interactions.

The dynamics and evolution of the Venus upper atmosphere and its direct interaction with the solar wind is a critical component of the reasons why this planet digressed from habitability. Understanding the physical processes responsible for the development of the present-day Venus atmosphere is vital to understanding the evolution of planetary atmospheres in general, including that at Earth.

Chapter 4

Sun-Solar System Connection: Technology Investments

Develop Technologies, Data, and Knowledge Systems to Improve Future Operational Systems

Innovation is the engine that drives scientific progress, through development of new theories, invention of new technologies that lead to improved measurements, and emergence of entirely new capabilities. SSSC must embrace the development, infusion, and study of new technology, both for its stimulating effect on science (enabling and enhancing new missions), and because of the key role that understanding and predicting the space environment presents for the safety and productivity of our global infrastructure that is increasingly space-based and of other NASA missions.

Continuing progress in the characterization, modeling, and prediction of the Sun-Solar System Connection (SSSC) will require technological development in a number of key areas.

Highly desirable capabilities include:

- Simultaneously sampling space plasmas at multiple points with cost-effective means (e.g., MMS, LWS Storm Probes, and Sentinels); measuring phenomena at a higher resolution and coverage in order to answer specific scientific questions (e.g, GEC);
- Achieving unique vantage points such as upstream of the Earth-Sun L1, polar orbit around the Sun, or even beyond the heliosphere;
- Developing the next generation of capable, affordable instrumentation;
- Enabling the return of vast new data sets from anywhere in the solar system;
- Synthesizing understanding from system-wide measurements using new data analysis and visualization techniques.

The highest priority SSSC technology needs follow these key focus areas:

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

Table 4.1 shows enabling and enhancing technologies for Sun-Solar System Connection missions. The table traces the dependence of these key technologies to high-priority missions and also outlines the importance of other areas such as avionics, formation flying, structures & materials, power, and low cost access to space. The number of spacecraft required versus time is displayed in Figure 4.1 entitled “Sun-Solar System Connection Cluster and Constellation Missions.” Missions with “clusters” of spacecraft (in the range of 2-6 spacecraft) seek lower unit costs, while constellations missions such as Magnetospheric Constellation (30-36) and Solar Wind Buoys (12-15) could be enabled by ST-5 nanosats.

The following sections give more detail for each of the high-priority technology needs.

1. Developing compact, low-cost spacecraft and launch systems

Because of the complexity and large scale of solar system plasmas, progress requires clusters or constellations of spacecraft making simultaneous multi-point measurements (e.g., Inner Heliospheric Sentinels, MMS, MagCon, and GEC). For multi-spacecraft missions enabling and enhancing technologies include the development of low mass, power, and volume instrumentation as well as low mass, economical spacecraft. These two developments are linked in the sense that smaller, better integrated, spaceflight instrumentation packages could be accommodated on smaller, less expensive launch platforms.

Reducing the unit cost of multiple space systems will require efforts on multiple fronts. Many system issues are wholly unrelated to typical performance-driven technology development. One important area of technology is the development of low-power electronics for space systems and instruments. Flight validation of one LPE component and technique, the CULPRIT Reed-Solomon Encoder on ST5, is scheduled for 2006. Support for further development was provided by the NASA' Exploration Systems Directorate in 2004 (ECT NRA). Power dissipation at the component level can be reduced by factors of 50-100 over conventional technology. If LPE technology were available system-wide, power consumption on satellite systems could be reduced by up to 70%, enabling system-wide benefits and providing spacecraft designers with greater flexibility reducing weight, size, and cost.

2. Enabling high ΔV propulsion (solar sails)

Progress in key areas of SSSC science requires access to unique vantage points both inside and outside the heliosphere. One key vantage point is high-inclination, heliocentric orbit, which would enable unprecedented imaging of the Sun's polar regions. Mission concepts relying on existing technology use either 5 years of solar electric propulsion to reach just a 38° inclination in the inner heliosphere (Solar Orbiter) or rely on a Jovian gravity assist and conventional propulsion to provide an eccentric 0.25 x 2.5 AU polar orbit (Telemachus).

The solar sail is envisioned as a cost-effective means of propelling spacecraft in the inner solar system to very high velocity ($\Delta v > 50$ km/s). Because sails rely on the Sun's continuous supply of photons to provide low-thrust propulsion, solar sails also enable missions in non-Keplerian orbits that are currently not feasible by other means. Solar sails would enable three important SSSC missions:

- Heliostorm, providing significantly greater warning of energetic particles accelerated by CME's via measurements upstream of the Earth-Sun L1 point;
- Solar Polar Imager, providing remote sensing of solar poles from a near-optimal vantage point--circular, 0.5-AU, 75° inclination heliocentric orbit;
- Interstellar Probe, a cost-effective means of sampling interstellar space.

A solar sail consists of a reflective membrane and supporting structure that is deployed or constructed in space. As a result of development by the In-Space Propulsion Technologies Project, sail technology has advanced considerably in recent years. In 2004, two 10-m systems were tested in vacuum on the ground, followed by two 20-m systems in 2005. This recent development has moved the solar sail from the realm of science fiction to science fact.

Because of the nature of a solar sail—a gossamer and reflective membrane meant for deployment and to fly in space—there are fundamental limits to further validation and maturation on the ground. Building, deploying and flying a hundred-meter-class solar sail for a strategic science mission will first require a solar sail flight validation or "Sail Demo" mission. The sail demo will develop and operate in space a deployable solar sail, one that provides measurable acceleration and that can be steered. The flight experiment will test and validate the models and processes for solar sail design, fabrication, deployment, and flight. Such models and processes can then be used with confidence to design, fabricate, and operate the larger solar sails needed for strategic missions.

A sail demo is a candidate concept for the New Millennium Program's ST9 mission scheduled for 2010. Scale-up of the technology to 100-m lengths needed by Heliostorm could occur 5-6 years after a successful sail demo. After flight of a 100-m-class solar sail and a few years additional development, scale-up to still larger sails such as for Solar Polar Imager (~160-m edge length) are imaginable from there. Three decades hence, the deployment of a truly monumental, high-temperature sail required by a mission like Interstellar Probe (200-m radius) could be facilitated by human crews operating near libration points.

3. Enabling the development of the next generation of SSSC instrumentation

SSSC missions carry a wide range of instrumentation, some designed to make in-situ measurements within space plasmas while others make remote sensing measurements of plasma processes occurring at the Sun, near the planets, or out to the edge of the heliosphere. The development of new instruments and instrument concepts is crucial to the future of SSSC science, driven by the need to refine and improve instruments, reduce their mass and power consumption and enable new measurement techniques. Progress in instrument technology development is needed at all technology readiness (TRL) levels, from basic concepts for new detectors (e.g. MEMS-based (microelectro-mechanical systems) plasma detectors that could be used on MagCon) to system level demonstration of improved instruments (e.g. Compact Doppler/Magnetographs for missions such as Doppler). The development of these instruments will proceed from formulation of new ideas and designs (perhaps based on technologies developed in other fields), basic proof of concept, fabrication of test models, laboratory testing, and finally flight validation. It is important to maintain a balanced program that supports all levels of this development, particularly the final stages that enable instruments to be used in-flight. The most costly and time consuming development stages are those directly preceding flight on science missions, largely because of the specialized equipment required. In order to continue to lead the world in space science research, NASA must support the development and maintenance of space-quality test facilities, including those capable of simulating the particle and radiation environments encountered during spaceflight missions. For some of these applications, NASA's low-cost access to space (LCAS) program provides an ideal avenue for testing and validation. A prime example of this paradigm is the development of top-hat style plasma detectors. These were first conceived for studies of the Earth's auroral regions, and were first flown on sounding rockets. Their successes in this area led directly to instruments being flown on highly successful magnetospheric missions. Another important avenue for assessing the effects of the variable space environment on potential flight instruments (and other technologies) is the LWS Space Environment Testbed (SET) Program.

