Sun - Solar System Connection

2005

Section Index

Notes on Draft 1 of the SSSC Foundation Roadmap Report – Feb 24, 2005
Note - A few sections have been updated since Feb 24.

This draft provides a skeleton outline of the Foundation Roadmap with some sections fleshed out a little more thoroughly than others.

The FRM team has taken a top-down approach to the development of the SSSC objectives, deriving them from the statement of the NASA Objective for the Sun Solar-System Connection provided by the agency.

Significant effort has gone into the expression of the three SSSC Science and Exploration Objectives and the statements of the supporting Research Focus Areas. Smaller teams have developed these and written the text presented in the draft. These supporting texts identify areas that are recognized to be incomplete (e.g. many of the investigations). They have not been reviewed by the entire team. Detailed comments and suggestions are most welcome.

As one might expect from a top-down approach there is overlap at the lowest level – investigations for different objectives often require the same observations in the end. These overlaps have not yet been addressed, but will figure in to the discussion of priority that has yet to take place.

In addition the team has identified the set of topics that will be addressed in the Foundation Roadmap. These range from context statements (such as our understanding of the evolving views of the Vision for Space Exploration), to some preliminary thoughts on program implementation (e.g. the exploitation and transformation of the SSSC Great Observatory), to discussion of critical program elements (e.g. the program for Low Cost Access to Space), and finally examples of accomplishment to support other sections of the document (for example the solar system-wide observations of the Halloween Storms in 2003).

These sections are in less polished form and so comments are welcome at any level. Particularly helpful are suggestions for areas that have been missed or are incomplete in scope. The sections on strategy and implementation are in particularly preliminary form and should be regarded as placeholders.

The FRM HAS NOT yet discussed implementation or strategy at any length. Nor have priorities been developed based on the objectives, research focus areas, and investigations.

We have commissioned a dozen definition studies and have a very large number of mission concepts to consider. The team expects to address this at our March meeting. As in the past, quad charts documenting possible missions will be part of the FRM Report.

Subject to the understanding that NASA HQ will need to react on a timely basis to shifting conditions, we also invite comments on specific implementation tactics (e.g. PI leadership, competitive selection of strategic mission content, or the trade-offs between size, scope, and schedule of STP missions).

The FRM report is intended to provide the material that will eventually become the formal Strategic RM as well as other material. The goal for the comprehensive Roadmap produced by the FRM team is to provide text that can be simply extracted for use in the SRM document.

Sun-Solar System Connections - NASA Strategic Objective 15: Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational systems.

SSSC Science & Exploration Objective F

Opening 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.

F.1 Understand magnetic reconnection to reveal the causes of solar flares, coronal mass ejections, and geospace storms.

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

F.3 Understand How Nonlinear Interactions Transfer Energy and Momentum Within Planetary Upper Atmospheres.

F.4 Determine how solar and planetary magnetic dynamos are created and why they vary.

F.5 Understand the role of cross-scale coupling in creating plasma boundaries and the significance of boundaries in controlling physical processes

SSSC Science & Exploration Objective H

Understanding the Nature of Our Home in Space

Understand how society, technological systems, and the habitability of planets are affected by the variable space environment.

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

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

H.3 Understanding the role of the Sun as an energy source to the Earth's atmosphere, and in particular the role of solar variability in driving change.

H.4 Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability

SSSC Science & Exploration Objective J

Safeguarding Our Outbound Journey

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

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

J.2 Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events..

J.3 Develop the capability to predict the propagation and evolution of solar disturbances (including shocks, and the acceleration and transport of energetic particles from solar, interplanetary, and galactic sources) to enable safe travel for human and robotic explorers.

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

NASA'S VISION

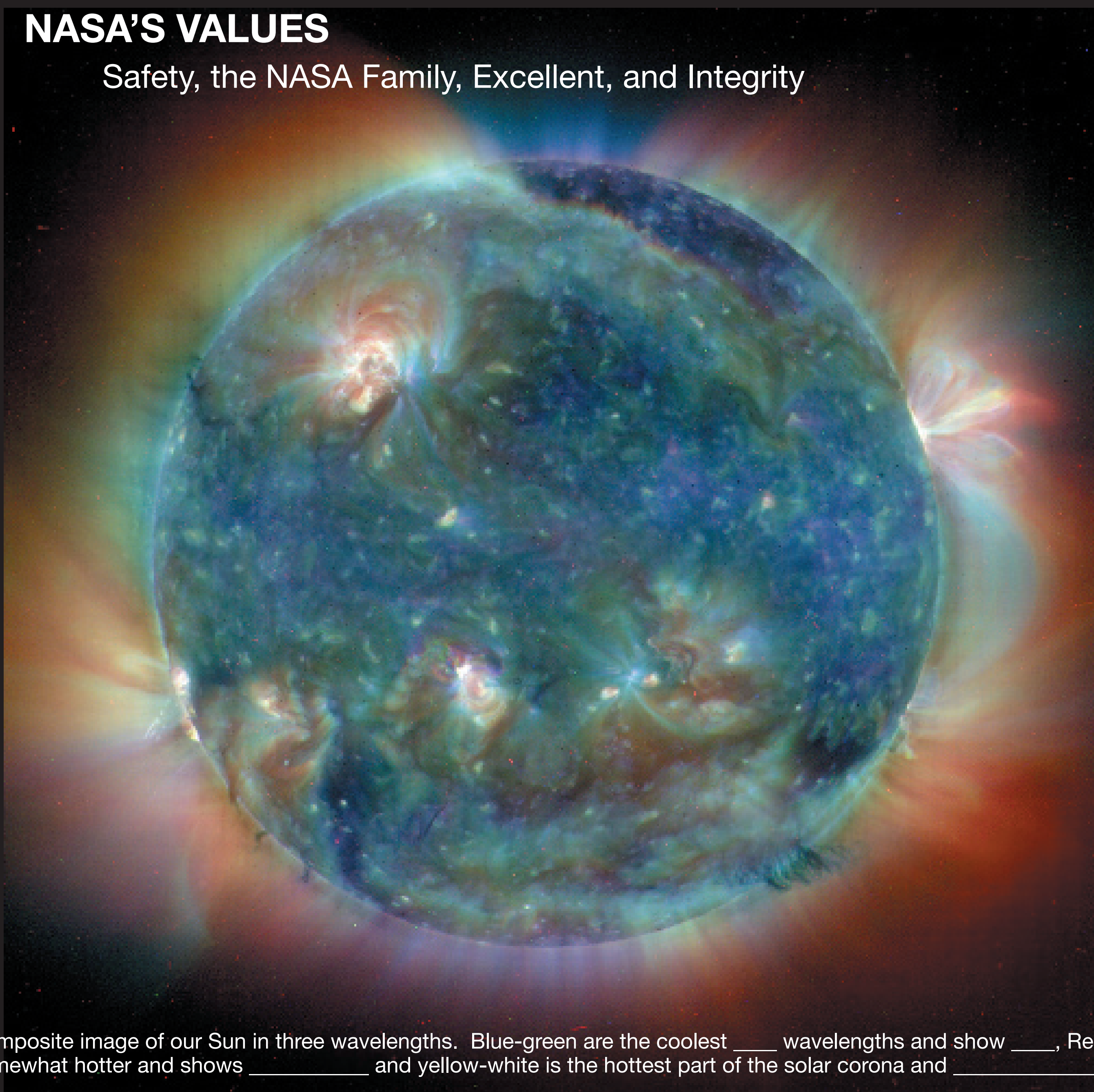
To improve life here,
To extend life to there,
To find life beyond.

NASA'S MISSION

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

NASA'S VALUES

Safety, the NASA Family, Excellent, and Integrity



Composite image of our Sun in three wavelengths. Blue-green are the coolest ____ wavelengths and show ____, Red is somewhat hotter and shows ___________ and yellow-white is the hottest part of the solar corona and _________________ ___

NASA STRATEGIC OBJECTIVE #15

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

INTRODUCTION - QUOTE

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

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

The biological effects of the ordinary energetic particle radiation environment outside of low-Earth orbit remain largely unknown. Astronauts aboard the ISS accumulate significant radiation exposure and energetic particle events significantly impact space station operations. Safe and productive travel outside Earth's protective magnetic cocoon, whether to the Moon or Mars, will require new predictive capability for solar particle events. Even well-designed hardware is damaged or degraded by extreme conditions in space.

Building on NASA's rich history of exploration of Earth's neighborhood and distant planetary systems, we will develop the quantitative knowledge needed to help assure the safety of the next generation of human and robotic explorers. Focused research addressing specific space environmental hazards will help guide the design and operation of safe and productive missions of exploration and discovery.

Space weather and solar variability affect critical technologies used on Earth as well, for example communications, navigation, remote sensing, and power distribution. Increasing reliance on vulnerable global systems demands active management to respond to variations in the space environment. Even small changes in the total energy output of the Sun over extended periods can affect the world's climate.

Predictive capability requires a deeper understanding of the fundamental physical process that underlie the exotic phenomena of space. This scientific exploration will target the highly coupled system that stretches from the Sun's deep interior to disparate planetary neighborhoods and the vast expanses of interplanetary space.

