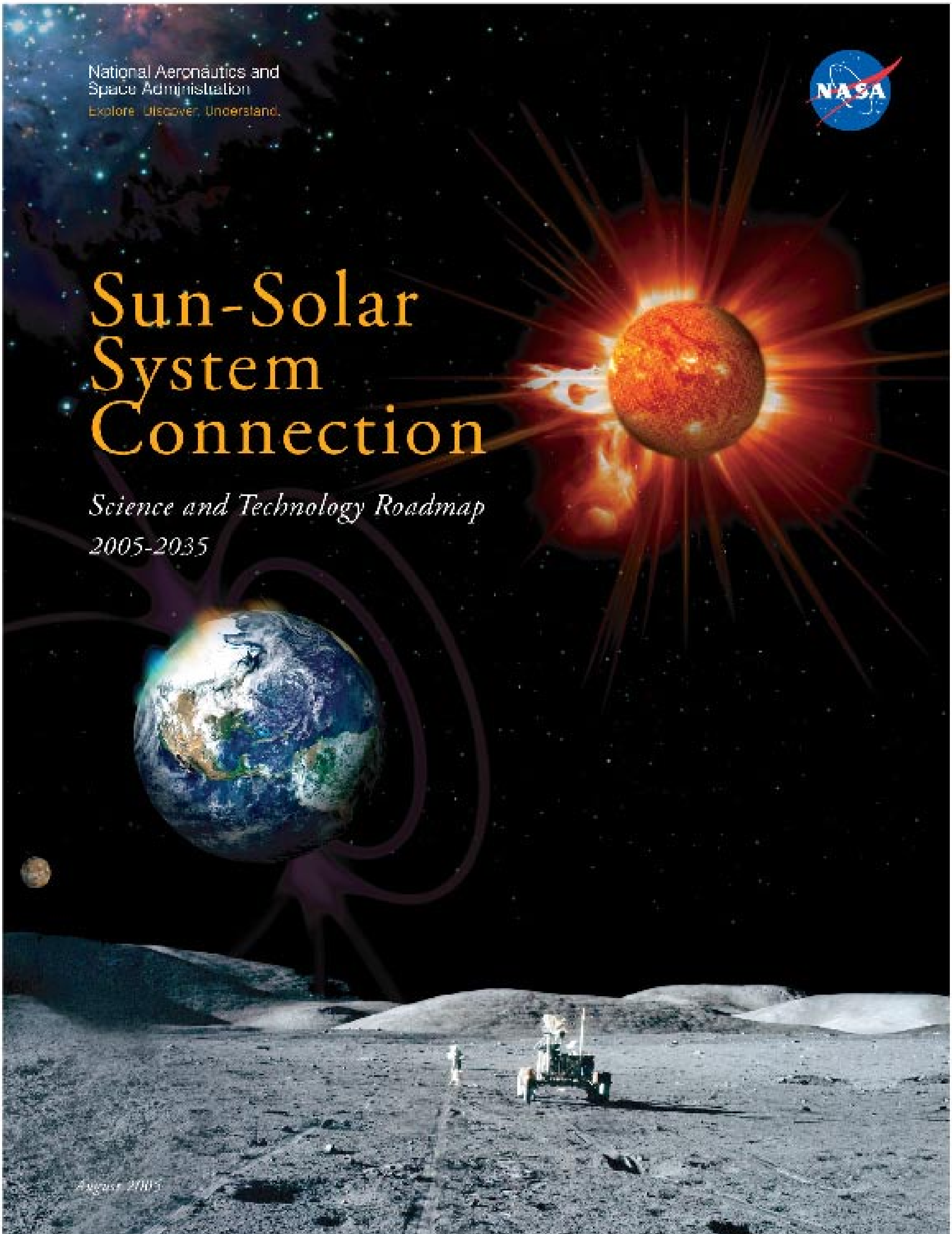
National Aeronautics and
Space Administration
Explore. Discover. Understand.

Sun-Solar System Connection

Science and Technology Roadmap

2005-2035

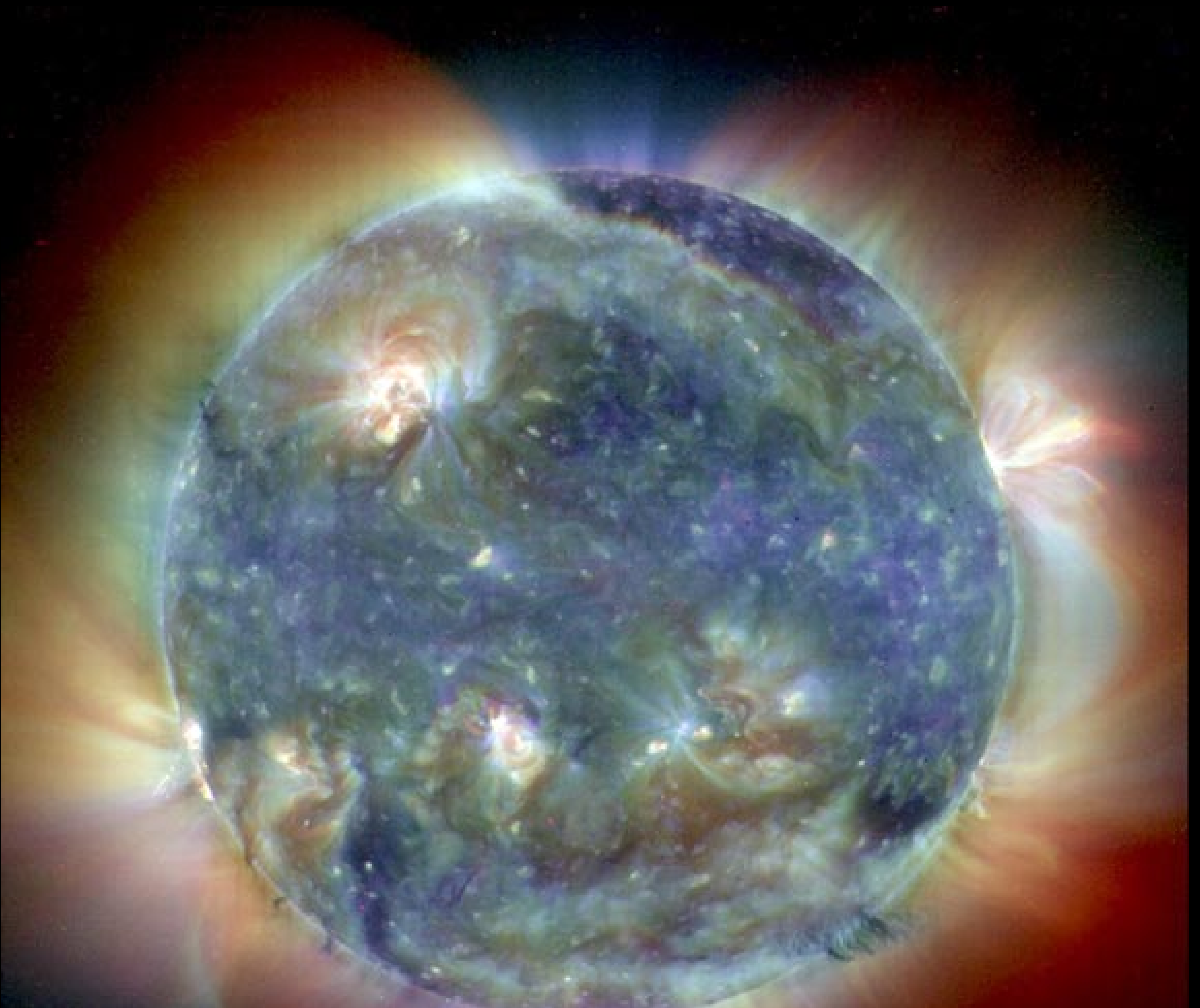


August 2005

How and why does the Sun vary?

How do planetary systems respond?

What are the impacts to humanity?



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. 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.

"Thought Generates Action" -
- C. Hobbs, Time Power, (1987)

It is a pleasure to accept the 2005 Sun-Solar System Connection Roadmap from our nation's science community. It describes a renewed strategic outlook to provide essential space environment knowledge for the benefit of society and for space exploration. It communicates our progress made to date, our plans for the future, and our opportunities for supporting the Agency's vision and mission.

The field of 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, has been vital to the emergence of a new view of the Sun and 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-too-distant future. 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 a common groundwork of inquiry spanning 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 these various disciplines of research, and that the results of this process will have not only cultural and intellectual value but will also be vital to the optimization of economic and political activities in the 21st Century.

This is our community's most ambitious roadmap plan to date. The program includes forefront research and technology development as well as the development of the most complex flight missions conceived. The program is a balanced portfolio of small missions and larger spacecraft with the goal of obtaining the best science at the lowest cost that meet NASA's standards for mission success. I am confident that the passage of time will validate the wisdom and choices of this roadmap committee and their consultants. It has been a privilege to associate with the people who have contributed their time and energy to the construction of this document.

To those involved, I extend 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.

Richard R. Fisher
Director, Earth-Sun Systems Division

The Sun-Solar System Connection Roadmap to Discovery

This is a Roadmap to a new understanding of the environment of our Earth, from its life-sustaining Sun, out beyond the frontiers of the solar system; from Earth's condensation out of the solar nebula, to the main sequence progression of our star into a red giant that will engulf the Earth. A widely dispersed collection of spacecraft now patrols this space, revealing not a placid star and isolated planets, but an immense, dynamic, and interconnected system within which our home planet is embedded and through which space explorers must journey. This coupled heliophysical system has evolved and will continue to evolve, with profound implications for our civilization.

The spacecraft of the Sun-Solar System Connection Program comprise a Great Observatory. Using them, we will study the Sun, the heliosphere, the Earth, and the other planetary environments as elements of a system that contains dynamic space weather and a climate that evolves in response to solar, planetary, and interstellar variability. We will continually evolve the great observatory by retiring old and adding new missions and instruments designed to answer the challenging questions confronting us now and in the future as humans explore the solar system.