Specific component technologies that would benefit SSSC missions include: large area, deep well CCDs, active pixel sensors, low-noise micro-channel plates, foil technology for ENA imagers, high performance EUV mirrors, UV blind ENA imagers, low-mass high-voltage power supplies advanced X-ray optics and detectors, thin solid-state energetic particle detectors, compact, accurate magnetic sensors and small dead-layer solid state detectors. At the system level, many payloads on future SSSC missions will be severely mass and power constrained (MagCon and Solar Weather Buoys, for example): Technologies that reduce sensor and electronics mass and power would be particularly useful. In addition to these focused technology needs, missions may benefit from serendipitous use of technologies developed in other fields. For example, the incredible shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and more power efficient ionization sources.

4. Enabling the return of large data sets from throughout the solar system

As our exploration of the Sun-Solar System connection proceeds, SSSC missions will place an increasing demand on NASA's communication resources. Many missions would be significantly enhanced by increased communications bandwidth. High bandwidth communication would benefit missions that image the Sun, such as Solar Polar Imager or Doppler, by allowing high cadence, high resolution imaging in multiple spectral channels. As solar remote sensing missions are deployed beyond Earth orbit, these benefits become more critical: missions such as SHIELDS or the Farside Sentinel will study the Sun from multiple distant vantage points, requiring spacecraft to be operated up to 2 AU from the Earth. Closer to Earth, missions will require multiple spacecraft to explore the geospace environment, separating the effects of variations in time and space and examining the structure of complex boundaries. Large numbers of individual spacecraft (in MagCon, for example) distributed throughout geospace will stretch the capabilities of the current communications infrastructure. As we venture further out in the solar system, with missions such as Jupiter Polar Orbiter (Juno), HIGO and Interstellar Probe, returning the required data places an increasing burden on spacecraft, driving cost and complexity. Considered individually, the above missions may be achievable with current technology, however pursuing system-wide SSSC science goals will be enabled by enhancements to our communications technology.

Several technologies will contribute to the solution to this problem. Planned enhancements to the Deep Space Network (DSN), replacing outdated 70m and 34m antenna with arrays of smaller antenna working at Ka-band, will increase the available bandwidth substantially, while also providing the flexibility to communicate with multiple spacecraft simultaneously. Using 200 such antennas, for example, would enable kilobit per second communications from an Interstellar Probe at 100 AU, providing the type of data provided by the ACE or Ulysses missions throughout the solar system to the edge of the heliosphere. Optical communication would also provide a substantial increase in communication bandwidth and additionally provide the capability for high-bandwidth point-to-point communication for missions monitoring the interplanetary radiation environment. The next generation DSN is expected to provide both enhanced RF and optical communications. Arrays of small antennas plus other RF improvements (transmitters, inflatable antennas, transponders, for example) together with optical communication would provide orders of magnitude increase in science data rates. RF arrays would also enable a significant increase in the number of spacecraft that can be supported, particularly in closely spaced clusters.

5. Enabling the analysis, modeling, and visualization of solar system plasmas

As we continue to explore Sun-Solar System connections, the requirement to effectively model the vast systems we study using sparsely sampled observations becomes more critical. Remote space weather predictive capabilities may even be required for explorers far from Earth. In many missions (e.g. the Inner Heliosphere Sentinels, MagCon, or SEPM) modeling will be a critical element of the mission itself, while other modeling efforts will be required to assimilate the data collected by multiple missions into coherent models. The necessary groundwork for these activities has already begun - examples include NASA's Information Power Grid, a joint effort between government, academia, and industry to provide large scale, distributed computing resources to the scientific and engineering communities. The Columbia supercomputer, uses 10,240 Intel Itanium 2 processors and provides an order of magnitude increase in NASA's computing capability. The goal of producing integrated models, and software frameworks that link these models, is also being addressed, with organizations such as NASA's Coordinated Community Modeling Center (CCMC),the NSF-funded Center for Integrated Space Weather Modeling (CISM) and the Center for Space Environment Modeling at the University of Michigan. These efforts are by definition cross-disciplinary, requiring expertise in numerical analysis, high-performance computational science, and solar, interplanetary, magnetospheric, ionospheric and atmospheric physics. Future modeling and theory programs will need to be expanded to handle the demands of increasingly complex data sets and simulations that encompass the entire solar, heliospheric and geospace environments. As new computer capabilities emerge, SSSC scientists will construct broader ranging and more complex models that will allow us to predict the behavior of solar system plasmas based on the assimilation of data from our SSSC Great Observatory.

One of the great challenges faced by current and future SSSC missions is visualization of complex data sets measured by multiple spacecraft in a simultaneous, coherent fashion. Current efforts include the VisBARD project, funded by NASA's Applied Information Systems Research Program. In this project, space science data are displayed three-dimensionally along spacecraft orbits that may be presented as either connected lines or as individual points. The data display allows the rapid determination of vector configurations, correlations between many measurements at multiple points, and global relationships. Events such as vector field rotation and dozens of simultaneous variables that are difficult to see in traditional time-series line-plots are more easily visualized with such a tool. Future data sets will be even more extensive requiring ever more sophisticated visualization tools.

In analyzing future spacecraft data and comparing them with data available from the rest of the SSSC Great Observatory, pattern and feature recognition will become increasingly valuable, allowing large datasets to be mined for events, particularly those detected by multiple platforms. Data structures like the Virtual Solar Observatory and Virtual Heliospheric Observatory will allow such mining, enhancing the value of our data repository and making data more accessible to the science community. Visual representation of imaging data is also critical to its analysis and interpretation, as well as providing a ready means to engage the public. A wide range of SSSC image data will be produced: gamma-ray, X-ray, ultraviolet, visible, infrared, radio, and neutral atom instruments will all produce data requiring image visualization. Tools aimed at producing images of these data are an important part of our current technology, however future missions (STE-

REO, SDO, IBEX, and GEMINI, for example) will continue to place demands on technological capabilities, as image formats increase in size and more complex multi-dimensional data sets need to be visualized.