Previous strategic road maps for understanding the Sun – Earth connection have motivated by basic questions: Why does the Sun vary? How do the Earth and planets respond? What are the implications for humanity? More recently the focus was on the understanding of the Sun, heliosphere, and planetary environments as a single connected system: Explore the fundamental physical process of space plasma systems. Understand the changing flow of energy and matter throughout the Sun, heliosphere and planetary environments. Define the origins and societal impacts of variability in the Sun-Earth connection.

In this Road map for the Sun – Solar System Connection we take a new approach. We derive our strategic priorities from a stated U.S. national objective for NASA: "Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational systems."

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. It is vital, compelling and urgent. We identify three science and exploration objectives. We will gain the knowledge needed to

œ 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.

œ Understand the nature of of home in space

Understand how society, technological systems, and the habitability of planets are affected by the variable space environment.

œ Safeguard our outbound journey

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

We are already transforming human understanding of this fascinating global system of systems, so closely connected that the same explosive event on the Sun can produce effects that span the entire solar system: spectacular coronal mass ejections, power outages on the Earth, degradation of solar panels on interplanetary spacecraft, fatal damage to instrumentation in Mars orbit, auroral displays on Saturn, and, months later, radio disturbances at the interface with the interstellar medium. By expanding and deepening that understanding, we will not only develop a predictive capability to address hazards to space travelers and to important technological assets closer to home, but we will learn how the fundamental space processes may interplay to affect the habitability of other distant environments, beyond our own solar system.

This endeavor requires a new science that synthesizes and transcends the traditional disciplines of Sun-Solar System Connection inquiry. A host of interconnected physical processes, most tied to solar variability, affect the habitability of space locales. Cosmic rays from interstellar space, dangerous high energy solar photons, damaging particles accelerated by shocks in the corona and solar wind, intense radiation trapped in planetary magnetic fields, and the many other menacing phenomena that impact the space environment cannot be understood in isolation.

Many of these phenomena are quite unfamiliar because they cannot be sensed directly. A strong solar flare that ionizes much of the sunlit upper atmosphere is insensible, except to those who depend on radio propagation or are sensitive to ionospheric scintillation for navigation.

Furthermore, most of the space regime is dominated not by the familiar forces of gravity and pressure, but by magnetism and electricity or a combination of them all. Measuring, characterizing, and understanding these processes cannot generally be done with images and common intuition. Localized measurements cannot be easily interpreted to generate a global picture. Conversely, the global picture does not provide insight into the physical determinants 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 directly 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 milliseconds.

The new science that addresses these important issues is a new science; it spans several traditional disciplines; and it is a science that as yet has no name.

Answering a specific science and 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 continuous series of velocity measurements at millions of locations on the solar disk, like those to be provided by the Solar Dynamics Observatory.

However, Sun – Solar System Connection science increasingly depends on combining multi-point in situ measurements with remote imaging. Only by combining these techniques in a great observatory can the complete physical system be adequately understood. Currently the SSSC Great Observatory includes satellites that travel in Earth orbit, hover near L1 – a million miles upstream in the solar wind, circle over the Sun's poles, and are encountering the first boundary between the interstellar medium and the Sun's domain, the heliosphere. As each set of scientific questions are answered, the observatory evolves with the addition of new spacecraft. Soon the two STEREO spacecraft will drift away from Earth to provide the first stereoscopic views of the Sun and another cluster of the four MMS spacecraft will fly in tight formation to explore the multiple scales of reconnection and particle acceleration in the magnetosphere of the Earth.

A Definition of Exploration

Something hidden. Go and find it. Go and look
behind the Ranges---

Rudyard Kipling (1865-1936), "The Explorers" (1903)

Exploration and Fundamental Science

On January 14,2004, NASA received specific instructions from President George W. Bush to undertake a space exploration program with a clear set of goals, including implementation of "a sustained and affordable human and robotic program to explore the solar system and beyond."1

1A Renewed Spirit of Discovery, the President's Vision for U.S. Space Exploration, The White House, January 2004.

The response of the NASA Science Mission Directorate to this challenge was:

Sun-Solar System Connections - NASA Strategic Objective 15: Explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by human explorers, and demonstrate technologies that can improve future operational systems.

Objective 15 introduces a greatly heightened emphasis on human exploration beyond the confines of the Earth-Moon system….and in particular, outward to Mars. 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."2

2"Science in NASA's Vision for Space Exploration", Committee on the Scientific Context for Space Exploration, Space Studies Board, National Research Council, The National Academies Press, February, 2005.

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 is also the necessary precursor to successful colonization and settlement. That necessity has been the motivation for mankind's greatest ventures into the unknown. Application of the scientific method is the only reliable way to reap the maximum harvest of the fruits of the exploration.

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". Whether the exploration is undertaken by manned or robotic missions, the survival of the missions must be ensured in an orderly fashion and at reasonable cost. Scientific knowledge is our only safe guide when entering unexplored regions, and application of sound scientific methodology is the only reliable way to guarantee the maximum fruits of the exploration.

For example, one of the pragmatic problems facing the successful implementation of the Vision Initiative is the present factor of 5 uncertainty either way of the biological effects of radiation in space---this means unacceptable design range of factor of 25. The resolution of this dilemma lies partly in prediction. If the astronauts (or equipment) can be "sheltered" from the worst-case radiation when given a reliable warning, the design problem may be tractable. Prediction is the ultimate validation of good fundamental science, and that is the standard that the community has set itself.

Another pragmatic problem is the design of the critical entry of a Crew Exploration Vehicle into the Martian atmosphere---which is 10% the thickness of the Earth's atmosphere, with corresponding dynamical complexities that threaten the aero-braking phase of the mission. The solution to the problem is to be found in a thorough understanding of those dynamics gained from scientific analysis theoretical models based extensive data-gathering efforts in the terrestrial and Martian atmosphere.

The scientists who can enable safe missions are the same ones who are studying fundamental processes on the Sun, the planets, and the heliosphere from its inner boundary to the outer boundary with the interstellar medium. These scientists are even now answering, and will continue to answer, the mission-critical questions because of the knowledge that they have gained and will continue to gain. They will also be there to reap the harvest of the scientific data gathered in preparing for and carrying out the Exploration Initiative.

The SSSC community is already providing scientific measurements and models that are essential to the implementation of the Vision of manned and robotic Exploration of the Moon and Mars. These parameterizations of the space environment are inputs required for the eventual solutions of the challenging engineering problems that must be solved for successful and economical Exploration.

At the same time, past and current SSSC missions are producing a steady stream of transformational science that is rewriting the textbooks of past decades. Think of Voyager-1 and its encounter with the puzzling outer boundary of the solar wind, featured by all the world's leading newspapers and magazines. Think of the scientifically and aesthetically beautiful images revealing the intricacies of solar magnetic fields captured in SOHO images or auroral images of the Earth, Jupiter, and Saturn.

However, these same exploration missions were also the ones that gathered the parameters being applied to the preparations for Vision Exploration, the critical parameters that were ready for application because they were digested and validated by the rigorous procedures of basic scientific research.

Nonetheless, this is just the beginning of the construction of the data base and knowledge repository that will be required to bring the Exploration Vision to a grand climax of technical and scientific achievement. The SSSC community knows how to respond to this call to action. It perceives the necessities of filling in the gaps in our knowledge of the space environment, It also realizes that the increased understanding must develop organically from a broad base of basic scientific research of fundamental physical processes.

What is becoming clear is that the pragmatic challenges of Vision Exploration will dictate re-focused and intensified scientific exploration. That new science 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 be understanding the details of the acceleration of solar energetic particles revealed by RHESSI if space scientists in the 1970's (Reuven Ramaty among them) 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 Foundation Roadmap is different 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 a continuity with past strategic planning. Missions advocated 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 Exploration. Good science cannot help but produce exciting discoveries while producing the results it has promised to obtain.**

Segue to:

SSSC Science & Exploration Objective F
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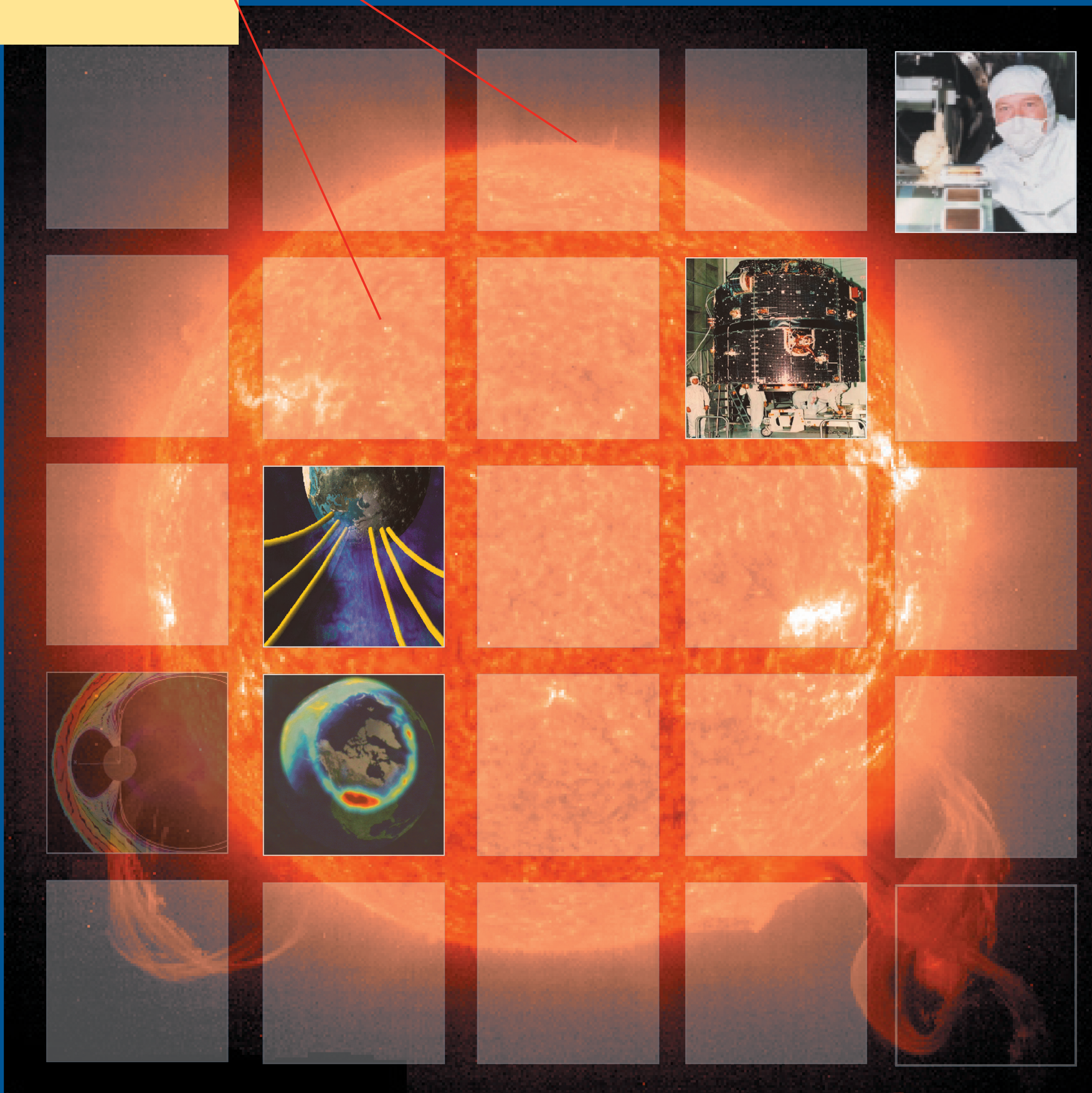
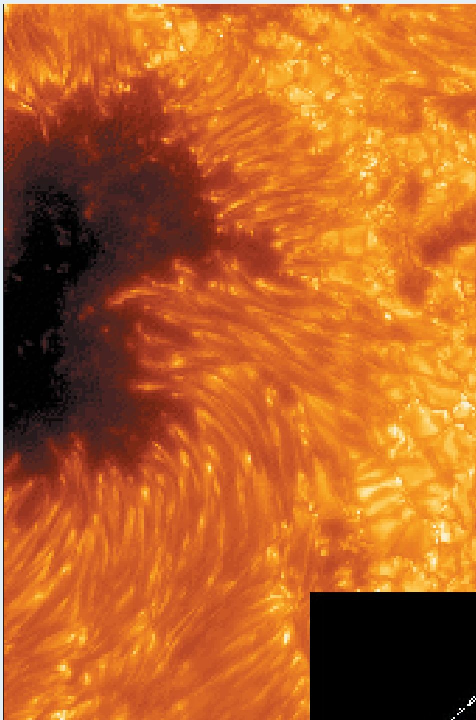
SSSC Science & Exploration Objective J
Safeguarding Our Outbound Journey
Maximize the productivity and safety of human and robotic explorers by developing predictive capability for the extreme and dynamic conditions in space.

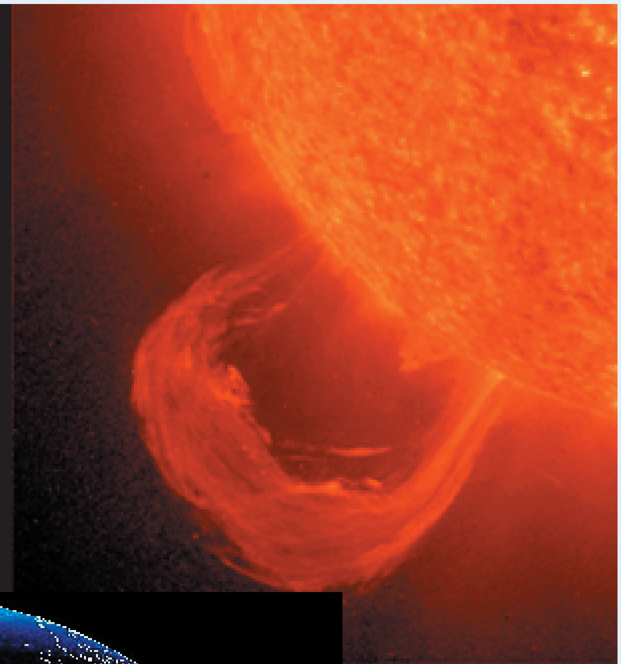
SSSC Science & Exploration Objective H
Understanding the Nature of Our Home in Space
Understand how society, technological systems, and the habitability of planets are affected by the variable space environment.

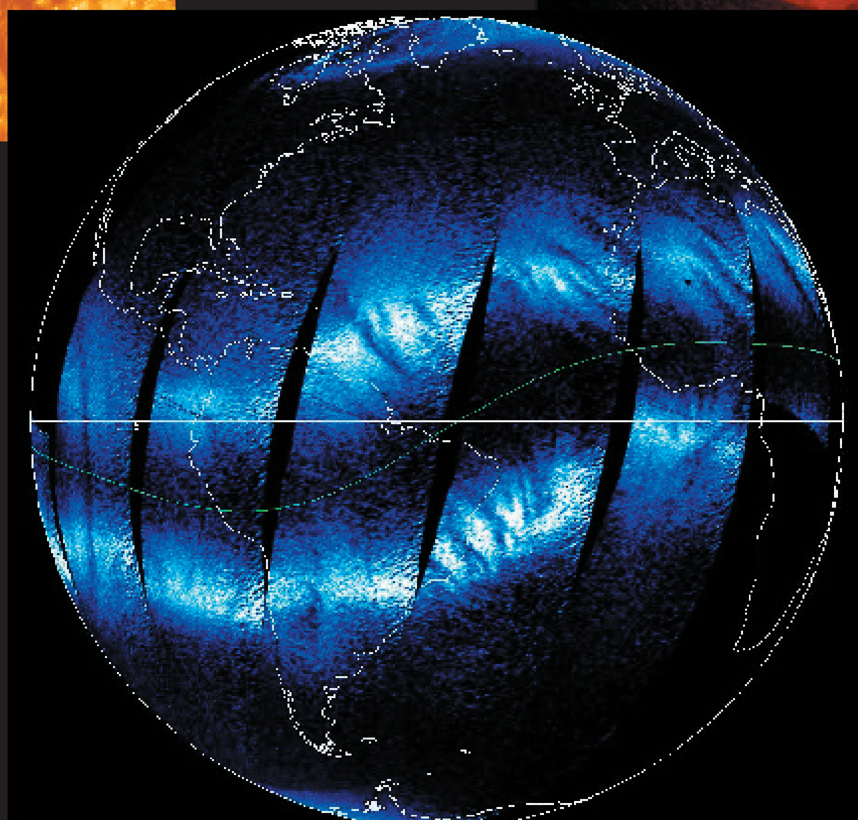
Fill all these squares with pictures representing the SCIENCE program ...



Section 1: SSSC Science & Exploration Objectives







Add more images of fine-scale structure ...

Objective F

Opening the frontier to space environment prediction

We will understand the fundamental physical processes important in space -- from the Sun to Earth, to other planets, and beyond to the instellar medium.

The sun, our solar system and the universe consist primarily of plasma, which results in a rich, complex and interacting set of key fundamental physical processes, including intricate exchanges with the neutral gas in planetary atmospheres. To predict the behavior of the complex systems that control the environments we will encounter on our return to the moon and journeys to Mars necessitates the development of a complete understanding of these processes. These key processes occur in many locations often with very different ranges of parameters and boundary conditions. As a result, both in situ and remote sensing observations are obtained, which often provides a three dimensional large-scale perspective, as well as a detailed small-scale microphysics view. Our ability to quantitatively examine the same process in different regimes with a range of diagnostics both tests our developing knowledge and enhances our understanding. All five research focus areas that comprise this objective share the universal themes of energy conversion and transfer, cross-scale coupling, turbulence and nonlinear physics – themes which are fundamental to the understanding of space and planetary systems. With our increasingly sophisticated understanding of these fundamental physics process, we will reach the frontier of developing the ability to develop predictive models. Objective F is, therefore, designed to provide the fundamental physics underpinnings that will enable the predictive capabilities to be developed as part of Objectives J and H.

The research focus areas that are included in Objective F have been selected because they are critical steps to providing the detailed knowledge base required to enable the safe and productive exploration via development of accurate forecasting of the space environment. These areas are magnetic reconnection, particle acceleration and transport, the nonlinear physics of energy and momentum transport and coupling in atmospheres, generation and variability of magnetic fields and cross-scale coupling in boundaries and large structures.