The three scientific and exploration objectives listed on the facing page form the basis for a sustained scientific research program that depends on assimilating new data, through analysis, into theory, modeling, and simulation. Our program pursues a deeper understanding of the fundamental physical processes that underlie the exotic phenomena of space, such as magnetic reconnection, while at the same time targeting specific hazards, such as solar energetic particles. The result will represent not just a grand intellectual accomplishment; it will also provide the predictive capabilities essential to weather prediction in support of future human and robotic exploration of space, and will also serve other societal needs for knowledge.

Over the next ten years NASA will launch spacecraft to investigate the dynamo deep within the Sun, image its roiling surface, and, when funding allows, probe the intricate structures of its torrid atmosphere. Constellations of spacecraft, separating variations in time and space, will measure the complex responses of the environments of the Earth, Jupiter and Mars to solar influences.

Later activities will push the limits of our technological capabilities. The power of the SSSC Great Observatory will expand to predict hazardous events wherever explorers may travel. A high-speed probe will directly measure the interstellar environment from which the heliosphere shields us. Resolved images of other stars will provide amazing insights into the varying activity of our own Sun. External influences affecting the habitability of planets, including our own, will be understood, as will the varying internal properties of planets, such as their magnetization.

How can this all be accomplished?

Implementation of this ambitious program requires a coordinated and comprehensive set of flight missions with supporting research and technology programs to develop models, theories, instrumentation and data assimilation techniques, to enable future science and exploration activities. Virtual observatories will provide data access and advanced information systems to assimilate the data and provide computing access. Sustainability will be achieved through training of new explorers in a renewed Low Cost Access to Space program. A vigorous education and public outreach program will inform the public about the important benefits of NASA's SSSC program.

The SSSC endeavor relies on five major mission programs. The Solar Terrestrial Probes focus primarily on fundamental science questions. Living With a Star missions and partnerships provide a working knowledge of those processes that directly affect life and society, providing a knowledge base to support future operational capabilities. The flexible Explorer program provides a means of achieving urgent strategic goals that is highly responsive to new knowledge, technology and priorities. Challenging Flagship and Partnership missions address important goals that cannot be funded in the baseline program. The overarching SSSC Great Observatory evolves through the coordination of all new and existing mission elements to effectively confront the broadest problems of understanding Sun-Solar System Connections.

The SSSC Roadmap Committees invite you to join us on this exciting program of exploration, discover, and service to humanity.

The Sun-Solar System Connection

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The Sun-Solar System Connection Great Observatory in Action

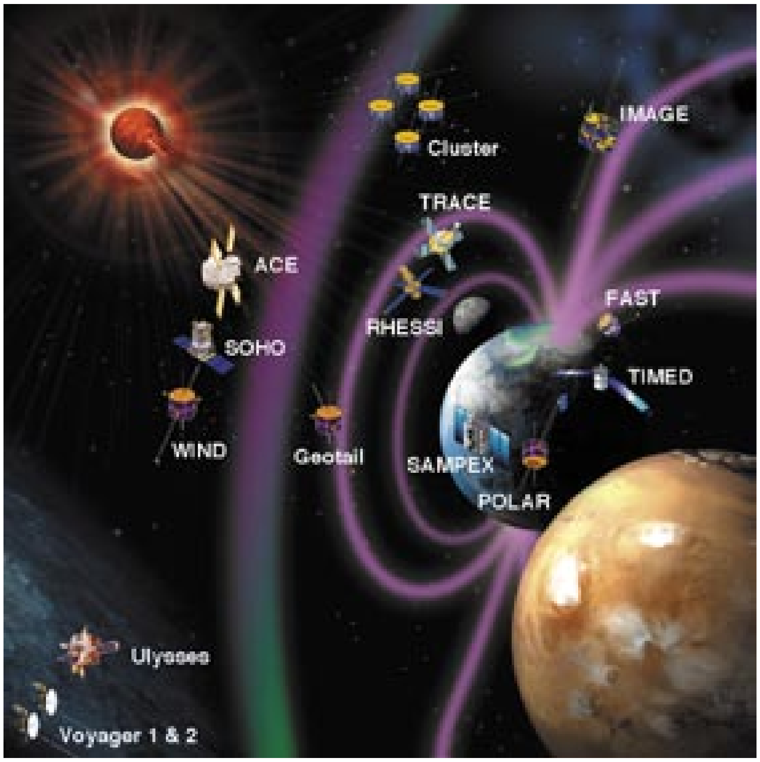
The 2003 Halloween Storms

During late October and early November 2003 a large cluster of active regions on the Sun produced an extended series of Coronal Mass Ejections (CMEs) that caused the most spectacular set of events ever observed to flow through the solar system. The solar storms, referred to as the 2003 Halloween Storms, drove a blast wave that pushed the solar system boundary about 1.5 billion miles deeper into interstellar space and expanded the volume of the Sun's corner of the galaxy by almost a third.

Only recently have enough research spacecraft been in place to track such blast waves as they propagate through the solar system revealing that solar storms are both universal and ubiquitous in their influence. This fleet of spacecraft, NASA's Sun-Solar System Great Observatory, observed the Halloween Storms as they blasted by Earth within a day and past Mars just a few hours later, they detected radio bursts from colliding CMEs as the storms streamed past Jupiter and Saturn. The most distant observations were taken at the outer edge of the solar system by the Voyager spacecraft almost eight months later.

At Earth, the storms produced half as much of the deadly 30-50 MeV particle radiation within a few days as the total emitted from the Sun in the previous 10 years and created a new radiation belt at Earth that lasted for several weeks. Southern Sweden experienced a blackout, surge currents were observed in Swedish pipelines, GPS signals were degraded or occluded, and several Mount Everest teams reported interference in high-frequency radio communications. The storms caused aircraft to be rerouted and spacecraft operators reported electronic upsets, data noise, proton degradation to solar arrays, orbit degradation, high levels of accumulated radiation, and proton heating. Fortunately, no NASA satellites near Earth were severely damaged, a tribute to advance planning and engineering, although the Mars Radiation Environment Experiment (MARIE) instrument on the Mars Odyssey spacecraft was disabled by radiation at Mar's orbit.

The Sun regularly sends out massive explosions of radiative plasma with the intensity of a billion megaton bombs hurtling through the solar system. Scientists have identified at least 13 other equally extreme events, including the historic Carrington event of September 1, 1859.



Such events, in addition to being disruptive to society, are important from a research point of view. Because they offer clearer signatures of the solar source mechanisms and propagation characteristics, the ensuing planetary effects and consequences can be unambiguously determined. The plasma, particle and electromagnetic consequences of such events are the focus of this roadmap. The goal of which is to understand the Sun, Heliosphere and Planetary environments as a single connected system and to apply this knowledge for the benefit of society and the exploration of the solar system. We will reach this goal by strategically evolving the distributed network of spacecraft we call the Sun-Solar System Great Observatory.

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SSSC RESEARCH FOCUS AREAS:

Open the Frontier to Space Environment Prediction

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

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.

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 how changes in the Earth's magnetosphere, ionosphere, and upper atmosphere change in order 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.

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.

Executive Summary

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 causal linkages between its elements. In late 2003 we observed an event that caused 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 its conductivity, moving plasmas generate electrical currents and magnetic fields. Many exotic phenomena ensue, some of which resemble turbulent fluid flows, but impart significant energy to a subset of particles; so much that they can be dangerous to semiconductor circuits or living tissue. Magnetic field lines act to organize their source plasmas into coherent cells, much as droplets of water are defined by surface tension. When such cells come into contact, their magnetic fields may reconnect, creating a coupling between them so that motions of one drive motions of the other. Electrical currents flow to generate the coupling forces, charged particles are accelerated, sometimes explosively as in solar flares.

Exploration of the universe has clearly shown that such electromagnetically driven processes act at the center of every stellar system. Our own solar system is controlled by the Sun, a magnetically variable star. Thus our solar system is the one part of the cosmos accessible to direct scientific investigation, and is our only hands-on astrophysical laboratory for understanding these universal processes.

Implementing 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.

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 one of the most compelling mysteries 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-1970'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 yet 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 general survey of the solar system is nearly 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 the universe. We have barely begun to scratch the surface of the history of our solar system over geologic time and have only recently determined 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.

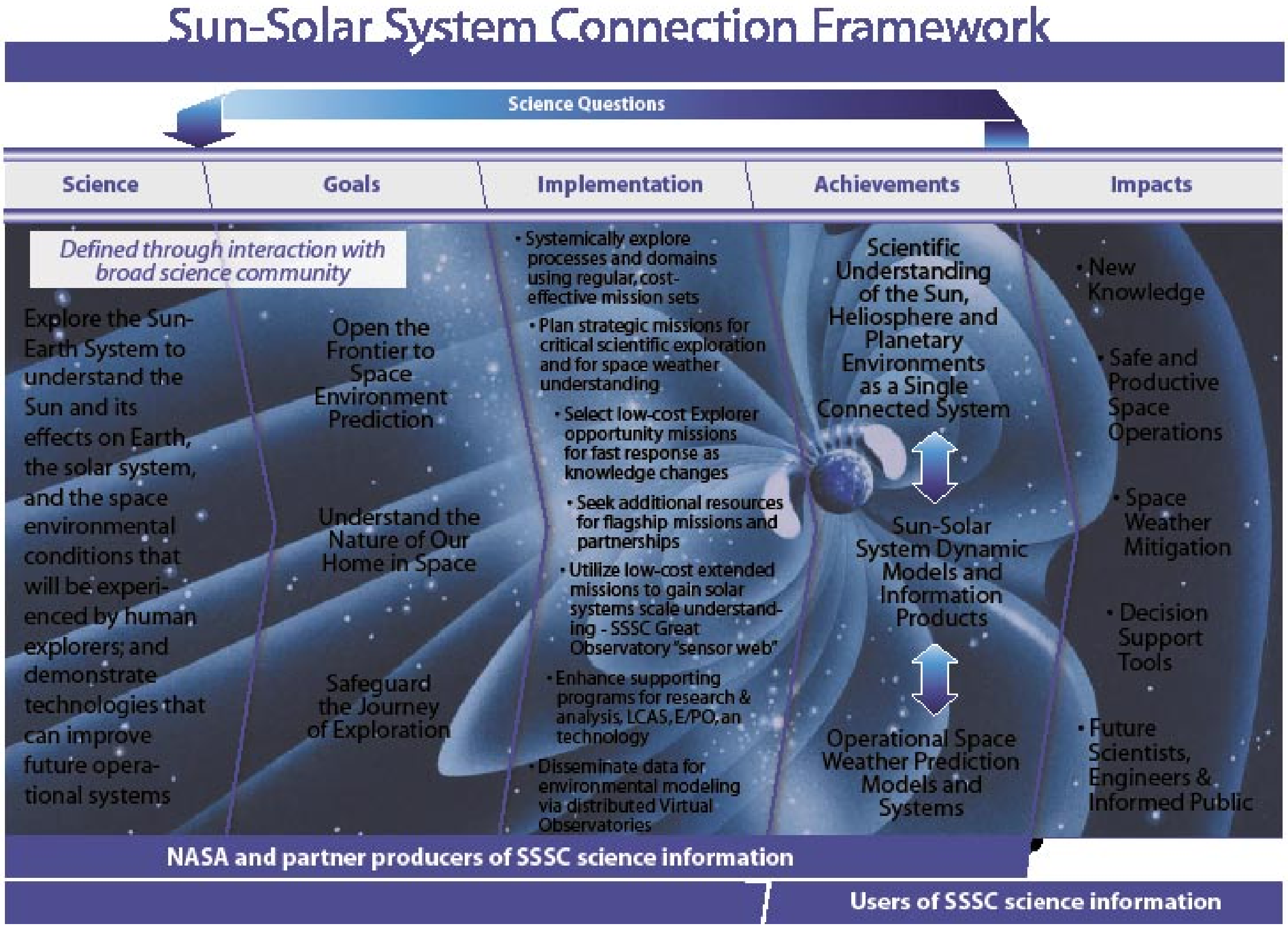
The United States is now embarking on an ambitious new journey of exploration to the Moon, Mars, and beyond. NASA has been challenged to establish a sustained presence on the Moon by the end of the next decade with the purpose of enabling Martian exploration thereafter. The will to achieve this Vision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