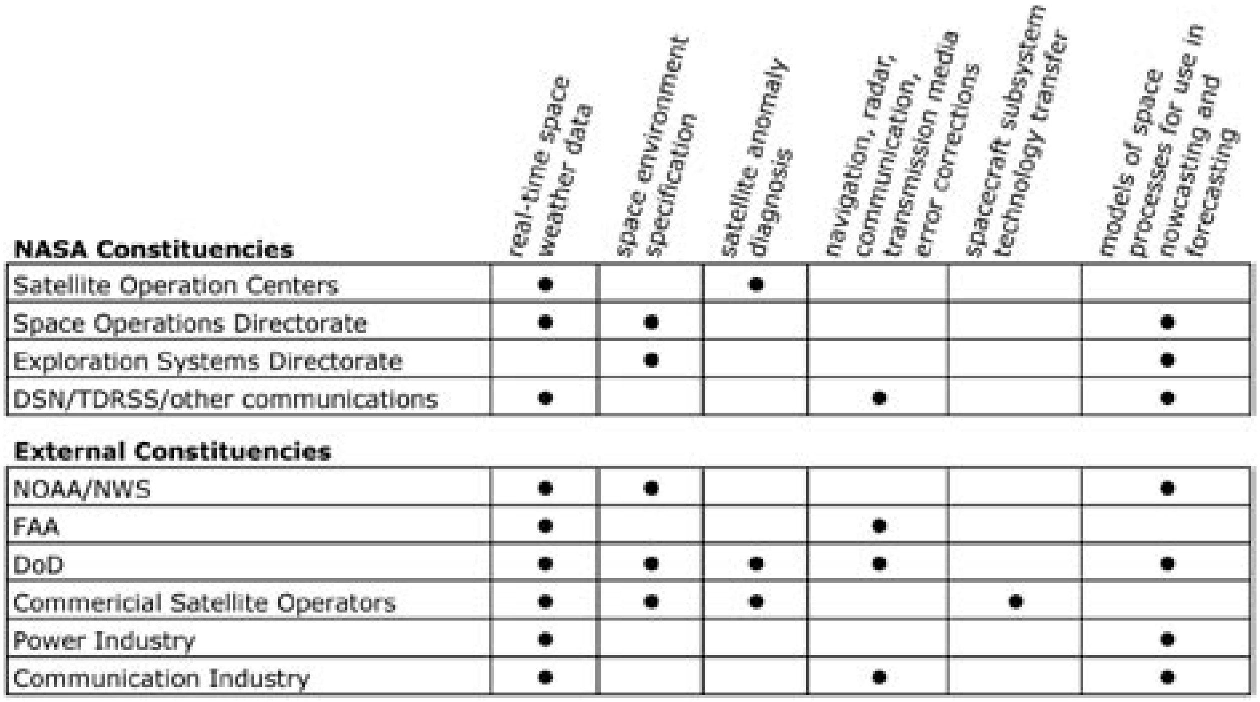
Part III:
Sun-Solar System Connection: Advancing U.S. Scientific, Security, and Economic Interests

National Policy Framework and External Constituencies

National Policy— In addition to the National Space Policy, the U.S. House of Representatives Science Committee approved House Con. Resolution 189:

The International Heliophysical Year (ihy.gsfc.nasa.gov): H.Con.Res. 189, Celebrating the 50th anniversary of the International Geophysical Year (IGY) and supporting an International Geophysical Year-2 (IGY-2) in 2007-08. The resolution calls for a worldwide program of activities to commemorate the 50th anniversary of the most successful global scientific endeavor in human history - the International Geophysical Year (IGY) of 1957-58. The resolution also calls for an “IGY-2” that would be even more extensive in its global reach and more comprehensive in its research and applications.

NAS-NRC Space Studies Board, Committee on Solar and Space Physics Report: Assessment of the Role of Solar and Space Physics in NASA’s Space Exploration Initiative, draft report due September, 2004. The report is intended to review the roles that the solar and space physics program should play in support of the new NASA exploration goals. Specifically, the panel will analyze the missions and programs that were recommended by the 2003 NRC decadal study for solar and space physics, “The Sun to the Earth--and Beyond,” and assess their relevance to the space exploration initiative; and will recommend the most effective strategy for accomplishing the recommendations within realistic resource projections and time scales.



NASA Constituencies	real-time space weather data	space environment specification	satellite anomaly diagnosis	navigation, radar, communication, transmission media error corrections	spacecraft subsystem technology transfer	models of space processes for use in nowcasting and forecasting
Satellite Operation Centers	●		●			
Space Operations Directorate	●	●				●
Exploration Systems Directorate		●				●
DSN/TDRSS/other communications	●			●		●
External Constituencies						
NOAA/NWS	●	●				●
FAA	●			●		
DoD	●	●	●	●		●
Commericial Satellite Operators	●	●	●		●	
Power Industry	●					●
Communication Industry	●			●		●

Table 1: NASA and external constituencies requesting and making use of new knowledge and data from NASA’s Sun-Solar System Connections group.

U.S. External Partnerships and Relationships

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities have become more obvious. The nation’s efforts to mitigate space weather effects have placed more urgency on the need to understand the Sun, heliosphere, and planetary environments as a single connected system. External constituencies requesting and making use of new knowledge and data from NASA’s efforts in this area include the Federal Aviation Administration (FAA), the

Department of Defense (DoD), National Oceanic and Atmospheric Administration (NOAA), the power industry, and the industry of satellite manufacturers and operators.

Constituencies within NASA include the Exploration Systems, Directorate, the Space Operations Directorate, the Deep Space Network, and the various satellite operations centers.

International Cooperation

International Living with a Star: In the January of 2002, the Interagency Consultative Group (IACG) established the Internal Living with a Star (ILWS) program. The IACG consists of the heads of the space science programs of the European Space Agency (ESA), Japan's Institute of Space and Astronautical Science (ISAS), the National Aeronautics and Space Administration (NASA, USA), and the Russian Aviation and Space Agency (RASA). The charter for ILWS is to "stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity". Contributing organizations are listed at http://ilws.gsfc.nasa.gov.

Currently Operating Missions with significant International participation:

Solar Heliospheric Observatory (SoHO): partnership with ESA

Geotail: partnership with Japan/JAXA

Cluster: partnership with ESA

Ulysses: partnership with ESA

Missions in Development with significant International participation:

Solar-B: partnership with Japan/JAXA, ISAS, PPARC

Stereo: contributions from CNES, Switzerland, DLR, PPARC, ESA, Hungary

THEMIS: contributions from Canada, CNES, DLR, and Austria

MMS: contributions from recently-selected international partners

AIM: agreement with British Antarctic Survey, Australia

TWINS: contributions from DLR

Near- term Mission Concepts:

Solar Orbiter: possible partnership with ESA

LWS/Geospace: possible contributions from to-be-selected international partners

LWS/Sentinels: possible contributions from to-be-selected international partners

Appendices

A. 2005 Sun-Solar System Connection Roadmap Team

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Assessment of Mission Size Trade-offs for NASA's Earth and Space Science Missions, Space Studies Board Ad Hoc Committee on the Assessment of Mission Size Trade-Offs for Earth and Space Science Missions, Space Studies Board, National Research Council, 2000, ISBN 0-309-06976-9.

The Role of Small Satellites in NASA and NOAA Earth Observation Programs, SSB, 2000

Radiation and the International Space Station: Recommendations to Reduce Risk, Committee on Solar and Space Physics and Committee on Solar-Terrestrial Research, National Research Council, 2000, ISBN 0-309-06885-1.