The fundamental importance of magnetic reconnection, the rapid conversion of magnetic energy to particle energy, in solar flares, CMEs and geospace storms is well recognized. This explosive release of enormous amounts of energy can have potentially devastating consequences for space assets and voyaging humans, as well as serious effects on

Priority Research Focus Areas

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

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

F.3 Understand How Nonlinear Interactions Transfer Energy and Momentum Within Planetary Upper Atmospheres.

F.4 Determine how solar and planetary magnetic dynamos are created and why they vary.

F.5 Understand the role of cross-scale coupling in creating plasma boundaries and the significance of boundaries in controlling physical processes worldwide communications. Magnetic reconnection is the focus of RFA F.1. Although we have developed an initial picture of where reconnection occurs and the observable results, the detailed physical mechanisms, in particular the microphysics and the role of large-scale topology, is not understood. The investigations will deliver the fundamental understanding of this universal process in the very different regimes where it occurs.

One of the primary results of magnetic reconnection is the acceleration of particles to high energies. Within the solar system many other mechanisms, including small-scale waves, shocks and quasi-static electric fields, energize particles. Because it is the energetic particles in the space environment that have the most direct impact on humans and robotic explorers, a detailed understanding of each of the acceleration processes, the regions in which they operate and the boundary conditions that control them is crucial to the exploration of space. Providing this understanding is one goal of RFA F.2. In addition, the origin and acceleration of the solar wind is a mystery. Although the bulk of solar wind particles are not energetic enough to damage spacecraft systems, much of the interaction between the sun and planets is mediated by the solar wind. It is, therefore, an essential component of the Sun-Earth system and the problem of solar wind acceleration must be solved and is included in RFA F.2.

RFA F.3 is designed to explore the fundamental nonlinear physics of energy and momentum coupling in planetary atmospheres. The upper atmospheres of planets are dramatically affected by energy inputs, including solar radiation, energetic particles from the aurora and ring/current radiation belts, and winds and other inputs from the lower atmosphere. This RFA is designed to provide a comprehensive understanding of the nonlinear processes and interrelated roles of these energy inputs. This is needed to enable the quantitative predictions of atmospheric structure that is essential for operations of satellites in the Martian atmosphere and mitigation of the effects of global change, as well as habitability of planets. The investigations focus on transfer of energy and momentum via gravity waves, energetic particle effects on atmospheric chemistry, and coupling between different plasma regimes. Additional fundamental processes include cross-scale coupling and development of nonlinear waves.

The existence of the magnetic fields of the Sun and planets is a critical element of the Sun-Solar System connection and is the focus of RFA F.4. The process which creates these magnetic fields – the dynamo problem – remains one of the outstanding problems in theoretical physics. How dynamos operate in such widely different conditions from stellar interiors to planetary cores is very poorly understood. Because the solar magnetic field controls the structure of the heliosphere and, thus, the entry of galactic cosmic rays into the solar system, it is imperative that we understand the origin and variability of the solar magnetic field. This is intimately linked to understanding the dynamo problem. The dynamo in the Earth's interior sustains the geomagnetic field, which provides the shield that enables life to flourish in the otherwise deadly radiation environment of the solar system. It is well known that the geomagnetic field varies in strength and has reversed multiple times in the history of our planet, which weakens this critical shield during this change. Solving the dynamo problem will provide the key understanding to allow us to better predict and anticipate changes in the magnetic fields at both the Sun and the Earth.

Our solar system and, in fact, the universe are made up of large regions of space with relatively uniform properties separated by very narrow boundaries. It is at these boundaries that much of the most interesting and important physical processes occur. The structure of the large spatial regions and their boundaries is also critical to understanding the modulation and control of fundamental processes including reconnection and particle acceleration and transport. An example is the modulation of galactic cosmic rays by the heliopause. RFA F.5 will develop an understanding of the significance of cross-scale coupling in these boundaries, as well as the role of boundary structures.

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

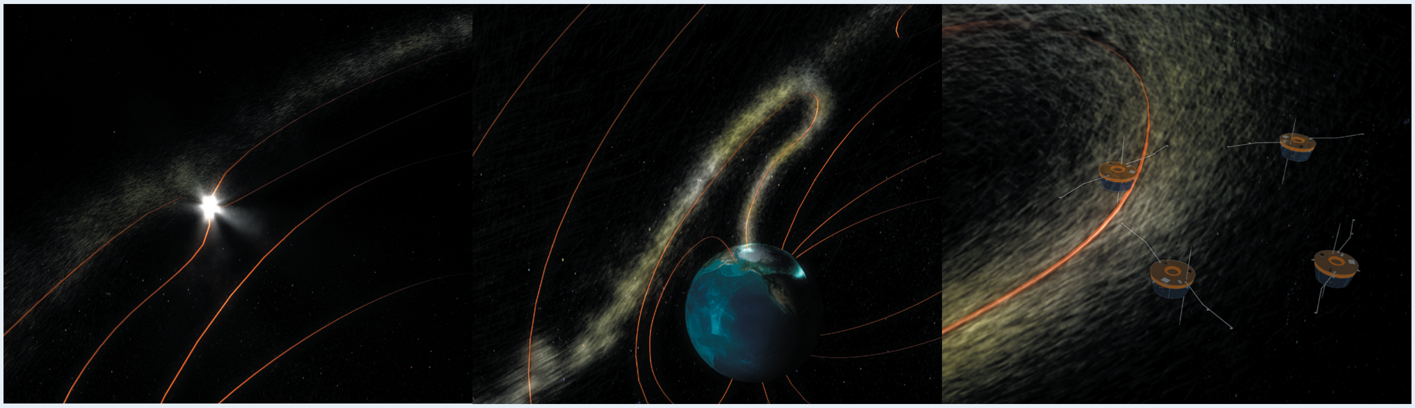
Reconnection is the rapid conversion of magnetic energy into particle energy, which has long been recognized as an important process in a variety of space plasmas ranging from the very low density magnetotail of the Earth to solar flares as well as in the laboratory plasmas of fusion machines. Solar flares, coronal mass ejections and geospace storms are all initiated and energized by reconnection -- often with potentially devastating effects to space systems. Although satellite measurements, laboratory experiments and simulations have provided good evidence for consequences of this process as well as a strong indication where the process is initiated, the detailed physical processes are not well-understood. The explosive conversion of magnetic energy originates in a volume of space known as the diffusion region, which is very small in comparison to the large scales in space. For example, the initiation of magnetic reconnection on the Earth's magnetopause (the boundary separating solar wind magnetic fields from the Earth's magnetic field) occurs in a region with an area of the order of hundreds of square kilometers on a surface that has a total area of approximately 60 billion square kilometers. Because this tiny initiation region exists on such a large surface, the physical processes that initiate and control reconnection are still poorly understood because it single spacecraft are often not in the right position to make the needed measurements. Reconnection is, therefore, a process in which cross-scale coupling is of paramount importance. It is also a process that accelerates 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. Reconnection can also sever large 'clouds' of hot plasma from the magnetic fields that anchored them. Fortunately, we have reconnection occurring in near-Earth space so that we have the possibility to make direct, in-situ high time resolution measurements of the reconnection process both at the magnetopause and in the magnetotail. This critical capability is provided by the Magnetospheric Multi-Scale (MMS) Mission. These measurements when combined with remote sensing of the Sun which provides details of the large- and meso -scale topology of the magnetic field, hold out the promise of an essential understanding of this fundamental process.

[must accurately address role in cme's . is reconnection important particularly in forming fast cmes and GeV particles]

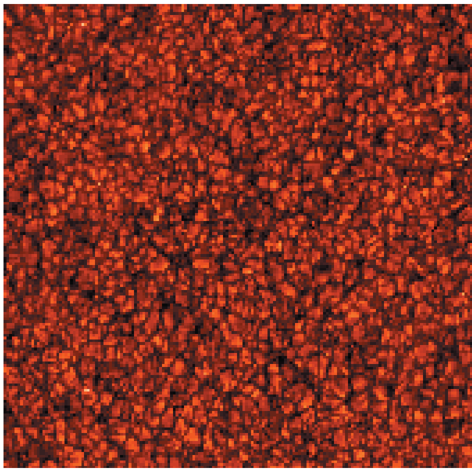
Investigation 1. What are the fundamental physical processes of reconnection on the small-scales where particles decouple from the magnetic field?

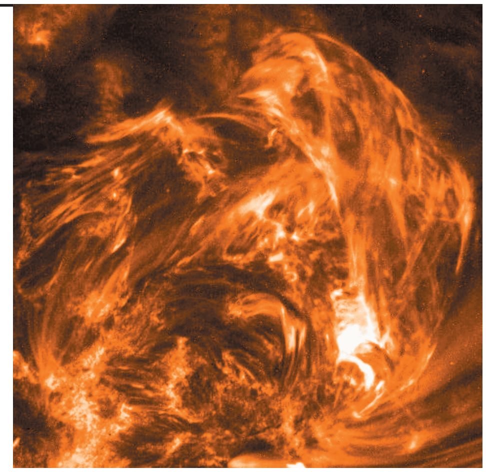
microphysics of mag reconnection [mms]

Recent in situ observations of reconnection by Wind, Polar and Cluster, in combination with state-of-the-art simulations, have provided a tantalizing glimpse of the complex and dynamic process of reconnection and the role of microphysics. To obtain the complete understanding required for predictive capability requires high time resolution measurements of particles and fields from multiple satellites with variable separations to probe processes from micro-scales to meso-scales.