Our upper atmosphere, 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 must develop a mature 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 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 together with modeling to provide 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.



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.

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.

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. Much can be learned by studying our own atmosphere and applying that knowledge to the exploration of other planets. Even a casual scan of the solar system is sufficient to discover that habitability, particularly for humankind, requires a rare confluence of conditions. 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 much more remains to be understood.

Safeguard Our 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.

The great variety of space environment conditions will have a significant impact on our future space explorers, both robotic and human. We plan to diligently pursue 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. Useful engineering data are already flowing into exploration-oriented planning and implementations because the Sun-solar system community has long been exploring 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.

These objectives 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. We will pursue a deeper understanding of the fundamental physical processes that underlie the most important controlling phenomena. Focused research programs addressing specific space environmental hazards will help guide the design and operation of space weather mitigation program for societal and exploration needs. These pursuits represent not just a grand intellectual accomplishment for our times - they also provide the knowledge essential to advance U.S. scientific, security and economic interests and serve the future exploration of space through the mitigation of space weather concerns. Herein, we describe current plans for NASA's research programs in this area and the guiding principles we will follow in pursuit of the forthcoming 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. Applying a requirements driven approach, each objective has been associated with Research Focus Areas (RFAs) 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. Singly, the missions investigate parts of our solar system. Working together, the missions constitute a highly capable SSSC Great Observatory; the Great Observatory constitutes a mission to investigate the inner workings of the Solar System as a whole. The missions will be supported by research and analysis programs, theory and modeling programs, technology development programs, and education and public outreach.

Investigations supported by missions that can be launched in the next ten years are described below. Subsequent mission candidates for each program are described in the full 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 provide knowledge about those aspects of the Earth–Sun system that directly affect 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 Ionosphere - Thermosphere Storm Probes and Imager, to be launched in 2015, will help scientists understand, to the point of acquiring a predictive capability, the effects of geomagnetic storms on the atmospheric region located approximately 50 to 800 miles above Earth's surface. Last, the Inner Heliospheric Sentinels, also to be launched in 2015, will provide understanding of the propagation and evolution of eruptions and flares from the Sun to planetary environments. Partnership is crucial to LWS and we recommend SSSC collaboration on ESA's Solar Orbiter mission in this time frame. In addition, LWS will sponsor Space Environment Testbeds to 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. The Jupiter polar orbiting Juno mission will enable us to compare the solar wind interaction for a rapidly rotating magnetosphere with that of Earth. The Aeronomy and Dynamics at Mars (ADAM) mission, a potential Mars Scout, will provide information about the Martian atmosphere in support of human and robotic exploration of Mars.

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

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 to 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. 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.

Equally important is the need to investigate the space weather and solar variability that affect critical technologies used on Earth, 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 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.

> 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.

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 physical and temporal 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 sensing. 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. The missions provide the measurements in multiple locations needed to resolve temporal and spatial changes and to understand the interactions of the complex systems of regimes that make up our solar system. As we progress in the exploration of space, this 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 whose data are available through virtual observatories. Researchers will work together to provide the timely, on-demand data and analysis to 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 (LCAS**) 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 often 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 are 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

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 across the solar system.

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

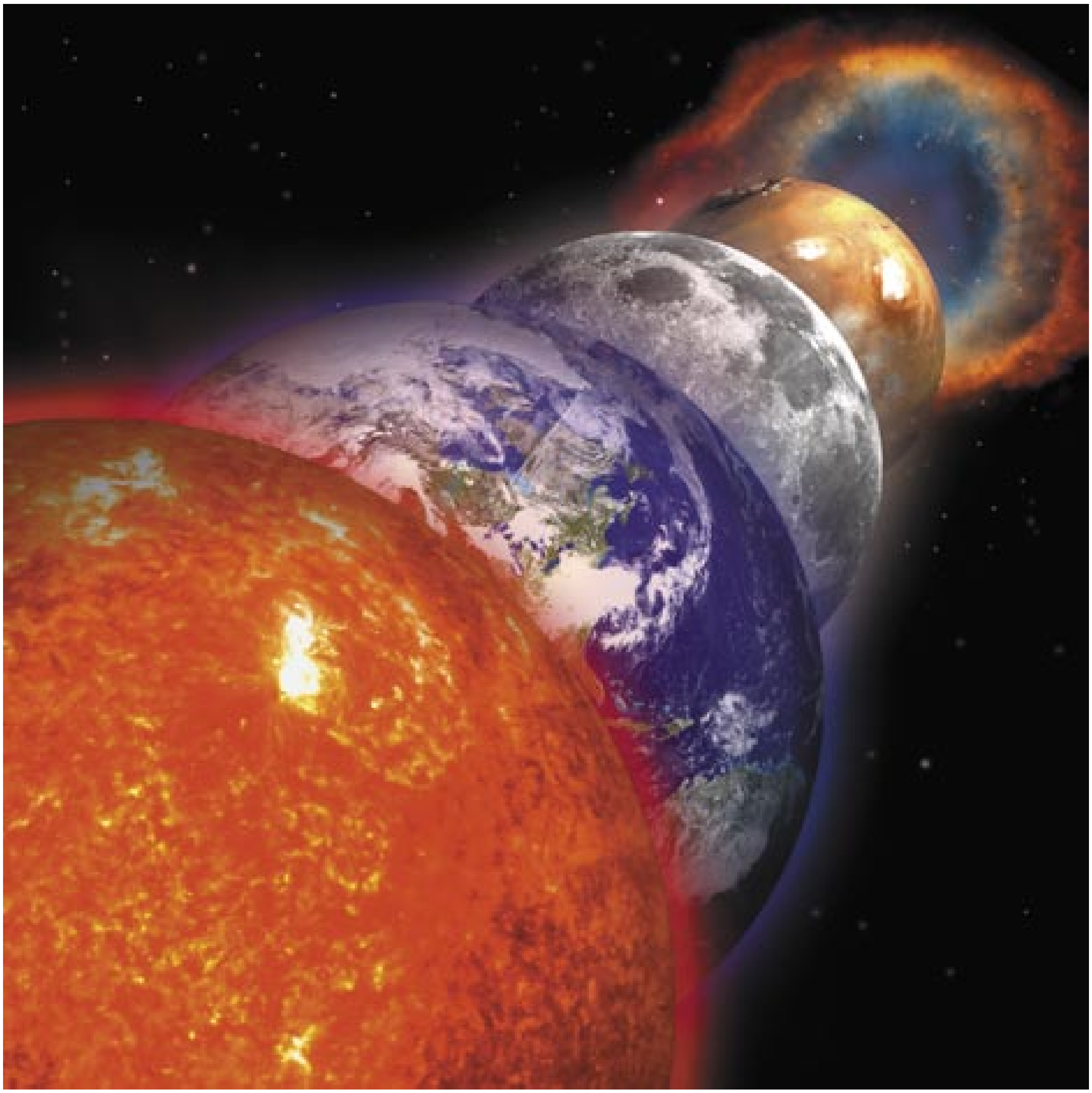
• NASA science helps us protect our society from hazardous space weather

• NASA science helps us understand climate change

• NASA science helps keep space explorers safe and supports exploration activities

This proposed SSSC program has been derived directly from NASA's new priorities. It should not be surprising 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."

Our present generation of space researchers has inherited a fantastic 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.



Sun, Earth, Moon, Mars, and Beyond...

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.

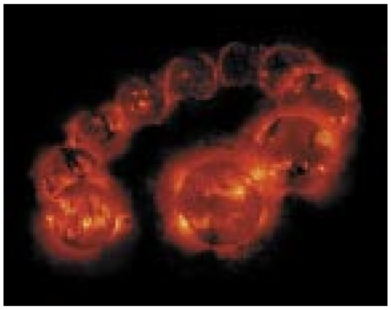
The new pragmatic challenges of the Vision for Space Exploration will dictate re-focused and intensified scientific exploration. This exploration will bring forth exciting discoveries, but only if it has the same broad scientific base that has nurtured the SSSC community to its current maturity. Why? 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.