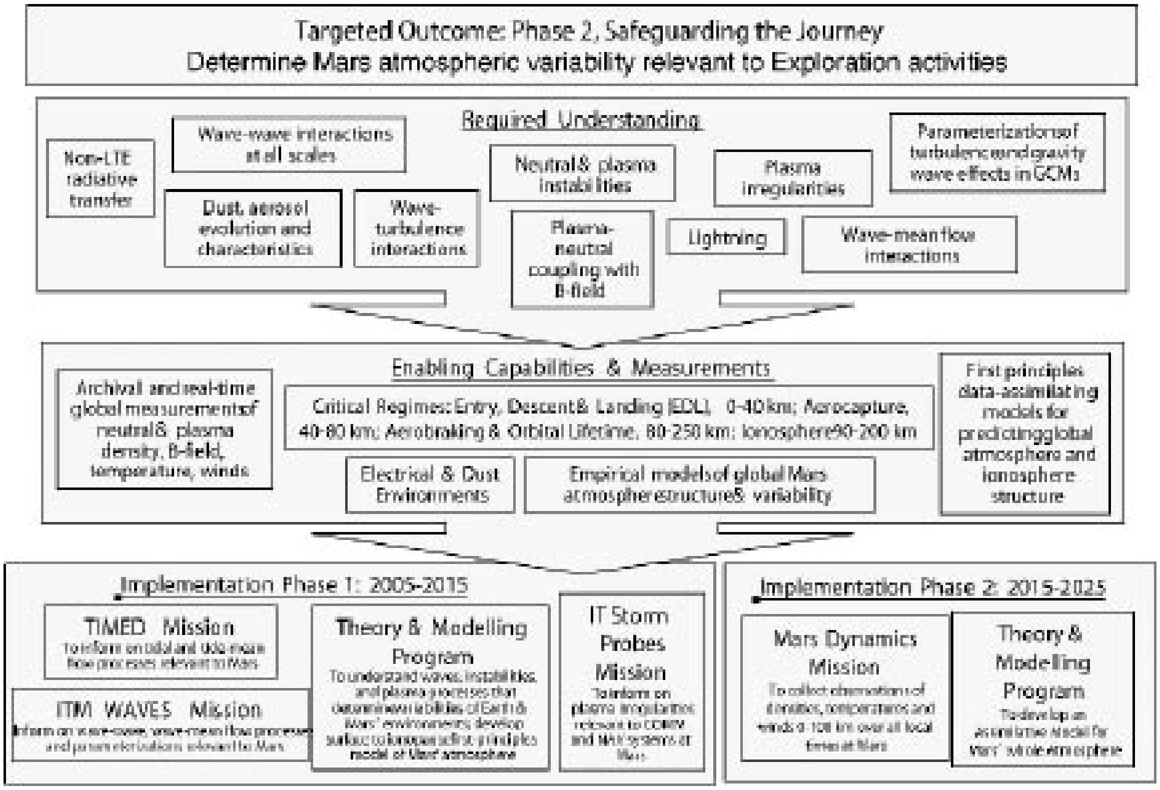
C. Reconciling the Roadmap and Decadal Survey Approaches & Results

Recognizing that a ‘business as usual’ approach was not likely to be effective, this Roadmap has taken a different approach to prioritizing the SSSC strategy. Beginning with the NASA strategic objective assigned to the new Sun-Solar System Connection division, the Roadmap Committees performed a complete requirements-driven derivation of a program to meet the nation’s needs. The committee was supplied by the reports developed by the NRC, including the Decadal Survey and the update to that survey. The committee was also informed by community input in form of formal reports, white papers, through a community workshop, and through personal contacts.

The three top SSSC objectives were broken down into research focus areas that support the achievement of the top-level goal. The focus areas in turn led to two somewhat independent, more detailed breakdowns of effort – investigations and targeted outcomes. This contrasts with past efforts that have been constructed essentially from the bottom up based primarily on scientific priorities and opportunities as well as the perceived needs of the users of SSSC science.

The investigations present the more familiar scientific approach to organizing the efforts, one that lays out a logical progression toward addressing the broad topics outlined in the research focus areas. The investigations are enumerated in Part II Chapter 1 with the descriptions of the research focus areas for each objective. With each investigation it was relatively straightforward to identify missions and supporting elements of the program required to made real progress. Setting priorities was more difficult.

The targeted outcomes provide an alternate basis for constructing a program; one that the Roadmap Committees found helpful for assigning priority to various components of the program. We identified for each research focus area the achievements that should be completed during each of the next three decades. The achievements are shown in Part II Chapter 2. Each achievement resulted in a flow-down chart listing first the required understanding, then the enabling capabilities and measurements, and finally the implementation linked to missions and other supporting program elements. One sample chart is shown in the accompanying figure.



The timing of the achievements was driven first of all by what is required to support the new Vision for Space Exploration with which NASA has been tasked. With an ambitious, though not fully developed, schedule for returning humans to the Moon for an extended period followed by human mission to Mars, certain information is critical for defining and designing a safe and productive exploration program. SSSC science contributes crucial information to inform and enable that phased effort and we have ordered our programs to provide the necessary information at the appropriate time. Of course exploration is more than human spaceflight and the program emphasizes robotic exploration in pursuit of transformational knowledge as well.

Second, the scientific development of the program requires a logical progression of discovery, understanding and prediction. While these go hand-in-hand and different parts of the program are in different stages, this criterion is similar to the drivers used to formulate our strategic plans in the past. The difference this time is that the scheduling is driven by more than just the simple desire to pick the questions that show the most promise for progress. This time we were looking for progress in particular areas.

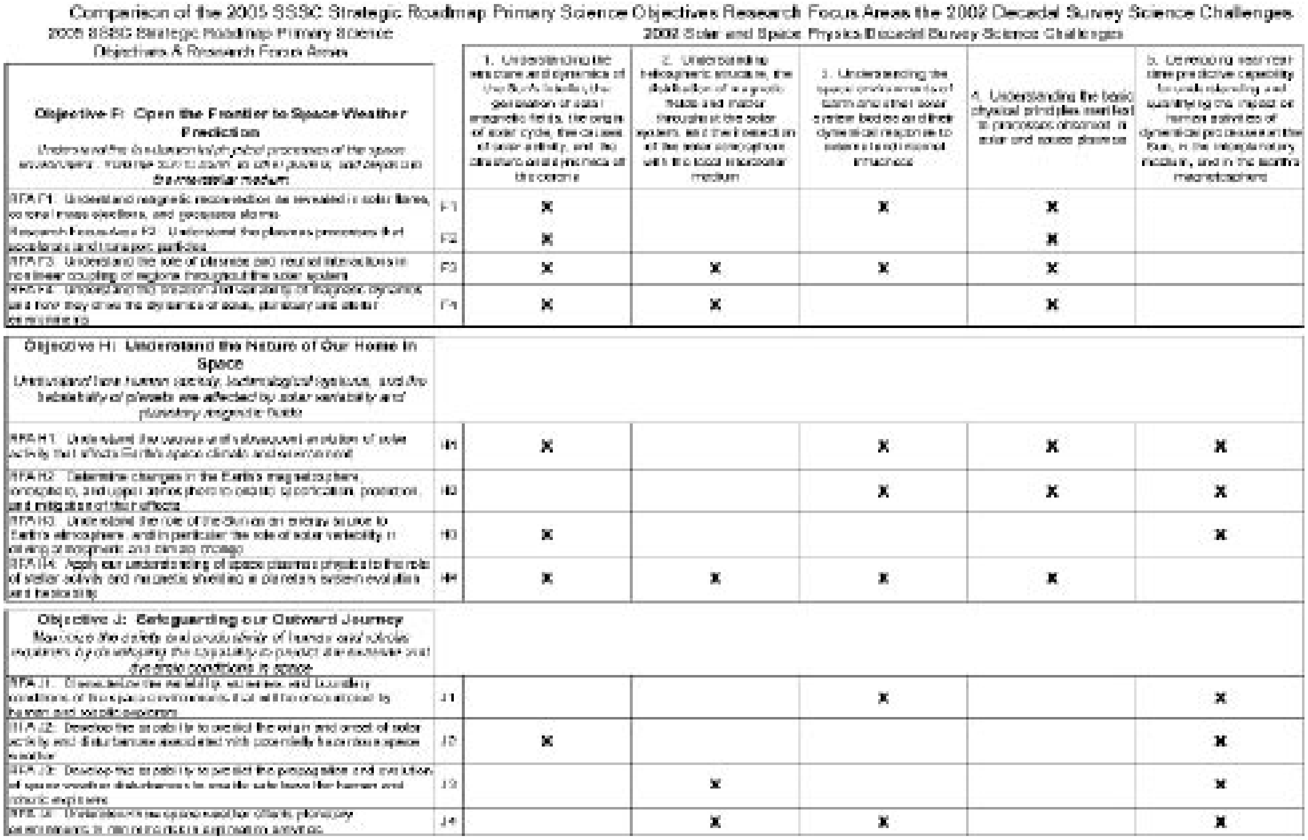
Our final criterion was to define a program that is possible to achieve – both technically and financially. This was a real challenge with the reduced funding available in both the Explorer and STP programs. Many important topics are deferred, put aside, or left for implementation in the Explorer program. The optimized plan restores many synergies lost in the realistic plan.