Show some reconnection sequence ... either at magnetopause, magnetotail, or on the sun ... make the "why this is important" point ... transfer of energy, mass ? site of explosive release?





Does something like this make a good sequence?? what would be in the middle? a big sunspot, and then a big sunspot with nasty polarity signatures? .... understanding how you get from such a pretty surface to a massive eruption is part of what section?? maybe we need something more specific to reconnection here and use these figures in another place .... Granulation region

Investigation 2. What is the magnetic field topology for reconnection and at what size scales does magnetic reconnection occur on the Sun?

Reconnection on the Sun occurs in a hot, million degree turbulent plasma under much different conditions than those in the Earth's magnetosphere. It is responsible for producing the most dramatic energy releases on the Sun in the form of flares and coronal mass ejections (CMEs), both of which are primary drivers of Space Weather. Reconnection is a complex process that is likely to occur in many different magnetic geometries and size scales, and under a wide variety of circumstances. Thus it is important in many different solar phenomena ranging from localized heating in naonoflares, particle acceleration in current sheets, global coronal heating, and possibly solar wind acceleration. These phenomena occur over time scales ranging from seconds to minutes and energy ranges from 1024 to 1032 ergs.

EUV and soft x-ray imaging of coronal loops provides the most direct evidence for reconnection taking place on the Sun. High time cadence images often show the rapid reconfiguration of plasma loops with concurrent large releases of energy. Persistent common reconnection events occur nearly continuously in active region structures that cover a wide latitiude band on the disk at solar maximum. The reconnection in active regions are due to the emergence and shearing of new flux across magnetic neutral lines and also due to the interaction of separate photospheric magnetic flux systems. By observing many of these events with high resolution imaging and spectroscopy in EUV and xray wavelengths, it is possible to identify the required conditions for reconnection, relate the physical parameters of the reconnecting environment to the energy released, and what are the important large scale morphologies that drive the reconnection process.

Reconnection occurs impulsively in coronal mass ejections (CMEs). In the standard CME model, an erupting flux rope leaves behind oppositely directed magnetic fields that are separated by a current sheet. Reconnection in this current sheet produces an arcade of post-CME loops. Magnetic reconnection is believed to have a two-fold role in the eruptive process for CMEs. First, reconnection breaks the magnetic field lines that pass over the flux rope and are anchored in the boundary surface at both ends. These field lines produce strong magnetic tension in a stretched configuration that would otherwise prevent the flux rope from escaping to form a CME. Second, reconnection dumps large amounts of energy in the lower atmosphere of the Sun, creating intense heating, which accounts for the traditional flare ribbons and loops and for the current sheet containing hot plasma.

Measurements of dynamical behavior of the magnetic reconnection products such as the separating flare ribbons on the solar surface and the growing flare loops in the corona can be used to better understand the main energy conversion process in the eruption. However if it is true that the current sheet itself contains essentially most of the physics behind the eruptive phenomena observed, then additional efforts should focus on it. Indirect evidence of CME current sheets is provided by the existence of hot plasma along a thin line trailing behind CMEs as seen in the emission of Fe XVIII at ~ 6 x 106 K. [insert image.]

Measurements of current sheet thickness, compression ratios, velocity inflows onto the current sheet, Alfven Mach number will provide constraints on the magnetic and electric fields in the current sheets. High spatial and temporal resolution observations are needed to resolve the locations and dynamics of the fine-scale structure at reconnection sites. Multi-wavelength broadband and spectroscopic remote sensing diagnostics of the temperatures, densities, and flow velocities of the plasma at the reconnection sites will be needed to follow the thermal history and energy budget of the plasma. Such measurements can constrain the reconnection and heating rates used in reconnection models.

[missions include RAM]

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

The existence of very high energy particles within the solar system is a impediment to the exploration of the solar system, particularly by humans due to the damage caused to both material and tissue by these particles. To mitigate the effects of these energetic particles, we must understand how and where they are accelerated and how they are transported throughout the heliosphere so that we can predict their behavior. Gaining this understanding is the focus of RFA 1.2. Although the particles are accelerated in many different locations within and outside the solar system, there are only a handful of processes that operate to accelerate particles to high energies. These include quasi-static electric fields parallel to the background magnetic field, wave parallel electric fields, stochastic (Fermi) acceleration and drift of particles along a component of the electric field.

Energetic charged particles (ions and electrons) are accelerated both at localized sites (solar flares, magnetotail reconnection sites, auroral double layers), and globally (coronal and interplanetary shocks, CIRs, GMIRs, termination shock). The particles then undergo complicated transport that distributes them through the global system. For example, the initial intensity of prompt solar energetic particles (SEPs) depends initially on the directness of their magnetic connection into the solar corona, while the total fluence (dose) of energetic particle radiation depends on the transient magnetic disturbances that CMEs produce on field lines beyond the exposure location. If we are to characterize the distribution of these particles (in energy, time, and space) sufficiently well so that we can design Exploration missions that are reliable and economical, we must understand both the dynamics of acceleration sites and the transport throughout the spatial structure of the system.

[must include acceleration of solar wind; also if we subsume #4 into 2 and 3, then want a discussion of how multiple mechanisms result in the very energetic particles, for example in CMEs acceleration via combinations of reconnection and shock acceleratio, in rad belts, initially by reconnection to inject into nr eath, then additional acceleration, etc]

Investigation 1. How are energetic particles accelerated in regions coupling very different plasma regimes?

Understanding the role of boundary conditions and drivers that control the size and development of the electric fields field that accelerate particles to high energies is critical to obtaining the complete understanding of acceleration in astrophysical plasmas. The myriad scales and types of structures in which such fields can occur result in a complex phenomenology that occurs almost universally within space plasmas. Examples include parallel electric fields in kinetic Alfven waves and in solitary waves. A complete understanding is necessary to provide predictive capability for such phenomena as solar energetic particles.

The Earth's aurora provides a unique opportunity to elucidate the mechanisms of energetic particle acceleration by parallel electric fields and waves. Previous rocket and satellite missions have provided evidence that energetic electrons and ions are produced by a wide range of processes, including large amplitude quasi-static parallel electric fields occurring in microphysical structures ('double layers'), wave parallel electric fields (KAW, electron holes, etc), and large perpendicular wave fields. The occurrence of these fields and the size of the acceleration are dependent both on the ionospheric and atmospheric boundaries and on the drivers in the magnetosphere. Despite our great knowledge of auroral physics, the fundamental understanding of the auroral acceleration process remains unsolved. The advent of multiple, small spacecraft that can allow us to connect many points in space at the same time gives us the opportunity to solve this longstanding problem in space science. The aurora is, thus, an excellent laboratory for studying coupled systems and the interaction of large and small scales. Making progress in this study requires extremely high time resolution measurements on multiple satellites.

[could also include acceleration in other coupled regions like plasmasphere/ring current]

Investigation2. How are energetic particles accelerated and modulated by structures over a range of scales from small-scale waves to the large-scale heliosphere?

The heliosphere is a huge structure ~100 AU in radius, and its interface region (heliosheath) with the VLISM (Very Local Interstellar Medium) extends outward for yet another several hundred AU. It is through this interface that galactic cosmic rays enter the solar system, while it is the details of the structure and dynamics of disturbances within the heliosphere (solar wind) that determine the solar-cycle modulations of GCRs. Recent energetic ion and electron measurements fromVoyager-1 at 85-95 AU have also revealed highly efficient particle acceleration in the vicinity of the expected termination shock.

[telemaches and higo]

[this section will also include mechanisms associated with inner magnetosphere particle acceleration, shock acceleration and wave acceleration. maybe need to modify investigation subsume investigation 4 into 2 and 3]

Investigation 3. What are the mechanisms of particle acceleration in reconnection?

One of the important components of the reconnection process is the acceleration of particles to high energies. Although some of the acceleration mechanisms are understood, there are many that are not. New instrumentation and multi-spacecraft studies have revealed surprising results. Recent studies of Cluster data have shown that ions can be ballistically accelerated to 10s of kV along the electric field in the region where they are no longer coupled to the magnetic field.

Investigation 4. How are particles accelerated in solar flares and CMEs?

Particle acceleration at the Sun occurs at CME shock fronts, in CME/flare current sheets, and at unresolved flare sites. The physical processes involved include Fermi acceleration, direct electric field acceleration, stochastic (wave-particle turbulence) processes or magnetic reconnection. All of these processes require a seed population in addition to a way for energizing the particles. A more complete understanding of these aspects can be provided by obtaining a comprehensive set of remote sensing and in situ measurements to characterize the source regions and the properties of the energetic particles that are produced.

Particle acceleration at CME shock fronts is the leading candidate for the production of gradual solar energetic particle (SEP) events. These particles (protons with energies > 1 MeV are the most serious component) are a major risk to human explorers in interplanetary space. Understanding the mechanism for their production is required for the development of an accurate predictive capability. Similar shocks undoubtedly occur over a range of distances as the CME propagates outward from the Sun.

Some features of the shock may be deduced from radio observations, and UV and white light coronagraphic observations. The plasma is compressed and heated as the shock sweeps through. The compression ratio of the shock can be estimated from suitable Type II radio burst data and independently from UV spectroscopic observations of multi-ion shock heating. When combined with white light and UV spectroscopic measurements, empirical constraints on the shock and CME speeds can be obtained. The resulting speeds show that the shocks typically flow slightly faster than the underlying CME plasma, as expected from theories of, e.g., piston-driven shocks.