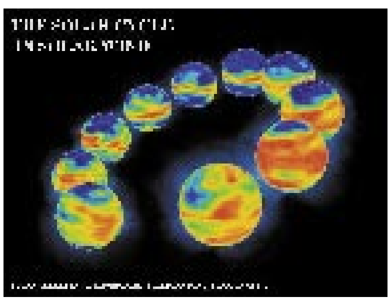
The Calm Between the Storms

Powerful events such as the 2003 Halloween space storms (page 4) 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 time scales 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 Earth's 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, dissociates, and ionizes the atmospheres of Earth and other 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 even in absence of solar events, with the whole array of energetic particle acceleration, aurora, and disturbances of satellites systems.

Coronal holes above stable solar areas power the solar wind, which carries magnetic fields with it. The magnetized solar wind, filling the heliosphere, deflects 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.

A New Science for the Age of Exploration: The Science of Exploration

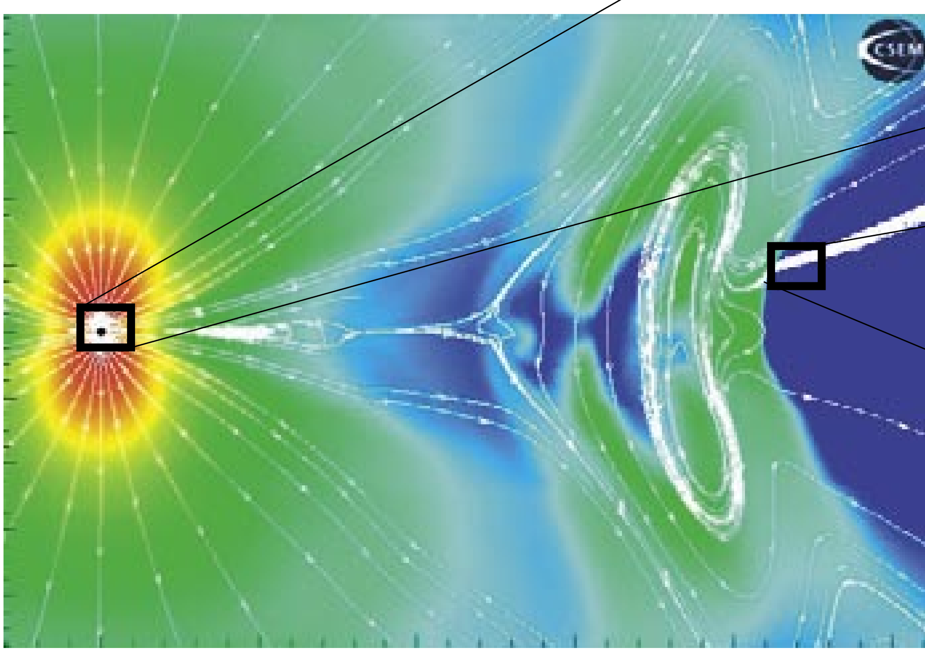
A New Science for the Age of Exploration

????????

Our program will help 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.



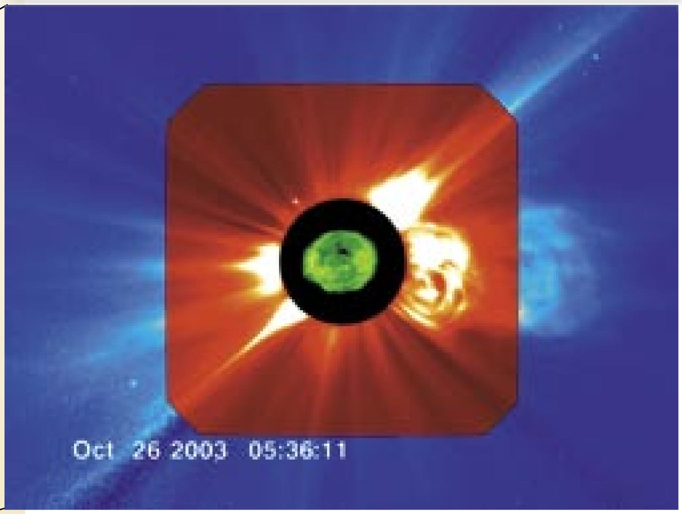
Several kinds of space plasma simulation models have been developed to provide a theoretical understanding of the flow of energy from the Sun through interplanetary space to the Earth's magnetosphere. This first frame illustrates the progression of a coronal mass ejection (CME). Shown are magnetic field lines (white) and magnetic field strength (low = blue to high = red) 20 hours into an event. The sun is the small black dot at the center of the red glow to the left. The CME is at the right riding on top of the expanding flow of the solar wind at speeds up to 2,000 kilometers per second.

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

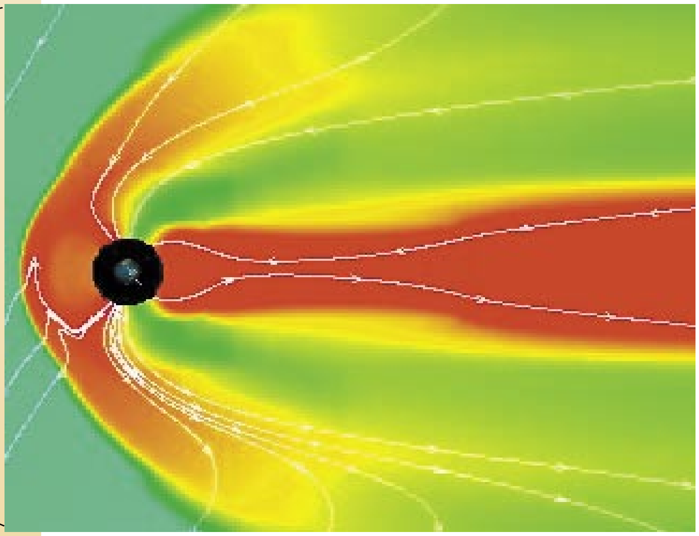
a) Identify the weakest links in our understanding of the coupled system and deploy targeted missions to resolve those science questions.

b) Utilize all NASA deployed assets as a dustributed sensor net to sample large-scale phenomena.

c) Combine these necessarily sparse data with modeling and theory to achieve system-wide understanding.

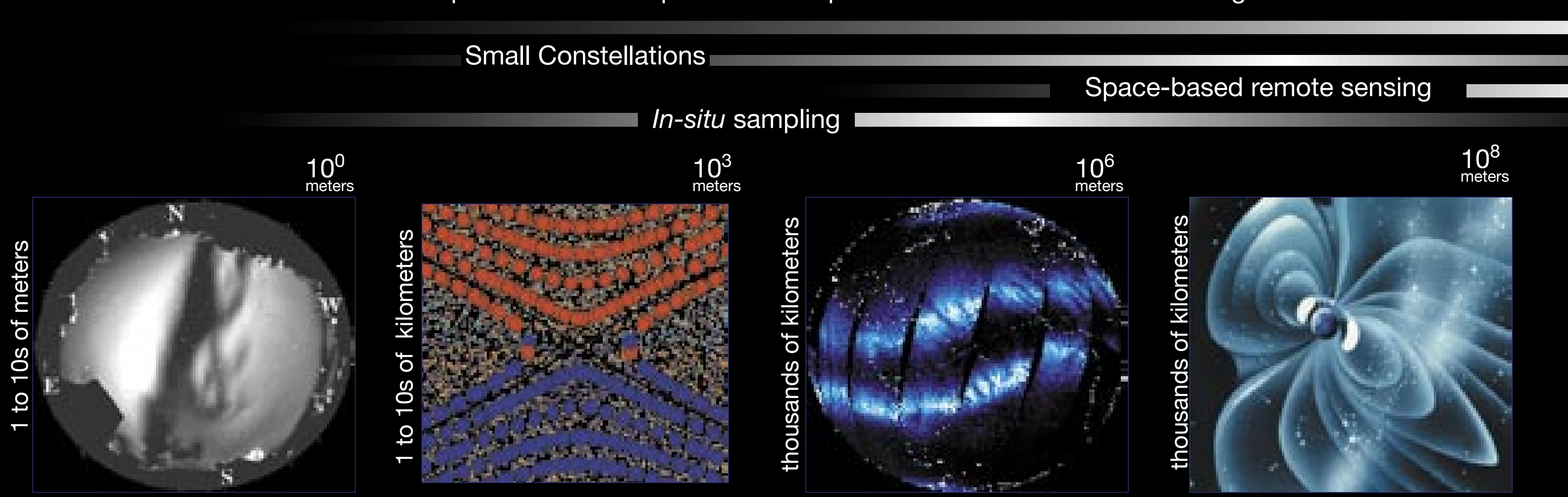


False color composite picture of the Sun illustrating the source of the disturbance shown in the simulation. The Sun is the center object in green. The areas in red and blue are views of the Sun's atmosphere (corona) where the CME can be seen as white areas moving rapidly away from the Sun.



This frame is a continuation of the same simulation as the CME impacts the Earth's magnetosphere creating a geomagnetic storm, which first manifests itself as large, episodic variations in the Earth's magnetic field. The electromagnetic pulses can produce a new radiation belt in minutes, not days, as normally occurs.