How did the resulting program compare to earlier recommendations provided in the decadal survey and previous SEC Roadmaps and NASA Enterprise Strategy?

The NRC and roadmap committees ended up in remarkably similar places. The science and exploration objectives, the research focus areas, investigations, and achievements match very well. There is a somewhat broader scope in this road map because of the connections with Earth science, the new emphasis on the journey of exploration, and the longer time period considered. The missions proposed include all the top priorities of the 2002 NRC Report The Sun to the Earth - and Beyond for NASA. Together with the completion of STEREO, Solar-B, and SDO and the continued operation of the SSSC Great Observatory, these include Solar Probe, MMS, RBSP & ITSP, JPO/Juno, IHSentinels, GEC, LCAS, MMS, L1/Heliostorm, GEMINI, L1 Monitor, Solar Orbiter, Explorers, and all of the relevant recommendations for vitality as well. (A few mission names have changed). Table B2 gives a detailed comparison between the 2002 Decadal Survey Science Challenges and the Research Focus Areas described in Part II, Chapter 1.

How can this be? 1) The basic science needed to predict conditions for safe and productive exploration is the same understanding required to handle the affects of the space environment on society. The requirements for the outward journey have been largely anticipated by LWS. 2) The strategy laid out in the past was robust, in the sense that the long-term objectives transcend most immediate changes in emphasis. Understanding of the entire system was crucial and remains crucial. The science questions and the order in which they must be addressed remain the same in order to open the frontier to space weather prediction. The STP missions fly at a slower rate, but the basic science they will provide serves the most important needs of the NASA vision. 3) With reduced resources the missions already initiated will take the remainder of the decade to complete. In our realistic scenario no mission will launch before 2015 that has not already begun and this time frame goes beyond the end of the decadal survey. Because these missions support the vision, the program looks very much the same in the near term as it did three years ago.

There are some important changes to the intermediate and long term program. The importance of the inner heliosphere through which disturbances propagate has increased. New missions to understand energetic particles have been identified and we have recommended increased collaboration with Earth science colleagues to understand the terrestrial radiation budget. There is also increased emphasis on the contributions our discipline can make to understanding the Martian atmosphere and the role space weather effects have on planetary habitability. Decision points have been set where choices need to be made about the direction of the program based on evolving priorities and what is learned in the mean time. As in previous Roadmaps, a suite of unfunded flagship and partnership missions has been identified to address problems that cannot be handled in the existing mission lines; however, some of the partnership missions have changed. The importance of L1 observations has increased. And, unfortunately, many of the intermediate term missions from the last Roadmap have been pushed farther into the future.



Comparison of the 2005 SSSC Strategic Roadmap Primary Science Objectives Research Focus Areas the 2002 Decadal Survey Science Challenges

2005 SSSC Strategic Roadmap Primary Science Objectives & Research Focus Areas		2002 Solar and Space Physics Decadal Survey Science Challenges				
Objective F: 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*		1. Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of solar cycle, the causes of solar activity, and the structure and dynamics of the corona	2. Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium	3. Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences	4. Understanding the basic physical principles manifest in processes observed in solar and space plasmas	5. Developing near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere
RFA F1: Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms	F1	X		X	X	
Research Focus Area F2: Understand the plasma processes that accelerate and transport particles	F2	X			X	
RFA F3: Understand the role of plasma and neutral interactions in nonlinear coupling of regions throughout the solar system	F3	X	X	X	X	
RFA F4: Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments	F4	X	X		X	
Objective H: 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*						
RFA H1: Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment	H1	X		X	X	X
RFA H2: Determine changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects	H2			X	X	X
RFA H3: Understand the role of the Sun as an energy source to Earth's atmosphere, and in particular the role of solar variability in driving atmospheric and climate change	H3	X				X
RFA H4: Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability	H4	X	X	X	X	
Objective J: Safeguarding 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*						
RFA J1: Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers	J1			X		X
RFA J2: Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather	J2	X				X
RFA J3: Develop the capability to predict the propagation and evolution of space weather disturbances to enable safe travel for human and robotic explorers	J3		X			X
RFA J4: Understand how space weather affects planetary environments to minimize risk in exploration activities	J4		X	X		X

C. Linkages between Sun-Solar System Connections and other NASA Activities

Sun-solar system connection (SSSC) science is focused on space plasma physics, which encompasses the sun and processes and phenomena that determine the space environment near the sun, the Earth-moon system, throughout interplanetary space to the very boundary of the solar system, and in the vicinity of every solar system body. To the degree that the space environment matters to humans or their technological systems, either on Earth or in space, SSSC science has application to human activities. Penetrating energetic particles and photons, produced by acceleration and radiation processes in space plasmas, profoundly and adversely impact any exposed living organism through cellular damage and mutation. They also adversely impact exposed technological systems through episodic and cumulative damage to microcircuits and cumulative degradation of certain materials. Therefore, processes that produce and transport energetic radiation are of direct interest to modern humans. Space weather in the vicinity of planetary bodies affects upper atmospheric state (density and wind distributions critical to vehicle aerocapture, ascent, and descent scenarios) and ionospheric state (spatial and temporal electron density distributions that influence navigation systems and all high band-width communications). The situation for long-duration space flight is somewhat analogous to deep-ocean operations of naval ships. Vessels are designed to survive in various climatic conditions; yet the weather, which can be extreme, limits operations and determines how vessels should be configured in any situation. Similarly, operations in space, i.e., EVAs, maneuvers, operations on lunar and planetary surfaces, and safe harbor (atmospheric) entrance and exit, will depend on the space weather. As in the modern terrestrial case, space weather awareness, understanding, and prediction will be essential enabling activities with respect to space exploration operations. Therefore, we recognize strategic linkages between the SSSC Roadmap and all three Exploration roadmaps (Lunar exploration, Mars exploration, and the development of the Crew Exploration Vehicle).

The effects of space weather on Earth's atmosphere are of special interest. Enhanced ozone depletion is a documented consequence of energetic particle precipitation. We are aware of space plasma processes that erode the Earth's atmosphere, removing ~103 kg of Hydrogen and Oxygen daily, and much larger quantities during space storms. We have performed computer simulations that lead us to infer even greater loss of atmospheric constituents at Mars, which lacks the shielding provided by an intrinsic magnetic field. The potential role of local space weather and/or solar variability in terrestrial climate change is as yet unknown. The state of the Earth's ionosphere is thought to be subtly modified by terrestrial seismic activity. Quantitative determination of the intrinsic terrestrial magnetic field requires an accounting of field sources external to the solid Earth. These external sources are dominated by electrical currents carried in the space plasmas surrounding the Earth. For these reasons, we also recognize strategic linkages between the SSSC Roadmap and the Earth Science Roadmap.