Reconnection in CME/flare current sheets are another leading candidate for solar energetic particle acceleration. These events may be responsible for the impulsive energetic particles observed at the Earth. Various acceleration mechanisms have been proposed to explain the very efficient energy conversion in these solar eruptions and a likely mechanism is strong turbulence due to the tearing mode instability. Efficient particle acceleration also requires a strong electric field (> 1 V/cm) which is induced by the reconnection in the current sheet. Since electrons and protons are accelerated in opposite directions by the electric field, their separation inevitably causes two-stream (Buneman) instabilities that can further excite ion-acoustic turbulent waves.

Significant progress in studying the process of magnetic reconnection in current sheets can be made by measuring reconnection inflow speeds from mass motions and estimating the thickness of the current sheet with UV and EUV spectroscopic imaging of the extended corona. These measurements can be used to provide estimates for the electrical resistivity (conductivity) in the current sheets, an important parameter for theoretical models. Measurement of the thickness of the current sheet, the speed of reconnection inflow near the current sheet, as well as the magnetic field around the current sheet are also needed to advance models of current sheet dynamics. particle acceleration in shocks in cme, vs current sheet in flare

Observations of photon emission (x-rays and gamma-rays) prove that particles are explosively accelerated to relativistic energies in the chromosphere and lower corona. Subsequent acceleration by shocks (CME-driven) in the solar corona and solar wind (ICMEs) is a comparably important mechanism. The initial intensity of prompt solar energetic particles (SEPs), however, depends initially on the directness of their magnetic connection into the solar corona, while the total fluence (dose) of energetic particle radiation depends on the transient magnetic disturbances that CMEs have produced on field lines beyond the exposure location

Investigation 5. What are the processes that accelerate 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 solar wind is the medium through which Space Weather disturbances propagate. Understanding how it is produced and what causes its variations will provide the foundation for understanding the propagation of CME shocks, corotating interactive regions, and galactic cosmic ray modulation.

SOHO spectroscopic measurements in the solar wind acceleration region (above 1.5 Ro) have demonstrated that the proton kinetic temperatures in coronal holes are larger than the observed electron thermal temperatures (~ 106 K). In fact the kinetic temperature for heavy ions like O5+ appears to be more than 100 times hotter than for the protons and these temperatures were found to be highly anisotropic (parallel temperature much higher than perpendicular temperature). In addition, the SOHO data show that oxygen ions flow faster than the protons already at ~2 Ro in coronal holes. What causes the preferential heating and acceleration of heavy ions is still not known. The observations suggest that ion cyclotron resonant absorption of high frequency Alfven waves may be responsible but other processes involving low frequency MHD or kinetic Alfven fluctuations may be involved also. The high frequency waves have not been directly observed and it is not known if they are produced by turbulent cascades from lower frequency waves or by impulsive shocks.

While the SOHO measurements of emission lines (velocity distributions) from heavy ions in a collisionless plasma can be used to reveal information about the processes taking place in the corona, it is still not known if these processes are also at work on the protons which make up the bulk of the coronal plasma. Furthermore, understanding the processes that produce the slow solar wind is more challenging than the case for the fast wind since these processes most likely occur at the transient boundaries between magnetically open and closed-field regions.

Additional measurements of solar wind properties in both coronal holes and streamers are needed from both in situ and remote sensing instruments in order to identify the relative contributions of different physical processes to the heating and acceleration of the all solar wind plasma components. Measurements of the kinetic properties of electrons and many more ions (i.e., a wider sampling of charge/mass combinations) are needed to better constrain the specific kinds of waves that are present as well as the specific collisionless damping modes. Measuring non-Maxwellian velocity distributions of electrons and positive ions would allow for testing of specific models of MHD turbulence, cyclotron resonance, and velocity filtration.

[see discussion under rfa 5. should probably be moved here]

F.3. Understand How Nonlinear Interactions Transfer Energy and Momentum Within Planetary Upper Atmospheres

The upper atmospheres of planets are dramatically affected by energetic inputs that originate at the Sun. The direct energy inputs and their immediate effects on the atmosphere are well-known, and include absorption of solar radiation at various levels, energetic particle precipitation, and the Joule dissipation of currents. However, there are many pathways by which solar energy is transformed and redistributed throughout the atmosphere until the energy is ultimately radiated to space; and, connected with these processes is much of the inherent variability of the atmosphere over daily to millennial time scales. Take the absorption of visible solar radiation at the surface of Earth as an example. Water vapor-laden air is heated, convectively rises deep into the upper troposphere where the latent heat of evaporation is released. The atmosphere is periodically pumped and heated over a range of spatial and temporal scales, giving rise to the excitation of a spectrum of small-scale gravity waves, tides, and longer-period oscillations. Other waves are generated by the solar-driven atmospheric flow over topography, which sets up periodic undulations that also excite vertically-propagating waves. Many of these waves are capable of propagating into the mesosphere and thermosphere where they can go unstable or dissipate through other processes, ultimately depositing momentum into the atmosphere. The atmosphere responds through modification of the mean circulation, resulting in adiabatic heating and cooling due to vertical winds, concomitant changes in the temperature structure, and the redistribution of radiation-absorbing minor constituents. 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. Other factors affecting the mean circulation, such solar UV radiation and externally-driven ozone changes, also modify the mean circulation and its interactions with the wave field. Similar processes and scenarios are also key to understanding upper atmosphere weather and climate on Mars and Venus.

This RFA focuses on those energy and momentum transfer processes that are characterized by nonlinearity, feedback and cross-scale coupling; in short, nonlinear interactions. Understanding in this area is needed to enable quantitative predictions of atmospheric structure for aerocapture and EDL at Mars, realistic simulation of long-term change in terrestrial atmospheres, and the response of Earth's thermosphere-ionosphere to solar wind-magnetosphere coupling. Investigation F.3.1 addresses the mutual interactions between gravity waves and the larger-scale components of the circulation, as well as with the turbulence field that they are hypothesized to generate. The relation between macroscopic ionosphere plasma properties and the mid-latitude plasma irregularities that are seen during magnetically active periods also fall within this investigation under the common theme of cross-scale coupling. In Investigation F.3.2 we consider the prompt and long-term modifications of ozone densities that result from energetic particle precipitation into the atmosphere. The large-scale circulation and turbulent mixing that drive the downward transport of NOx to the ozone-rich stratosphere are those described in Investigation F.3.1, thus serving to link these two investigations. Finally, Investigation F.3.3 seeks to understand the nonlinear feedback processes that control the coupling between the high-latitude ionosphere and the magnetosphere over a range of spatial and temporal scales. Fundamental to this understanding are the mechanisms that control energy and momentum transfer between the charged and neutral components of the plasma.

Investigation .3.1 Understand the nonlinear dynamics governing transfer of momentum and energy between different spatial and temporal scales.

An important mechanism for transferring momentum and energy within the atmosphere is through the generation, propagation and dissipation of gravity waves. Gravity waves are generated by convection and latent heating, geostrophic adjustment, instabilities, and flow over topography in the lower atmosphere. The waves grow exponentially with height, and eventually undergo dissipation at higher altitudes where they deposit net momentum and heat into the atmosphere. It is well accepted that the meridional circulations in the middle atmospheres of Earth and Mars, and the accompanying deviations of their temperature structures from radiative equilibrium, are fueled by the dissipation of vertical propagating waves originating in the lower atmosphere. Often, dissipation involves convective or dynamic instability and the transition to turbulence. Turbulence is important for the net vertical transport of heat, momentum and constituents. Gravity waves also interact with global-scale atmospheric tides and planetary waves and modify their behavior. In addition, gravity waves are launched from regions of intense auroral heating, and propagate horizontally, carrying energy and momentum to the low-latitude thermosphere and ionosphere. Gravity waves are also thought to provide the seeding mechanism for the onset of ionospheric instabilities at the magnetic equator that eventually lead to plasma depletions, irregularity formation and the radio wave disruptions know as ‘Spread-F’ and ‘scintillations’. The fundamental physics of how gravity waves are generated, how they interact with other scales of motion, and how they undergo instability, break and create turbulence is poorly known. Subgrid parameterizations of gravity wave effects, which are essential for realistic general circulation model simulations of the atmosphere, cannot be developed until these basic physical processes are understood. Advances in this area require development of theory, intensive numerical simulations, high spatial and temporal measurements, and global measurements from space that delineate the sources, sinks and propagation characteristics of the waves throughout the atmosphere. The WAVES Mission is intended to meet the need for the global characterization of waves required for further development of theory, models and comprehensive understanding of the phenomena, at the same time providing insight into phenomena responsible for many characteristics of Mars’ atmosphere pertinent to exploration mission requirements. The Tropical ITM Coupler Mission focuses on the troposphere-ionosphere wave coupling processes specific to equatorial latitudes.