Interacting Powers of Ten: Our work over the past few decades have taught us enough about our local space environment to know that our task to produce reliable space weather predictions is a formidable challenge



ionospheric irregularities

diffusion regions of magnetic recommention

planetary-scale waves

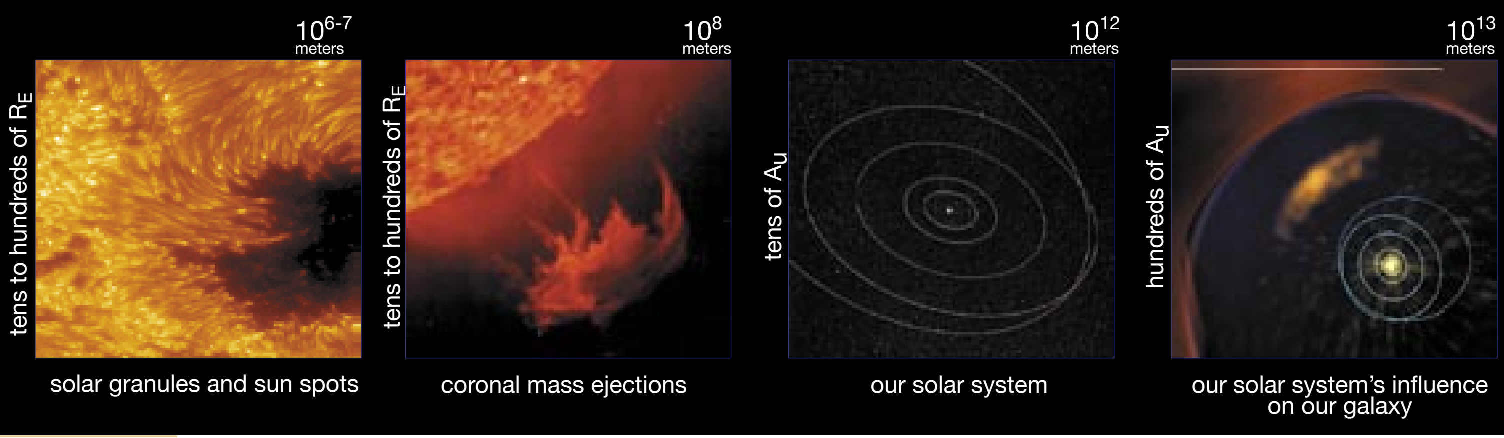
planetary magnetospheres

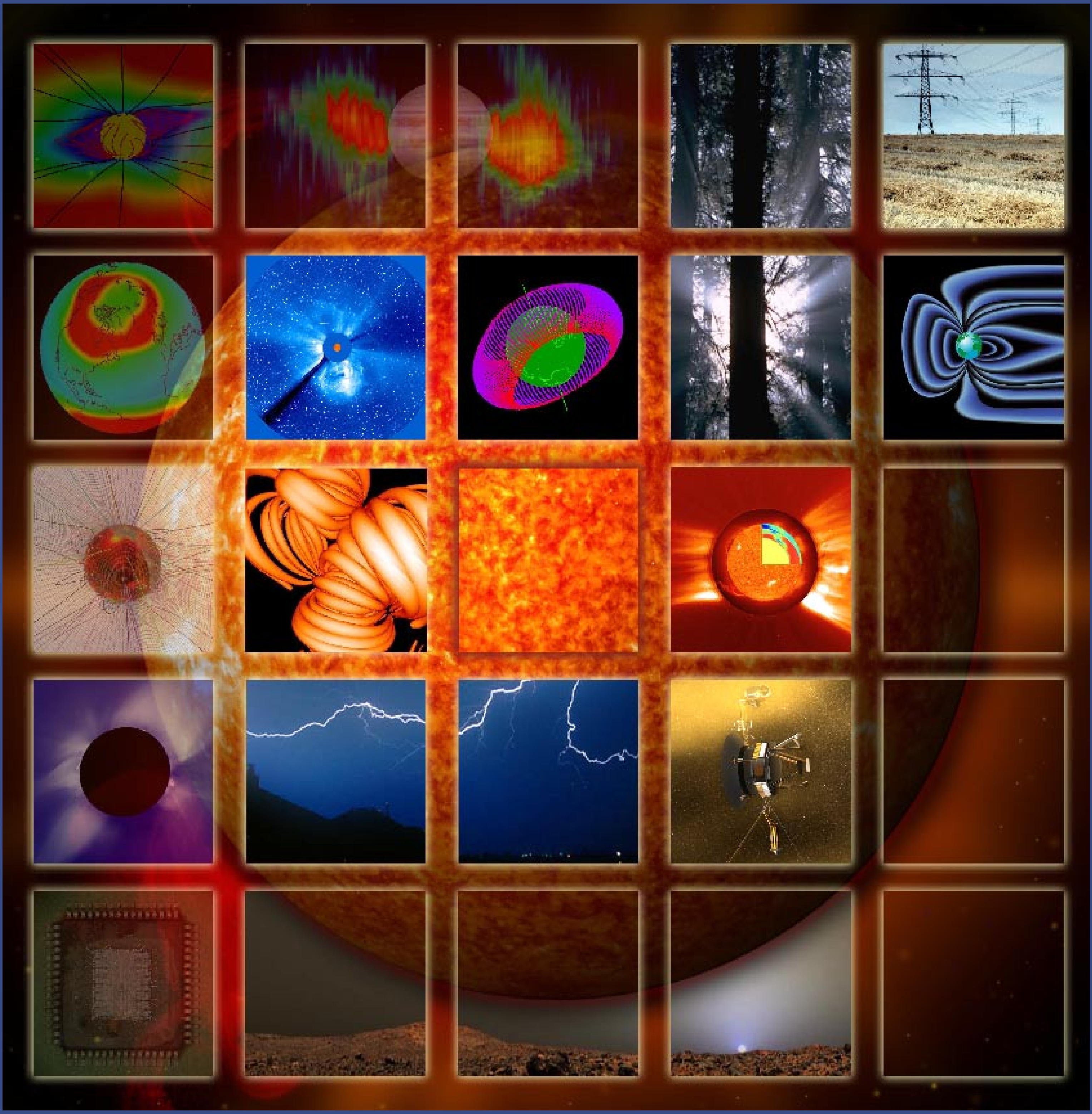
Challenges to achieving a quantitative, predictive understanding of this complex "system of systems"

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

Observations will be needed of solar system-scale and planetary- scale phenomena, and of microphysical plasma processes, which require a range of observational techniques: in situ, imaging, constellations, and the SSSC Great Observatory.

Solar System Great Observatory



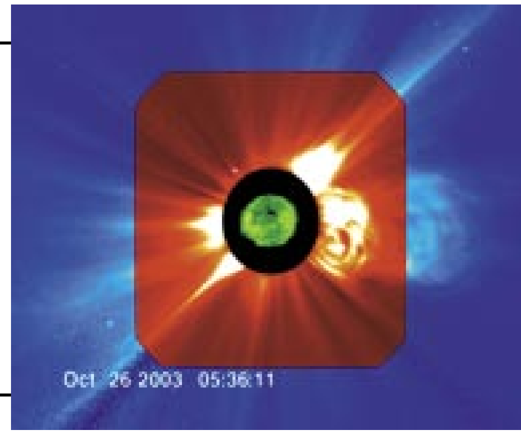


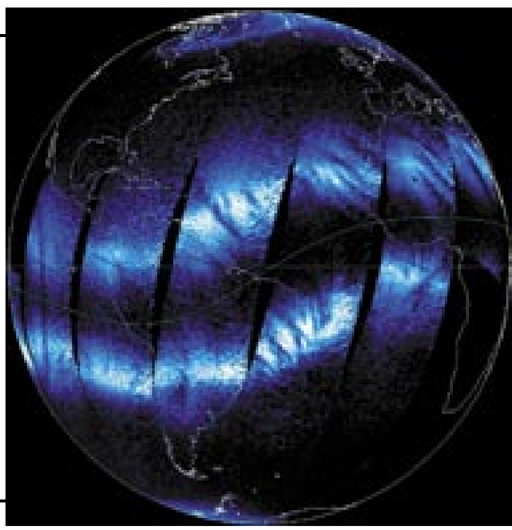
Achieving the Vision
Sun-Solar System Connection

SSSC 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



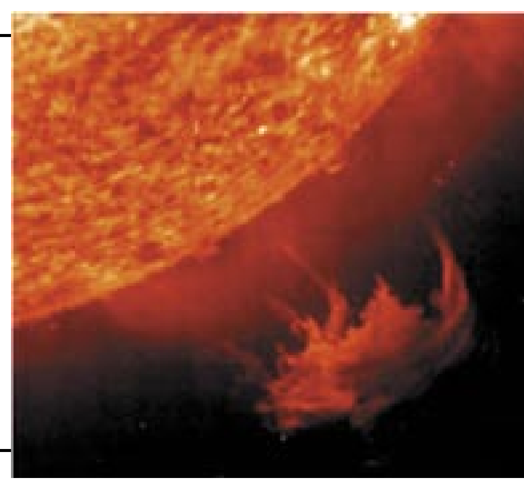


Understand the Nature of Our Home in Space

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 fantastic 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 (page 4). 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:

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

Our upper atmosphere, 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. Technological systems are disrupted and 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 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, together with modeling to provide 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:

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

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. Much can also be learned by studying our own atmosphere and applying that knowledge to the exploration of other planets. Even a casual scan of the solar system is sufficient to discover that habitability, particularly for humankind, requires a rare confluence of many factors. 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:

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

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. Useful engineering data are already flowing into exploration-oriented planning and implementations because the Sun-Solar System Connection community has been exploring 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.

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

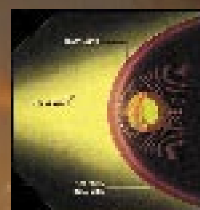
Sun-Solar System Connection Physics-
Three Forces:

- Gravity
- Pressure
- Magnetism

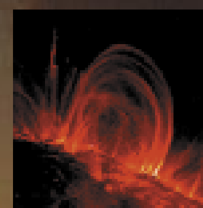
Galaxies

Planets

Heliosphere



Stellar Magnetism

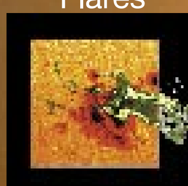


Space Weather

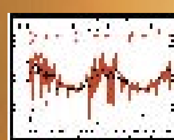
Stars/Sun:

CMEs

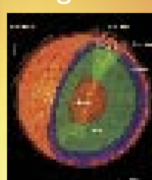
Flares



Total Solar Irradiance & Climate

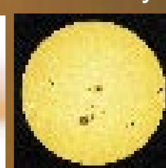


Magnetars



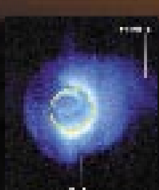
Shocks

Solar Variability

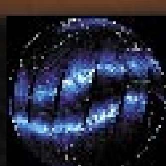


Planets:

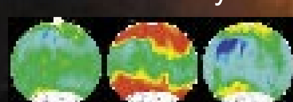
Aurorae



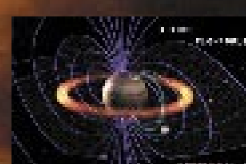
Ionospheres



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 relationship between the Sun and the heliosphere; the interfaces between planets, their magnetospheres and the heliosphere; and the boundary between the solar system and the galaxy

Objective F

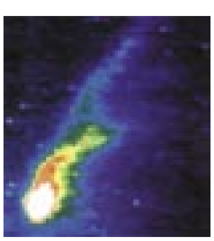
Open the Frontier to Space Environment Prediction

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

The Sun, our solar system and the universe consist primarily of plasma. Plasmas are more complex than solids, liquids, and gases because the motions of electrons and ions produce both electric and magnetic fields. The electric fields accelerate 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 variability of the Earth's ionosphere, the tenuous upper atmosphere of Mars, and even the fantastically energetic spinning pulsars that spray out beams of x-rays. 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.