The same processes and phenomena that drive space weather in our solar system also shape the environment throughout the universe. We have a typical, variable, main sequence star (the Sun) in our back yard. We live on a fully habitable planet that is largely protected from elements of our local space environment by a magnetic shield (what we call a magnetosphere), a feature not shared by all astronomical, or even planetary bodies. As we try to understand the remote universe and its potential to evolve life, it is imperative that we take as full account as possible of the 'specimens' we hold in our hands, so to speak. Therefore, we recognize important linkages between the SSSC Roadmap and other scientific roadmaps that seek to understand nearby planetary systems (SRM03) and the larger universe (SRM08) and also between the SSSC Roadmap and the roadmap to search for other habitable planets (SRM04).

Linkages Between SSSC Strategic Roadmap and NASA Capability Roadmaps

Continued progress in Sun-Solar System Connection (SSSC) science requires new capabilities based on the development of new technology. Future technology needs are driven by diverse requirements. Cluster and constellation missions are required to simultaneously sample large-scale space plasmas at multiple points (Magnetospheric Constellation, Inner Heliospheric Sentinals, Solar Weather Buoys, Dayside Boundary Layer Constellation, Inner Magnetospheric Constellataion). Highly focused missions require improved measurement resolution and sensitivity (MMS, GEC, RAM, MTRAP, GEMINI, DOPPLER). Missions with special orbital requirements will need in-space propulsion. Examples include requirements to dwell at a point upstream in the solar wind from the L1 libration point (Heliostorm), to achieve a polar heliocentric orbit (Solar Polar Imager), or to escape from the solar system (Interstellar Probe). As the missions in our roadmap are developed, they will require new technologies in instrumentation, data visualization, communication, and analysis systems. Future SSSC technology needs fall into several focus areas:

Propulsion and Power: A number of SSSC missions will study solar system plasmas from unique vantage points. Propulsion systems that can supply a larger delta-V than conventional rocket engines, or that can provide large delta-V without a large mass or power penalty, can enable such challenging missions. For high-performance, cost-effective propulsion in the inner solar system, or for exiting the solar system in timely fashion, solar sails are the ideal choice. Significant ground demonstrations of solar sail technologies have been performed already. We encourage continued development of this technology and support the idea of a flight demonstration during Phase 1 of this roadmap (CY 2005 – 2015). We also encourage renewed capacity to produce RTGs that have low-EMI, high-efficiency power conversion.

Micro-spacecraft: Owing to the large scale and complexity of solar system plasmas, future discoveries will depend on deployment of spacecraft in clusters and constellations, making simultaneous multi-point measurements within plasmas under study. Enabling technologies will include low mass/power/volume instruments, and low mass, low cost spacecraft.

DSN: NASA's Deep Space Network (DSN) is evolving to meet the communication and navigation needs of the agency's increasingly complex, data-intensive missions. Analysis of Sun-Solar System Connection roadmap missions suggests that, over the next 25 years, downlink rates will need to increase by a factor of at least 1,000, even from the more distant regions of our solar system. The trend toward multi-spacecraft missions will likely cause a large increase in the number of such supportable links back to Earth. Near-Earth missions should use and cultivate the continued evolution of commercial space networks.

Advanced Modeling: Advanced supercomputing is a vital capability for enabling space weather model development and innovative data analysis and visualization. Examples of successful innovation in this area include NASA's Information Power Grid, Project Columbia, and the VisBARD project.

Instrumentation: Many future SSSC missions will require development of new scientific instrumentation, including large focal plane arrays, large-scale adaptive optics, and solar-blind energetic particle and photon detectors. The development of hyperspectral and 3-dimensional detectors are needed for solar and geospace remote sensing. Miniaturization of high voltage power supplies will relieve mass and volume resource constraints. Increased quantum efficiency of UV and EUV detectors will enable significant savings in mass as small but sensitive instruments can be developed. The shear strength and impressive electronic properties of carbon nanotubes may lead to the development of stronger, lighter materials and power efficient ionization sources. Conductive polymers and other exotic materials and coatings may lead to development of solar blind detectors, new and better dust analyzers, and miniature mass spectrometers. It is important to develop and maintain ground test facilities for simulating particle and radiation environment in space. Radiation test facilities will be particularly important as technological innovations and the push to develop more power efficient instruments results in smaller electronic instrumentation. Ground testing is extremely valuable, but NASA's low-cost access to space (LCAS) program is required for complete testing and full validation of advanced instrumentation. An area of instrumentation where we should place significant development effort is in imaging, which provides more information than any practical number of single-point measurements. Imaging is crucial to understand the complex interacting set of systems that make up the sun-solar system if we are to have properly constrained and accurate predictive models that are critical to support exploration, including a sustained human presence in space. The three primary imaging tools include Energetic Neutral Atom (ENA), Radio Tomography, and Photon Imaging, that includes x-ray, extreme ultraviolet (EUV), far ultraviolet (FUV), visible (VIS) and infrared (IR).

Space Environment Testbeds (SET): SET is a technology development project that performs spaceflight experiments of new approaches for mitigating the effects of the dynamic space environment that are driven by solar variability. Its investigations validate new hardware, methods, models, and tools, all geared toward mitigating the effect of the space environment on systems.

D. External Cost Drivers Beyond Our Control

Scientists and engineers working on Sun-Solar System Connection science have overcome many of the problems of building, flying, and operating space missions. But our science is affected by factors beyond the control of the community. Each is founded on rational decisions made by groups in the larger society which we work within. Like Reinhold Niebuhr, we need "the serenity to accept the things [we] cannot change, the courage to change the things I can, and the wisdom to know the difference."

SPACE LAUNCH COST IN THE FREE MARKET. The single largest cost in most space missions is the launch vehicle. Unlike other technologies, the cost to orbit a kilogram has been nearly constant over the past decade. Why is the cost per mass so expensive? Space launchers are the most difficult challenges in engineering and manufacture because the forces and energies present in a launch vehicle are so high that they prevent graceful failures. From 1988 to 1999, 4% of launches failed in ways that required their destruction to insure public safety; as an Aeronautics and Space Engineering Board report states "Destruct commands are often superfluous because vehicles explode or break up because of dynamic forces." In the early years of spaceflight, NASA solved this problem by building duplicate satellites, so that one might succeed if another failed. Today the response of the users has been to emphasize reliability of a small number of satellites.

The commercial space market provides about half of the global demand for launch vehicles. The 2004 FAA/COMSTAC forecast of commercial demand shows that the launch rate is static at ~22 per year from 2000 until 2013. The principal change has been the demand for very large satellites, with the average mass per satellite growing from 2,400 kg in 1993-94 to 4,100 kg in 2003-04. The recent development of EELVs by the DoD suggests that their needs are similar to those of the commercial market. Some of the other Federal space activities, including NASA, also need large spacecraft and launchers. Taken together, the manufacturers of space launchers have good reason to focus on larger vehicles. The constant, small numbers of launches prevents economies of scale. To recoup the high development costs of new launchers, it is desirable to stop the production of older, smaller vehicles. Opportunity for small, simple, inexpensive, or risky payloads is absent when only large, expensive vehicles are available. Only large, expensive spacecraft make economic sense.

Yet, many NASA science missions can be accomplished with much smaller, less costly spacecraft. The SMEX, MIDEX, Discovery, ESSP, and New Millenium mission lines are all highly productive and depend on smaller vehicles.