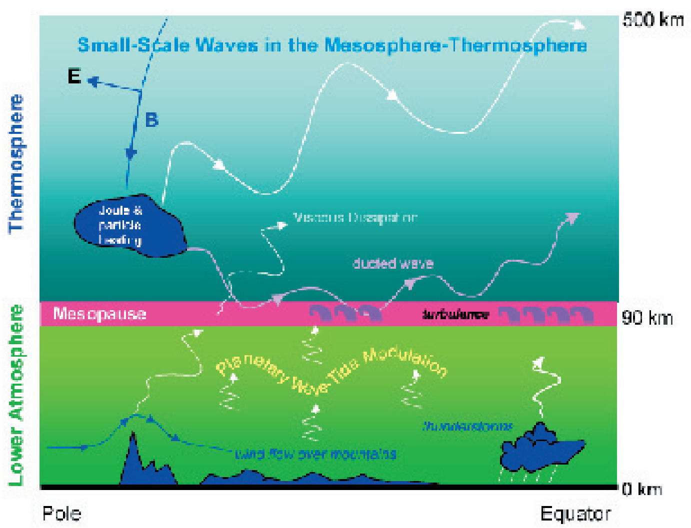
The theme of cross-scale coupling is also pertinent to outstanding problems in the ionosphere involving the formation of small-scale structures or plasma irregularities. Plasma irregularities interfere with communications and navigation systems. In many cases the ionosphere is preconditioned by large-scale processes in a way that leads to the initiation of instabilities and subsequent irregularity formation. While some understanding exists for the onset of plasma irregularities at equatorial and polar latitudes, the processes relating to the origin and evolution of newly-discovered storm-time mid-latitude ionospheric irregularities have not yet been identified. Our ability to characterize these irregularities and to understand their driving mechanisms suffers from a lack of basic measurements and from limited theory and modeling. In addition, the basic processes governing the onset, spatial extent, temporal evolution, intensities and spectral properties of these irregularities have not been characterized and in some cases never even measured. The LWS ITM Storm Probe Mission is designed to address the above shortcomings in the characterization and our understanding of mid-latitude ionospheric irregularities.

Investigation .3.2 Understand how energetic particles chemically modify planetary environments

Energetic particle precipitation (EPP) perturbs atmospheric composition through dissociation and ionization processes, excitation of atmospheric species, and chemical pathways that are coupled with dynamical transport. EPP is responsible for planetary aurorae and, in Earth’s atmosphere, the production of odd hydrogen (HOx) and odd nitrogen (NOx). These constituents play major roles in controlling global distributions of ozone. For example, NOx is created in the mesosphere and thermosphere by EPP, and transported downward in the polar night, in the absence of photo-dissociating solar radiation. Once in the stratosphere, catalytic reactions leading to the destruction of ozone can occur. The largest NOx increase in the upper stratosphere ever observed occurred in April 2004 and is attributed to EPP. The major unknown in this problem is the spatial and temporal variability of the energetic particle spectra over time scales ranging from hours to decades. Thus, the physical processes fundamental to auroral precipitation, solar flare production of energetic protons, and electron precipitation from the radiation belts are key to our understanding of this phenomenon. In addition, the processes controlling the transport of NOx downward to the stratosphere, including nonlinear interactions between gravity waves, the mean circulation and turbulence, are not well understood. Finally, the dynamical-chemical feedback mechanisms that are important to determining the final atmospheric response need to be identified and understood. The primary mission that supports this investigation is the Sun-Earth Coupling by Energetic Particles (SECEP) Mission, although the WAVES Mission will provide significant insight into the processes that enable the downward transport of NOx during the polar night.

Investigation .3.3 Understand how the magnetosphere and the ionosphere-thermosphere (IT) systems interact with each other

The exchange of energy and momentum between the magnetosphere and the ionosphere-thermosphere (IT) system strongly affects the behavior of both regions. Understanding how this exchange takes place on different space and time scales is essential for understanding and predicting both the quiet- and storm-time behaviors of these geospace regions. The exchange takes place mainly in the IT "boundary layer" between about 100 and 170 km, where ion motions undergo a transition from dominance by collisions with air molecules at lower altitudes to dominance by electromagnetic fields at higher altitudes. It is here that energetic particle precipitation increases ionization levels and enhances the inherent electrical conductivity of the region, modulating the magnetosphere-ionosphere electrical circuit that transfers the energy. The rate of energy and momentum transfer is also influenced by winds that are set into motion by collisions with the rapidly moving ions, creating a time-dependent feedback. The strong heating produces vigorous vertical motions of the air that mix the constituents unevenly and change the ion loss rate, affecting the ion densities and electrical conductivities. The fundamental processes that determine the rates of energy and momentum exchange on different scales, the manner in which the magnetosphere and the IT system respond to this multi-scale exchange, and the character and strength of the various nonlinear feedbacks, are poorly understood. The Global Electrodynamics Connections (GEC) Mission seeks to provide the measurements needed develop this understanding, which is key to enabling accurate prediction of IT space weather.



Investigation .3.4.A dusty plasmas topic. may go here or perhaps in RFA 5.

RFA F.4. Determine how solar and planetary magnetic dynamos are created and why they vary

The existence of the magnetic fields of the Sun and planets is a critical element of the Sun-Solar System connection. The process which creates these magnetic fields – the dynamo problem – remains one of the outstanding problems in theoretical physics. Dynamos occur on scales from the planetary to the galactic, and all involve the motion of an electrically conduction fluid. At Earth the molten iron core of our planet is driven by the release of thermal and gravitational energy that drives the dynamo. In the Sun, convection driven thermonuclear fusion drives the motion of the conducting plasma. The dynamo process involves the twisting and folding of magnetic fields so as to change and amplify the magnetic field. However, just how dynamos operate in such widely different conditions from stellar interiors to planetary cores is very poorly understood.

The solar magnetic field is the ultimate source of energy for acceleration of solar particles to high energies and controls the structure of the heliosphere and, thus, the entry of galactic cosmic rays into the solar system. These are key parts of the Sun-Solar System interaction and are important for exploration. The rotation of the Sun is governed by the hydrodynamic Navier-Stokes equations. Models built on these equations should be able to describe the observed differential rotation of the Sun in which higher latitudes rotate more slowly than lower latitudes. However, thus far, models have not reached this goal. Helioseismology has shown that the radiative interior of the sun rotates almost as a rigid body, and it is in the Sun's convection zone that the differential rotation occurs. This region of shear flow is known to play a major role in the Sun's dynamo as the non-uniform rotation tears and bends the Sun's magnetic field. The clues to understanding this important region appear to involve a variety of sizes from larger, easily observed features to much smaller scales still beyond our current observational capability. By coupling ever-advancing theoretic models with improved observations from space, we will understand how the differential rotation occurs and how this leads to the 22 year periodicity in the solar magnetic field.

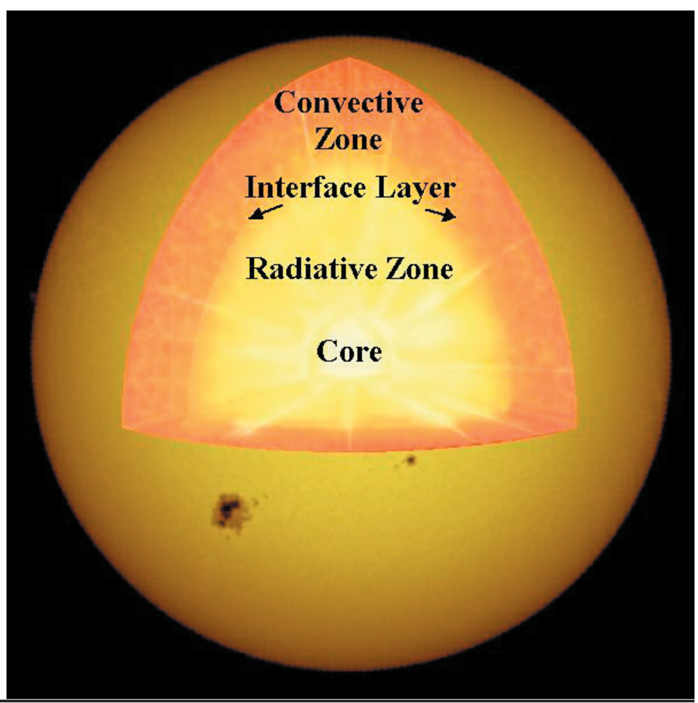
At the magnetized planets, including the Earth, the same basic physical processes as those at the Sun operate, but the specifics are sufficiently different to make planetary dynamos a different but closely related area of study. The dynamo in the Earth's interior sustains the geomagnetic field, which provides the shield that enables life to flourish in the otherwise deadly radiation environment of the solar system. It is well-known that the geomagnetic field varies in strength and has reversed multiple times in the history of our planet, which weakens this critical shield during this change. For many of the planets, a common feature is the dipole character of the gross magnetic field. The dominance of the Coriolis force in the motions of conduction planetary interiors provides a mechanism for understanding this feature and why the dipole axis is usually closely aligned with the rotation axis. However, this fails to explain planets such as Uranus and Neptune which have very different magnetic fields. Why is this and what are the physical mechanisms that lead to this difference?

Solving the dynamo problem will provide the key understanding to allow us to better predict and anticipate changes in the magnetic fields at both the Sun and the Earth. This understanding is essential to describing the coupled Sun-Solar System Connection and has important implications for the exploration of our solar system.

Investigation F.4,1. What are the causes for long-term variations in the solar cycle and how can these changes be predicted?