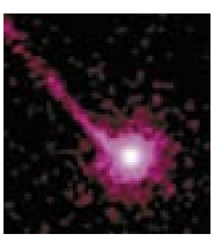
Prediction provides the ultimate test for scientific understanding.

The strategy for prioritizing 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

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.

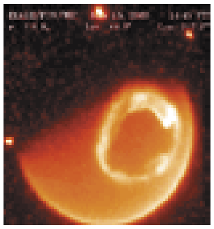
large-scale boundaries or by coupling between regions with very different conditions (for example, cold, dense neutral atmospheres with energetic particles).

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 can seriously affect worldwide communications. Although we have developed an initial picture of where reconnection may occur and the observable results, the detailed physical mechanisms, in particular, the microphysical processes and the role of large-scale topology are not understood. This focus area (RFA F.1) will deliver a fundamental understanding of this universal process in the very different regimes where it occurs.



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 energetic particle 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 step-wise 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, from Earth's aurora to the solar corona.

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 electrodynamic processes in the ionosphere and thermosphere 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 ensue 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 – 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.

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 at the Earth and at what size scales does magnetic reconnection occur on the Sun?

F2. Understand the plasma processes that accelerate and transport particles

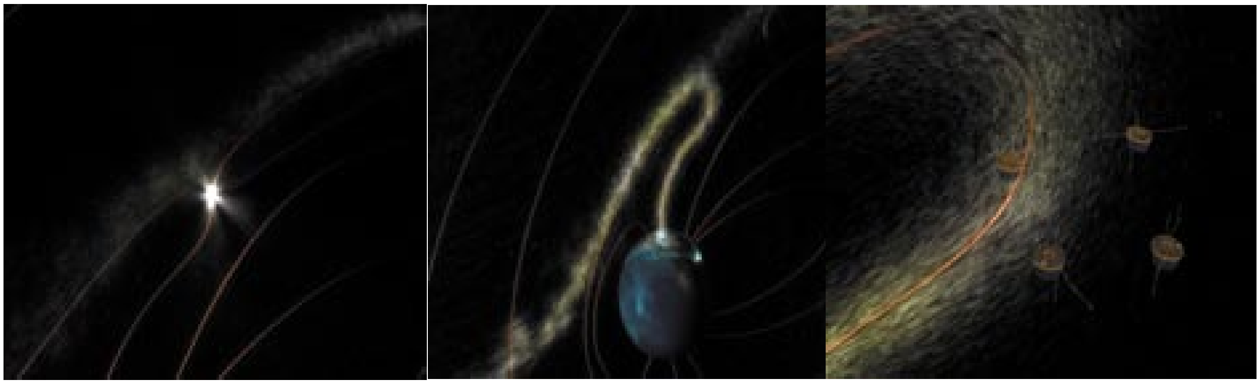
1. How are charged particles accelerated to high energies?
2. How are energized particles transported?
3. How is the solar wind accelerated and how does it evolve?
4. How are planetary thermal plasmas accelerated and transported?

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 does the neutral environment in planetary and cometary systems affect their 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?



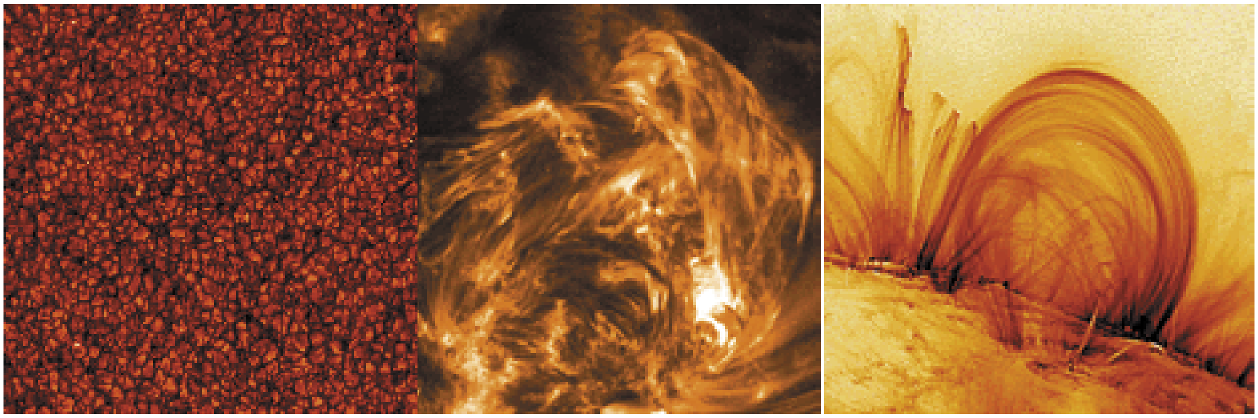
One type of reconnection takes place when the Earth's usually impenetrable magnetic field fractures and has to find a new stable configuration. Until the field mends itself, solar protons leak through the gap and jet into Earth's atmosphere, precipitating aurora and ionospheric currents. For a predictive 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. While there have been a few encounters with the diffusion region in the near-Earth environment, systematic in situ study of this region is just beginning. Current solar imaging is insufficient 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? What is the 3D structure of the reconnection region and how does this structure affect particle acceleration?



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 from coronal loops 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 acceleration regions), 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.

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, including Earth, 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 lower 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. The atmospheric mean circulation is thereby modified, resulting in changes to the temperature structure and redistribution of radiation absorbers and emitters. 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 are also key to understanding the upper atmosphere weather and climate on Mars and Venus.

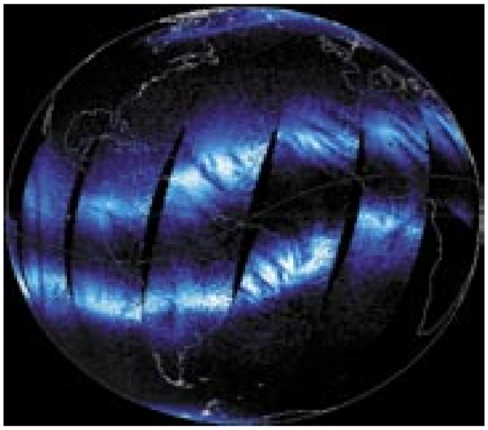


Image of electron density enhancements (equatorial arcs) in the Earth's ionosphere. The transport of plasma away from the equator results in alternating traveling bands of enhanced and depleted density. These exist during the daytime and most of the night and create enhanced media transmission errors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

The ionospheric electron density distribution depends on thermospheric composition and winds, together with electric fields that can be generated within the I-T system or imposed from the magnetosphere. In turn, the ionospheric plasma can inhibit or accelerate thermospheric winds that produce electric fields via an electrodynamic interaction. The interactions and feedback mechanisms remain a mystery due to a lack of simultaneous measurements of all the parameters that describe the fully coupled system. These interactions can occur on a global scale, but can also produce mesoscale structures such as high latitude thermospheric density cells that affect satellite orbits, or midlatitude electron density enhancements that disrupt aircraft navigation systems being implemented by the FAA. In addition, smaller scale structures cause ionospheric irregularities that degrade communication systems.

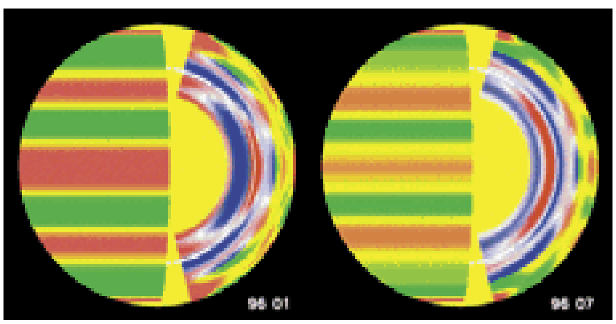
Turbulence is another example of a very important multi-scale, nonlinear process that transports particles and fields effectively, but is not well understood. Numerical simulations and laboratory experiments demonstrate that, in the presence of rotation or magnetic fields, turbulent motions create small-scale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

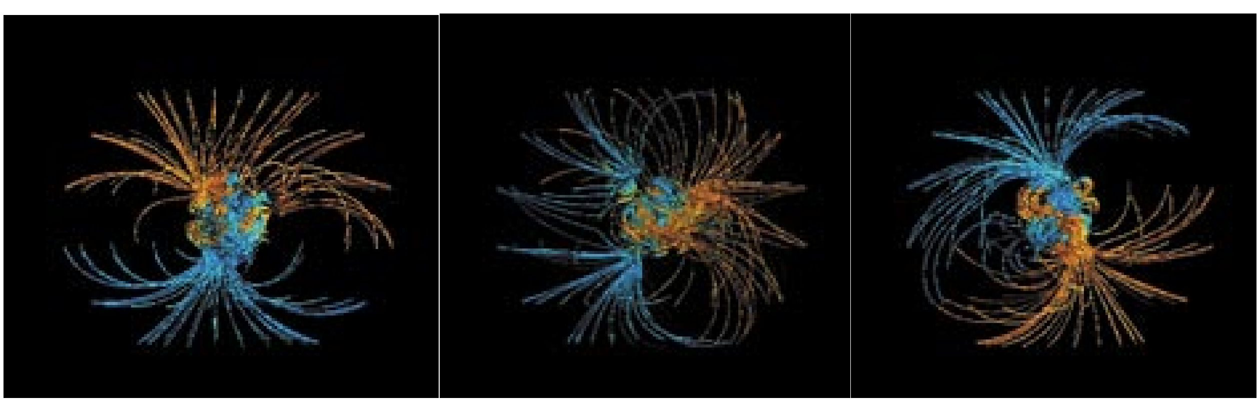
RFA F.4. Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.