PUBLIC TRUST AND RISK TOLERANCE. NASA provides the visible demonstration of the value of American technological society to solving grand problems. The inspiration provided by a great success such as the Mars Rovers is matched by the disappointment and concern attached to failures of other missions. Success and failure are visible and owned by the American public.

Personal freedom is one foundation of American society. We accord individuals the right to pursue activities that have significant risk of failure, even injury or death, as a price of that freedom. These private risks, taken voluntarily, are accepted. Risk in systems supported or controlled by tax funds is not accepted. Public safety and fiscal responsibility require detailed investigation to determine causality and future improvement. Examples include airline or other controlled transportation accidents, military accidents, and NASA accidents.

NASA missions are growing in size, cost, and complexity. Growing complexity drives a compounding of levels of risk management, including detailed process control, frequent reviews, and larger requirements on project management. Risk management seeks to minimize avoidable failures which impose delay and unplanned costs on all missions because they share common technologies independent of their science focus. As with other complex aspects of our society, the cost of risk management is an increasing fraction of the total.

Yet, risk is a critical part of the process of learning to succeed. NASA fosters future success by offering broad range of projects and missions to permit new generations to learn through trial and error, and help the best progress to larger projects. The desire to minimize risk must be tempered by a desire to maximize success.

NATIONAL SECURITY. Space technology provides unique contributions to national security, in reconnaissance, navigation, and communication (and space weather effects on such systems). American technological advantages over potential adversaries drives restrictions on civilian space interactions with foreign collaborators. Recent increases in these restrictions, founded in the International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR), apply even to interactions with friendly nations. NASA has accorded Principal Investigators (PI) freedom to involve foreign collaborators. The cost of these positive foreign interactions is increasing to insure the required compliance with ITAR/EAR restrictions. One result is decreased opportunities for the cost-sharing of space missions.

Yet, foreign contributions, such as the Huygens lander on the Cassini mission, have improved the quality of many science missions. Strengthening the technical teamwork between the U.S. and our partners permits activities that could not be achieved separately.

NASA AND EXTERNAL FACTORS. These problems are opportunities for NASA leadership. Fiscal responsibility, scientific and technological opportunities are strong arguments for working to maintain a range of launch vehicles, both large and small. This is a Capability important to NASA.

The public and future scientists are inspired by spaceflight because it challenges us to advance the limits of our abilities. Engaging the public in the challenges and inherent risks of pioneering spaceflight and exploration is an opportunity for E/PO on these issues in modern systems. NASA's work with its communities to develop the most cost-efficient methods for appropriate risk management of complex space projects is a Capability that can improve many areas of our technical society and economy.

Foreign collaborations add value that advances America's space goals. Aiding its projects to achieve cost-effective compliance with ITAR rules is a Capability important to NASA. Continued dialog and negotiation between NASA and the other relevant agencies to develop and clarify more appropriate rules for space research missions will enhance those agencies' Capability for dealing with other critical technical issues.

E. SSSC Mission Studies:

The following Roadmap Mission Quad Charts were prepared to provide a summary level description of the missions identified in the 2005 Roadmap. Additional mission quad charts identifed as * are included to archive community ideas and missions identified in previous roadmaps that were actively discussed but not included in the 2005 Roadmap narrative. The level of study maturity for these roadmap missions varies from a quad chart concept and description, to engineering concept and Vision Mission studies conducted during and between roadmaps, and finally to missions in pre-formulation and science definition team study, formulation and implementation. The current SSSC Explorer, STP and LWS missions in formulation and implementation are included to connect the present program through science objectives and achievements with the missions described in this Roadmap. The evolution of mission priorities derived from the NASA Strategic Planning and Budget process provides the direction and pace of additional studies for selected missions to raise their study maturity level in support of this process.

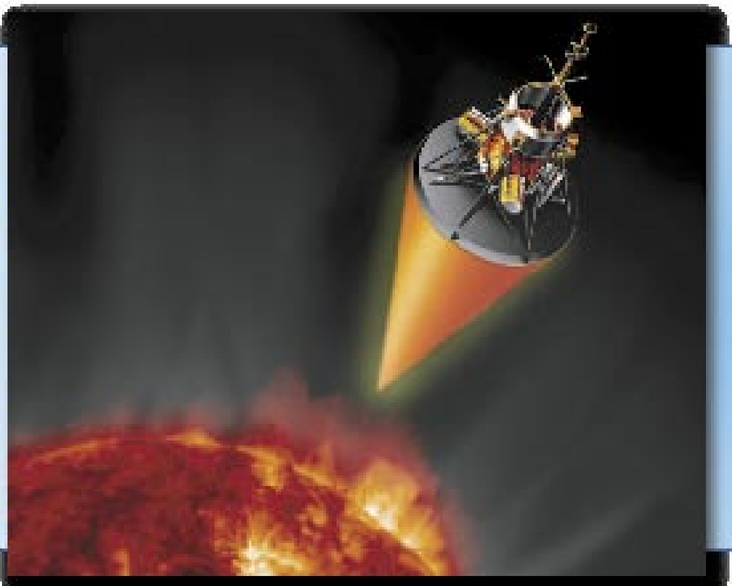
Alphabetical Listing of Quad Chart Summaries

Aeronomy of Ice in the Mesosphere (AIM)
Auroral Acceleration Multi-Probes (AAMP)
Aeronomy and Dynamics at Mars (ADAM)
Bepi-Colombo (BC)*
Dayside Boundary Layer Constellation (DBC)
Doppler
Farside Solar Observer
Geospace Electrodynamic Connections (GEC)
Geospace Magnetospheric and Ionospheric Neutral Imager (GEMINI)
Geospace System Response Imager (GSRI)*
Heliospheric Imager and Galactic Observer (HIGO)
Heliostorm
Interstellar Boundary Explorer (IBEX)
Inner Heliospheric Sentinels (IHS)
Inner Magnetospheric Constellation (IMC)
Interstellar Probe
Io Electrodynamics
Ionosphere Thermosphere Mesosphere (ITM) Waves
Ionosphere-Thermosphere Storm Probes (ITSP)
Janus*
Juno
L1 Diamond*
L1 Earth-Sun
L1 Mars
L1 Mission
L1 Solar-Climate Connection Explorer
Lunar Imaging Radio Array (LIRA)*
Magnetic TRAnsition region Probe (MTRAP)
Magnetosphere-Ionosphere Observatory (MIO)*

Magnetospheric Constellation (MC)
Magnetospheric Multiscale (MMS)
Mars AeronomyMars Atmospheric Reconaissance Survey (MARS)
Mars Dynamics*
Mars GOES
Near Earth Solar Coronal Explorer (NESCE)*
Neptune Orbiter
New Horizons (Pluto)*
Radiation Belt Storm Probe (RBSP)
Reconnection and Microscale (RAM)
Solar-B
Solar Connection Observatory for Planetary Environments (SCOPE)
Solar Dynamics Observatory (SDO)
Solar Energetic Particle Mission (SEPM)
Solar Heliospheric & Interplanetary Environment Lookout for Deep Space (SHIELDS)
Solar Imaging Radio Array (SIRA)
Solar Orbiter
Solar Polar Imager
Solar Probe
Solar Sail Flight Validation (Sail Demo)
Solar-TERrestrial RElations Observatory (STEREO)
Solar Weather Buoys (SWB)
Space Environment Testbeds (SET)
Space Physics Package and Interface*
ST-5 Microsat Technology Constellation Validation
Stellar Imager
Sun-Earth Coupling by Energetic Particles (SECEP)
Sun-Earth Energy Connector (SEEC)
Telemachus
Time History of Events and Macroscale Interactions During Substorms (THEMIS)
Titan*
Two Wide-Angle Imaging Neutral-Atom Spectrometeres (TWINS)
Tropical ITM Coupler
Venus Aeronomy Probe
Whole Sun Sentinels*