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.

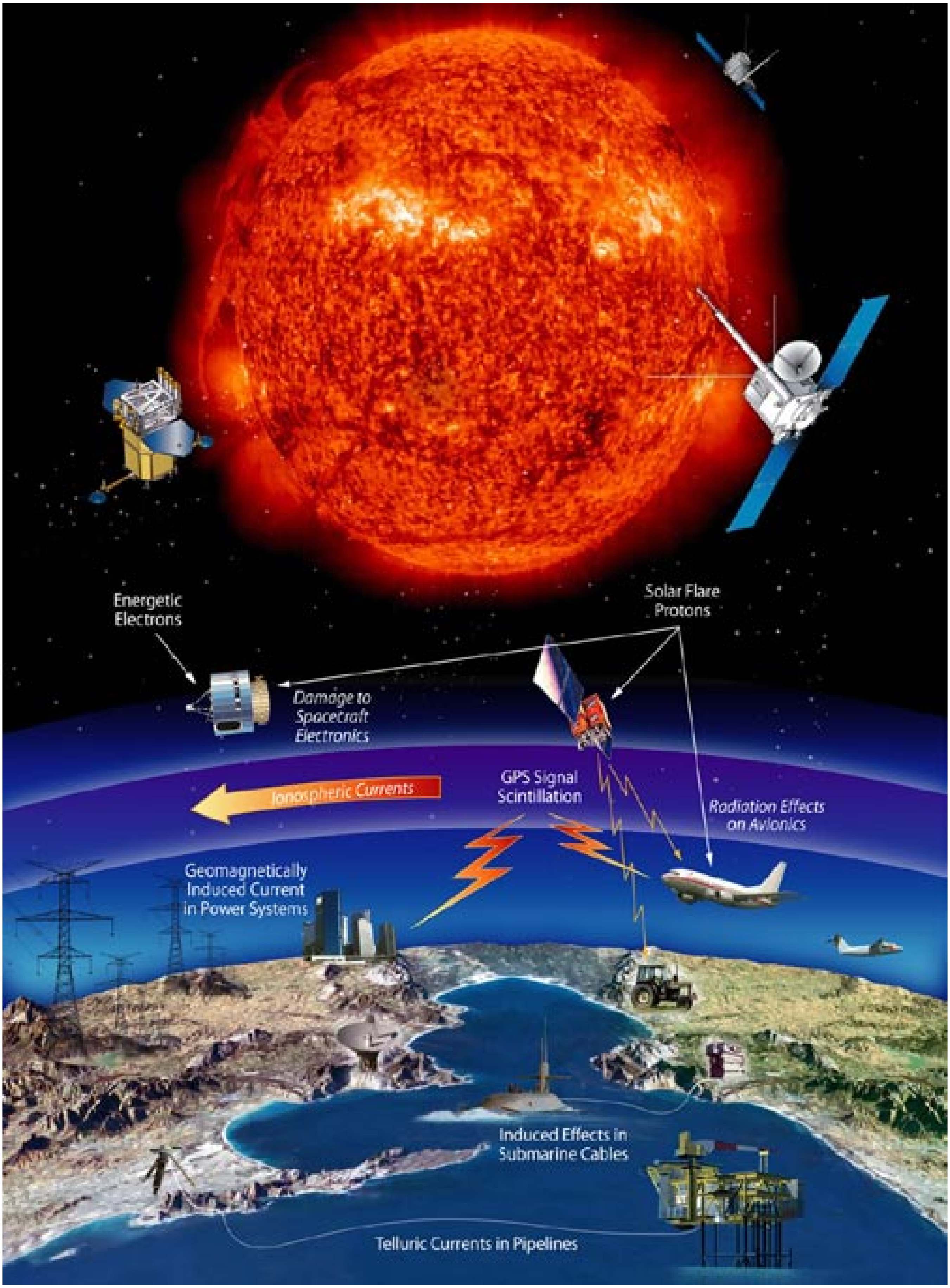


The figure shows the residual solar rotation speed after removing the average differential rotation. The cut-away shows the surface velocity on the left of the disk and a cross-section of the interior on the right. The two figures show how the rotational profile changes over six months.

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.



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]

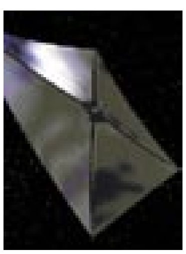

Energetic
Electrons
Solar Flare
Protons
Damage to
Spacecraft
Electronics
GPS Signal
Scintillation
Ionospheric Currents
Radiation Effects
on Avionics
Geomagnetically
Induced Current
in Power Systems
Induced Effects in
Submarine Cables
Telluric Currents in Pipelines

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 sustain our society, including communication, navigation, and weather monitoring and prediction. We are living with a star.



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.

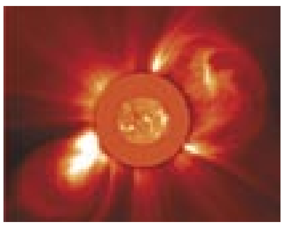
This context is not limiting. As we extend our presence throughout the solar system, we are interested in the planetary environments awaiting us and how the study of these environments can be applied to our home on Earth. Habitability, for humankind in particular, requires a rare congruence of many factors. 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 ionosphere, thermosphere, magnetosphere plasma environment 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 from external drivers. Coupled systems also 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.



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:

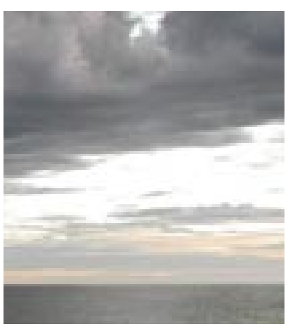
H1. Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment.
1. How do solar wind disturbances propagate and evolve from the Sun to Earth?
2. What are the precursors to solar disturbances?
3. Predict solar disturbances that impact Earth.

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?
4. How do local interstellar conditions influence the Solar System's space environment and what are the implications for the formation, evolution, and future of life in the solar system?

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; 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.



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.

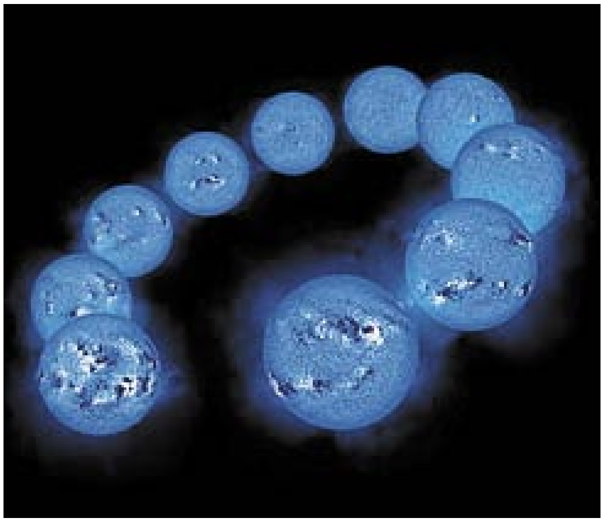
Stellar Variability and Magnetic Shielding. Other planets and other stars provide illuminating perspectives for understanding the Earth and Sun. RFA H.4 addresses the long-term impact of interactions of the solar wind with Earth, other solar system bodies, the local interstellar medium, and the study 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.

The interaction between the solar wind and the interstellar medium created boundaries that shield us from most of the hazardous galactic cosmic radiation. The properties of the local interstellar medium and the solar wind change over the course of time. How do these changes affect the biosphees of planets like Earth? 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.



CAPTION

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.

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

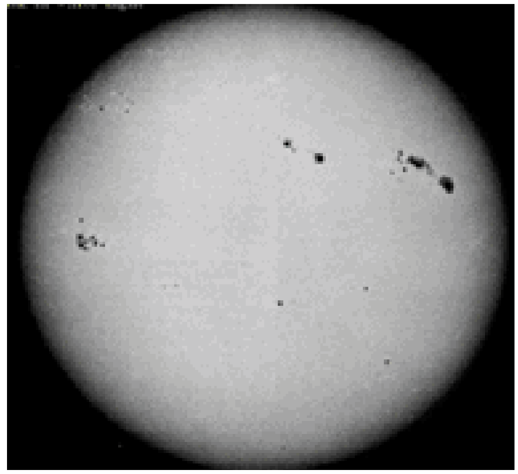
The near-Earth space environment, geospace, is unique in the solar system and central to the protection of Earth and its inhabitants. This region includes the magnetosphere, ionosphere, and thermosphere (MIT) bound together as a tightly coupled system that interacts with the neutral atmosphere below 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, greenhouse gases generated in the troposphere, wave-particle interactions, and auroral current systems are equally important and must be investigated. The consequences of internal drivers include both the natural variability of the MIT system and anthropogenic effects.

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. The technological systems sensitive to disturbances in geospace are increasing in importance and urgency to human society.

The electromagnetic, dynamical, and aeronomic processes that couple the inner and outer regimes of geospace remain unresolved. The exchange od mass and energy between these regions during both quiescent conditions and disturbed times must be understood before predictive capabilities, or strategies to mitigate adverse space weather effects, can be developed. Energetic solar and magnetospheric particles penetrate below the MIT domain into the middle and lower atmosphere, and establish the need to better understand the chemical and dynamical effects on the whole atmosphere.

CAPTION

Research Focus Area H.3: 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.



CAPTION

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 mesosphere and thermosphere are 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. The ionosphere-thermosphere plays an equally important role in protecting life on Earth, since it is the atmosphere's shield against solar EUV radiation.

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 high time-resolution spectral observations of solar energy deposition measurements of the atmospheric response, as well as theory and modeling of dynamical processes that distribute effects of solar energy.

Research Focus Area H.4: 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. The heliosphere shields the solar system from galactic cosmic radiation. 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? The solar wind, where it meets the local interstellar medium (ISM), forms boundaries that protect the planet from the galactic environment. The interstellar interaction depends on the raw pressure of the solar wind and the properties of the local interstellar medium (density, pressure, and bulk flow). These properties, particularly those of the ISM, change over the course of time, and change dramatically on long time scales (1,000 years and longer) as the solar system encounters interstellar clouds. How do these long-term changes affect the sustainability of life in our solar system? Understanding the nature of these variations and their consequences requires a series of investigations targeting the structure of the heliosphere and its boundaries and conditions in the ISM. 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.

FIGURE

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.

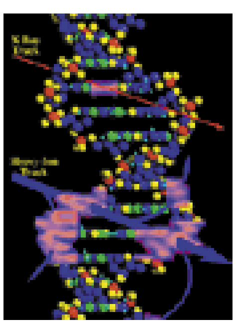
Humans will work with robots and vehicles on Mars. Safe and productive expedition activity will depend on accurate forecasting of surface and space weather conditions in order to mitigate risks but avoid false alarms.

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 actual events, 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.

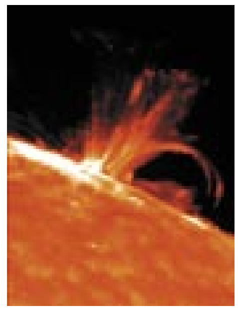
These steps are not necessarily sequential and some capability already exists in each area. One of the first major challenges is to determine more precisely what capabilities are needed and when. Our Objective J focuses on the science necessary to ensure safety and maximize productivity of both human 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 human and robotic space travel across the inner solar system.

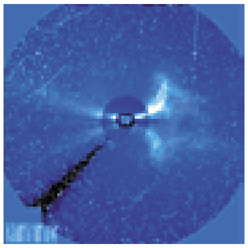
Objective J is divided into four priority Research Focus Areas (RFAs). The first aims to adequately characterize the important environments. The second and third build on the first and focus on developing the capability to predict solar activity and understand the propagation and evolution of consequential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



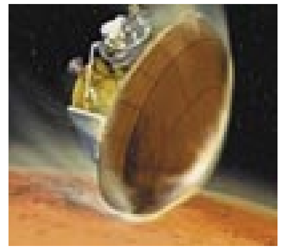
Characterization of Space Environments. RFA J.1 focuses on determining the full range of extreme conditions that may occur in the inhospitable environments that human and robotic explorers will encounter. Learning these limits takes more than just observational surveys; it requires basic understanding 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 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.



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.



Propagation to Explorers. 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. 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. 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.



Space Weather Effects on Planets. Hazards in planetary environments must also be understood, characterized, and mitigated. 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 are 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.

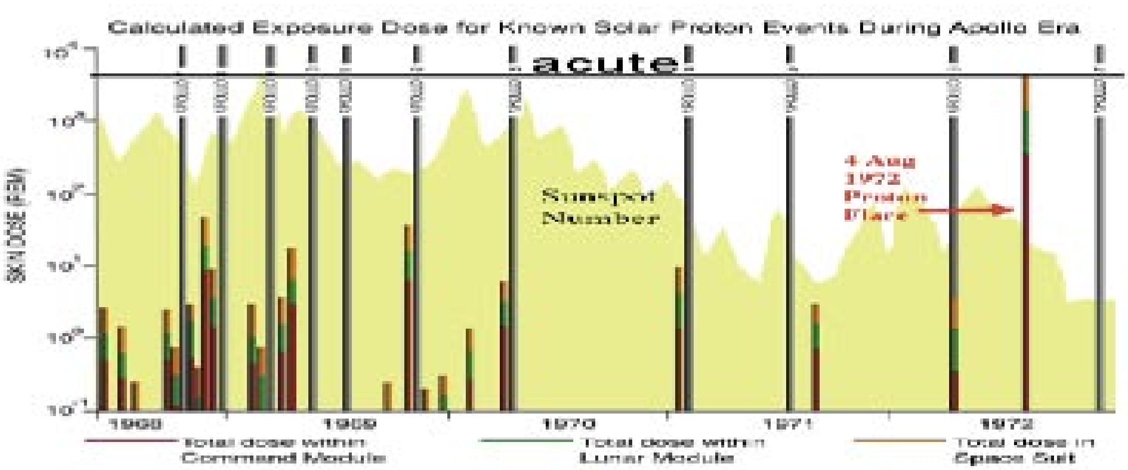
1. What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances, and what determines their magnitude and energetic particle output?
2. What heliospheric observations, and empirical models are needed to enhance the predictive capability required by future human and robotic explorers?

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?



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.

Research Focus Area J.1: Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

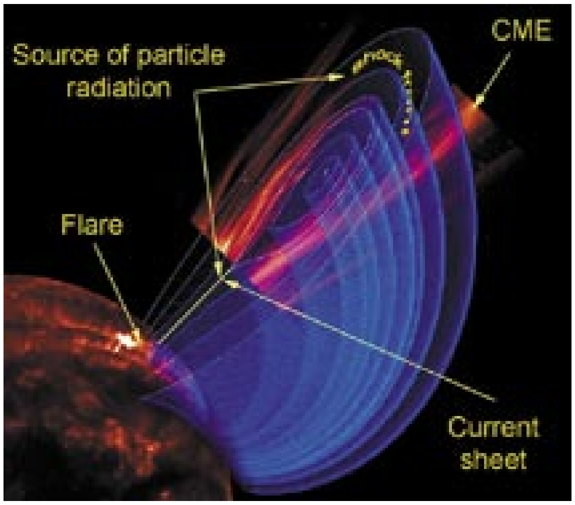
Mitigating future risks to long-duration space flight requires knowledge of two elements for operational planning: the anticipated background environment and the worst-case transient event environment. The primary goal of space environment characterization is to establish the range of variability both 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 produces 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.

Because the near-Earth geospace region is the launch and staging point for outbound missions, the landing point for return missions, and the site of much of our space-based communications and logistical infrastructure, characterizing the variability of extremes of the hazardous radiation environment within the Earth's magnetosphere is critically important for safeguarding exploration activities. For example, we are currently unable to distinguish among a growing number of theories relating to the function and evolution of new radiation belts, how energetic and hazardous they can become, or the relative importance of several particle acceleration and loss mechanisms.



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

Research Focus Area J.2: 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. Coronagraph observations of a CME leaving the Sun may give 1-2 days warning of the gradual events. To give warning of the near-relativistic impulsive events or to increase the warning time of CMEs and gradual events will require the capability to forecast the origin and onset of solar activity and disturbances from observations of the Sun itself. Successful forecasting of space weather depends on 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 CMEs and flares 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 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 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).

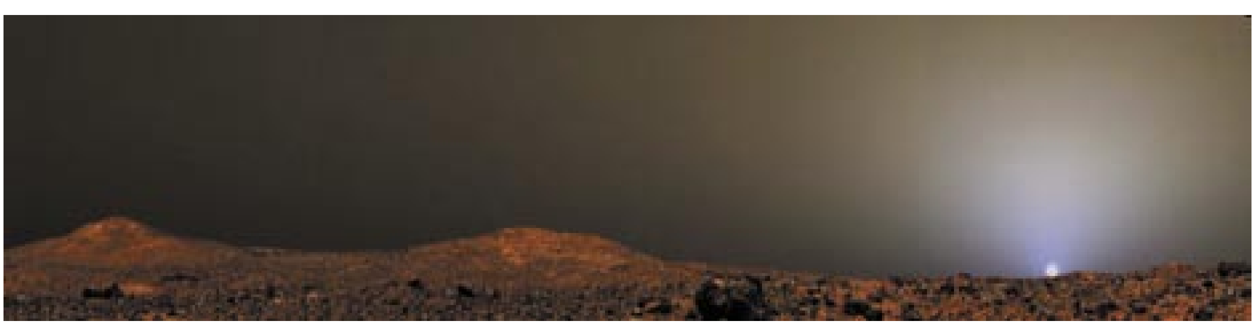
Research Focus Area J.3: Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

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 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. Remote sensing measurements, both spectroscopic and imaging, 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. 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.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.



Martian Sunset

Research Focus Area J.4: Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

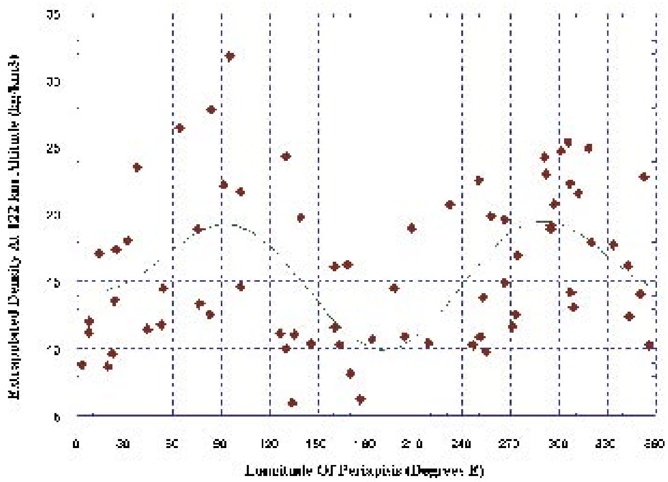
Human and robotic exploration of our solar system will necessarily be influenced by the planetary environments encountered. Both the plasma and neutral atmospheres of the planets, including Earth and Mars, impact exploration activities. Surface-to-orbit and surface-to-surface communications are sensitive to 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 known problems with lunar dust.

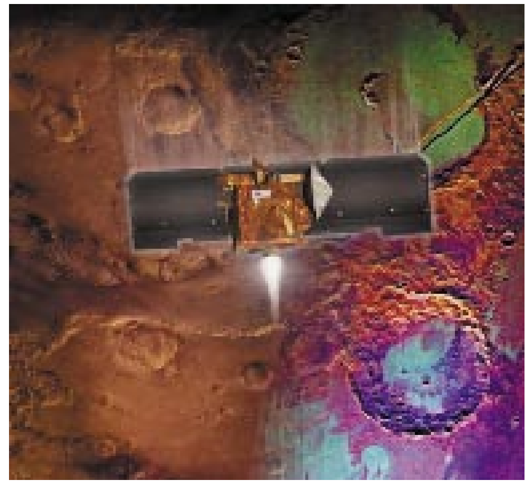
Planetary environmental conditions develop through the interaction of the solar wind with the planetary magnetic fields and plasmas as well as through the interaction of solar photons with plasma and neutral populations and with the atmosphere below. To understand the planetary conditions essential for 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 human 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).





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.