SSSC Landmark Discovery Missions

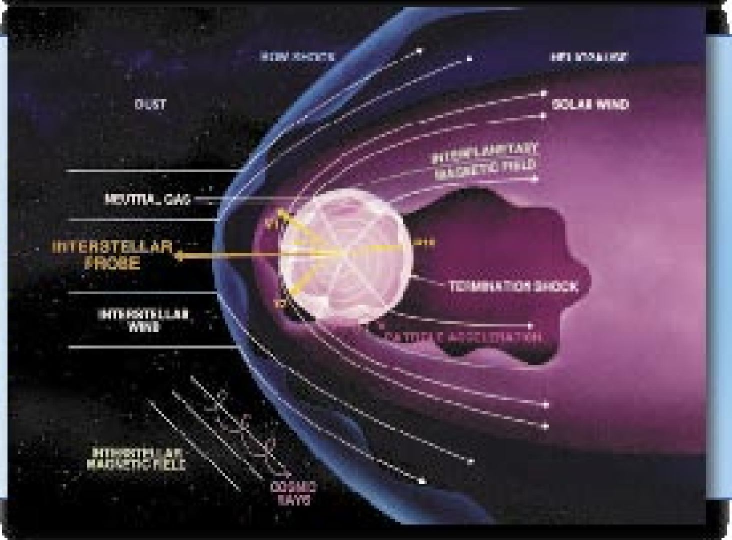
NEAR-IMMEDIATE TERM



Solar Probe

- Measure magnetic reconnection at the Sun
- Thermal shielding protection for in situ solar wind measurement at 4Rs

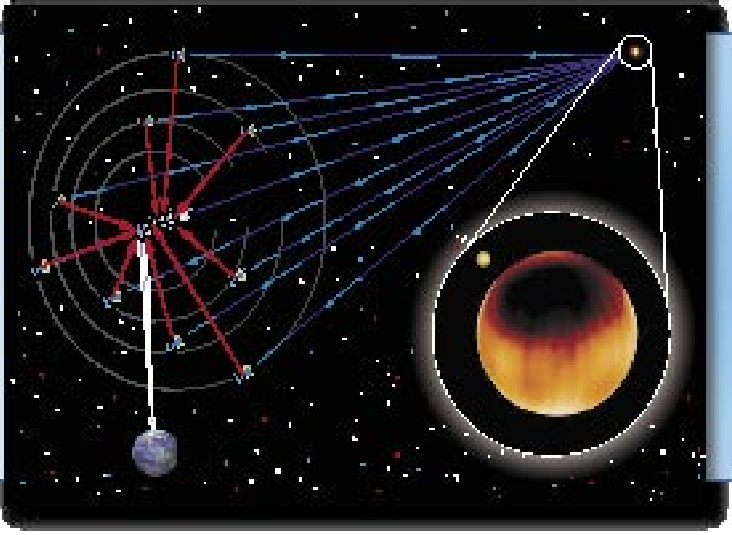
LONG-TERM



Interstellar Probe

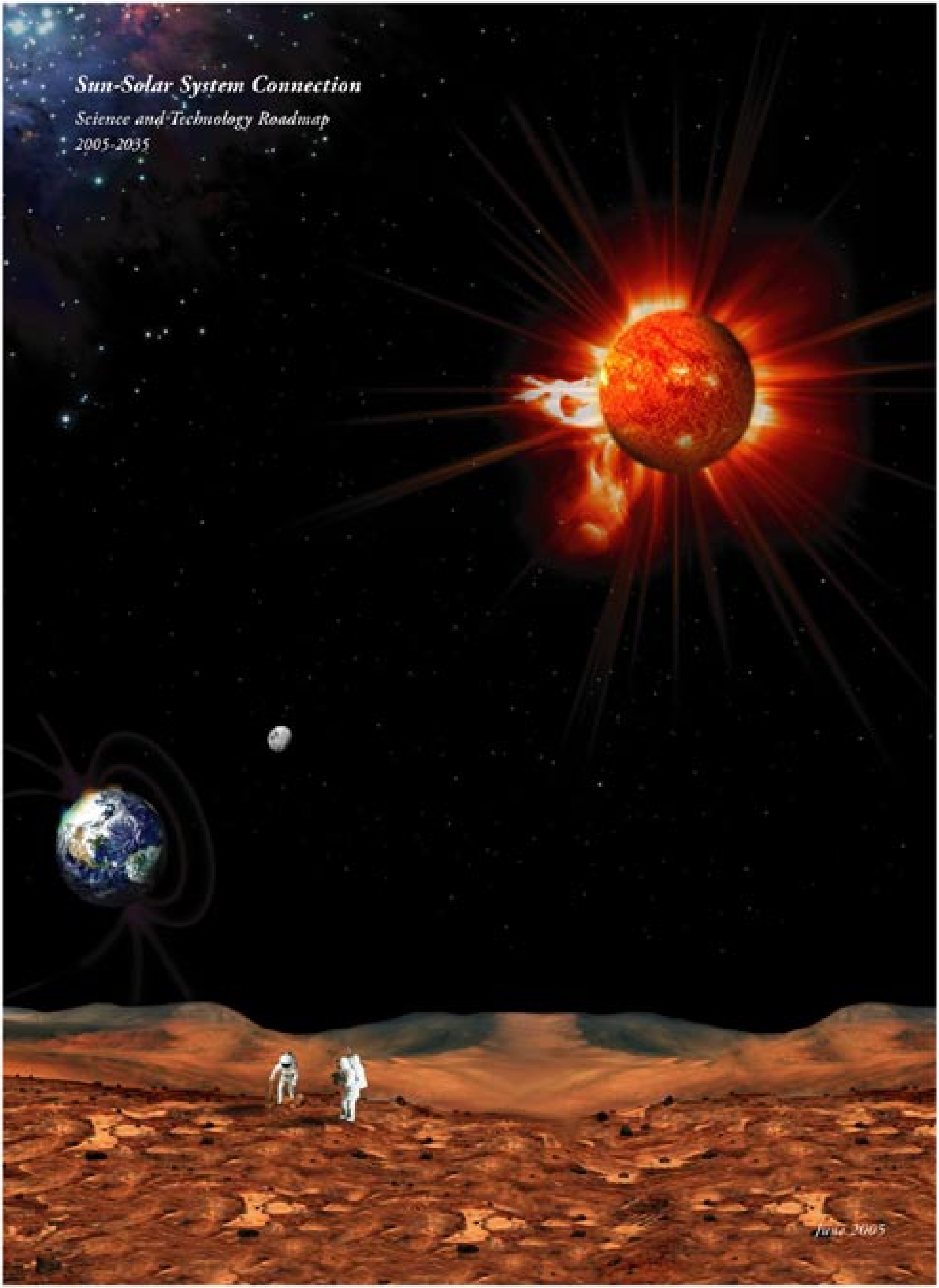
- Analyze the first direct sample of the interstellar medium
- Advanced propulsion for 200Au in 15 years

FAR-TERM



Stellar Imager

- Image activity in other stellar systems
- UV interferometry in space with precision formation flying autonomous constellation



Sun-Solar System Connection

Science and Technology Roadmap

2005-2035

June 2005