Helioseismic data from SOHO and ground-based observatories have revolutionized dynamo theories by placing the dynamo action at the base of the convection zone, in a rotationally sheared layer called the tachocline. The correct meridional circulation, which transports the magnetic fields (near the surface) towards higher latitudes and then down to the tachocline layer at the poles, has proved to be a key ingredient in determining the length of the solar cycle. Now for the first time models can use the meridional flow patterns from previous cycles to predict the length of the next cycle.

These dynamo models can now predict the cycle length but not the amplitude or whether the cycle will be double peaked. For example we do not know why the last two solar cycles have had relatively small maxima for the sunspot number. This type of information is critical for long-term planning of solar activity and would have obvious applications in trying to understand past periods of reduced solar activity.



It is challenging to be able to predict variations in cycle maxima or even Maunder minimum type periods. This would require models that incorporate more physics to explain the nonlinear interactions of convective motions, differential rotation, and magnetic field buoyancy in the Sun. Future models are needed to provide a physical explanation for the observed radial variation of the solar rotation and a better understanding of magnetic field diffusion in the tachocline layer. More accurate helioseismology data are also needed to pin down critical details of the subsurface flows and magnetic flux transport in the Sun.

- (long-term planning for lunar/mars colonies),

- solar dynamo: prediction of solar cycle What is the mechanism for diffusion of strong magnetic fields in the Sun?

- What produces the Sun's differential rotation?

prediction of emergence of active regions (short-term warning

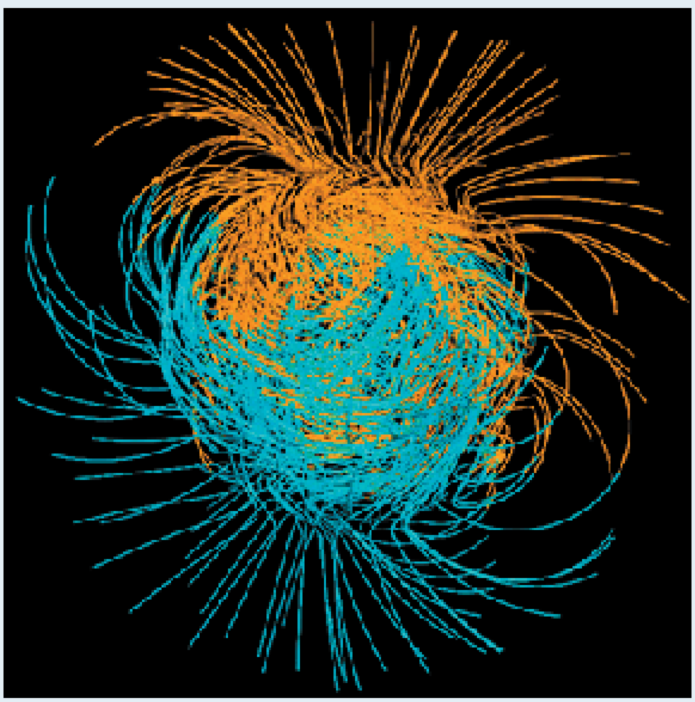
prediction of Maunder minimum (Ice ages ?, ozone holes?

Investigation 2: Planetary

Earth dynamo: prediction of magnetic field flipping

How do dynamos depend on the properties of planetary interiors?

What other forces besides the Coriolis force come into play in planets such as Neptune and Uranus?



How important is convection to the dynamo problem in the giant planets?

[connection to our nasa division Earth]

F.5 Understand the role of cross-scale coupling in creating plasma boundaries and the significance of boundaries in controlling physical processes

[alternate suggestions for rfa: Understand the Sun's interaction with the local galactic medium or, Understand the global mechanisms of the heliospheric cavity]

[to suggest the idea of understanding the physical processes important at the boundaries of different plasma regimes - e.g. the edge of the heliosphere, magnetospheric boundaries, and the inner corona. it is not clear that this RFA is needed. it appears that all these topics can be included in the other 4 rfas]

It has become evident that stellar winds are a ubiquitous phenomenon. While we can detect and sometimes crudely image the cavities that these winds create in their local interstellar medium, only in the case of the Sun can we hope to understand quantitatively the mechanisms shaping the plasma, magnetic, and particulate neighborhoods of planetary systems. Although Earth and the inner solar system lie buried deep within the heliospheric cocoon, their environment is nonetheless influenced by the modulation of galactic cosmic ray by the heliosphere as a whole. In addition, particles accelerated at the boundary between the interstellar medium and the solar wind also impact the inner heliosphere.

Investigation 1. Probe the physical origins of the solar wind.

[this duplicates investigation F2.5 and should probably be moved there]

Although many theories and hypotheses have been advanced to explain coronally driven stellar winds, to this day the actual physical mechanism (or mechanisms) that heat the solar corona remains an enigma. Given the complexity of the problem, it appears unlikely that remote sensing observations and theoretical approaches will ever on their own resolve the issue. In situ measurements, challenging though they may be to obtain, are critical to determining the physical means by which the solar wind is accelerated to the high speeds observed in the interplanetary medium.

Investigation 2. Explore the physics of the termination shock

[if we keep rfa 5, then this should be broadened to discuss socks in general]

The Voyager spacecraft are on the verge of crossing the boundary between our heliosphere and the external galactic medium. Determining the properties of this one accessible boundary underpin all our efforts to understand analogous boundaries about other stars. It is also key to understanding the penetration of galactic cosmic rays into the inner solar system and the modulation of that flux.

[also IBEX; should this investigation be rewritten to deal with shocks in general?]

Investigation 3. Understand the generation and propagation of energetic particles on a heliospheric scale.

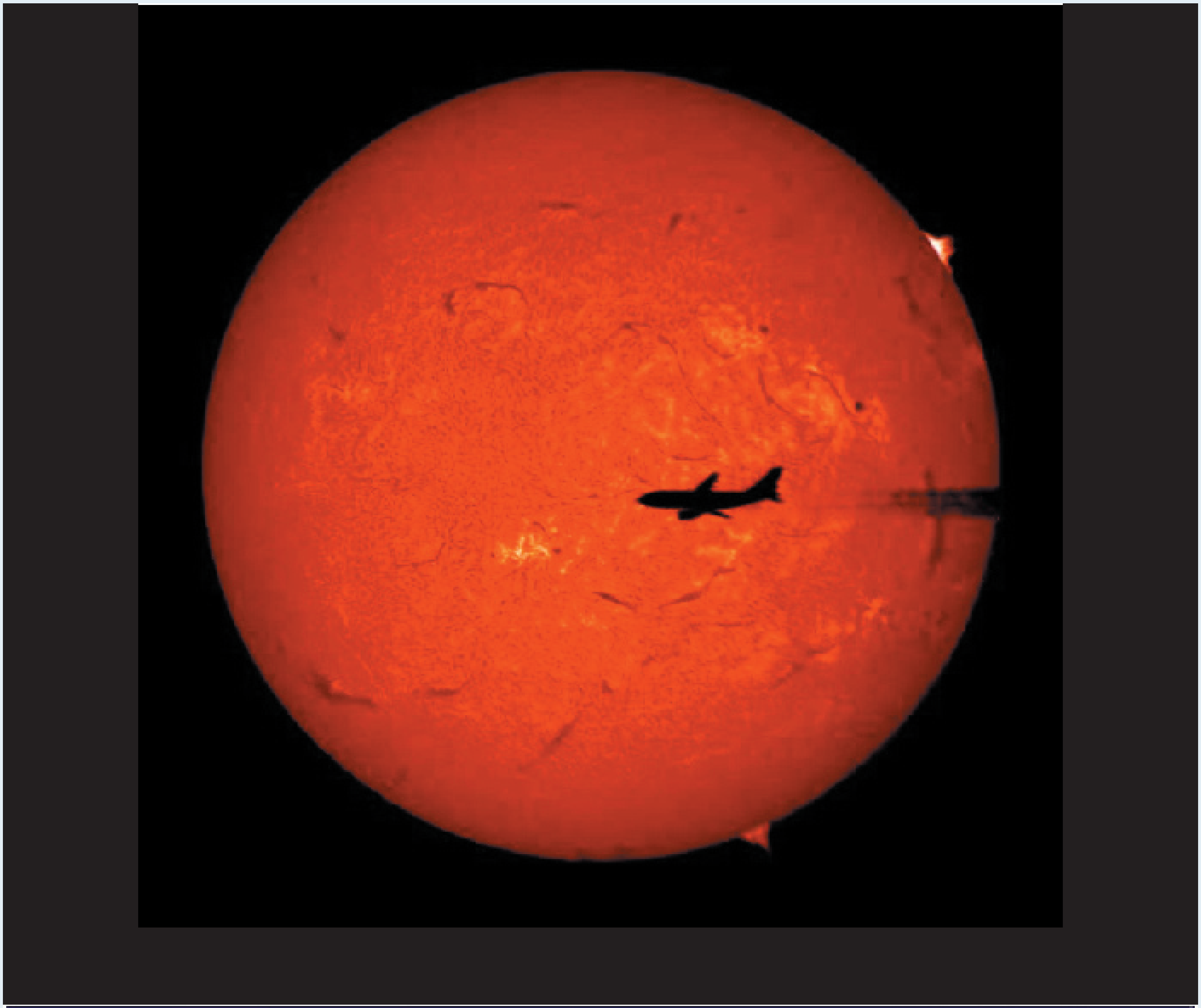
[note: this duplicates investigation F 2.3 and should probably get moved to that discussion]

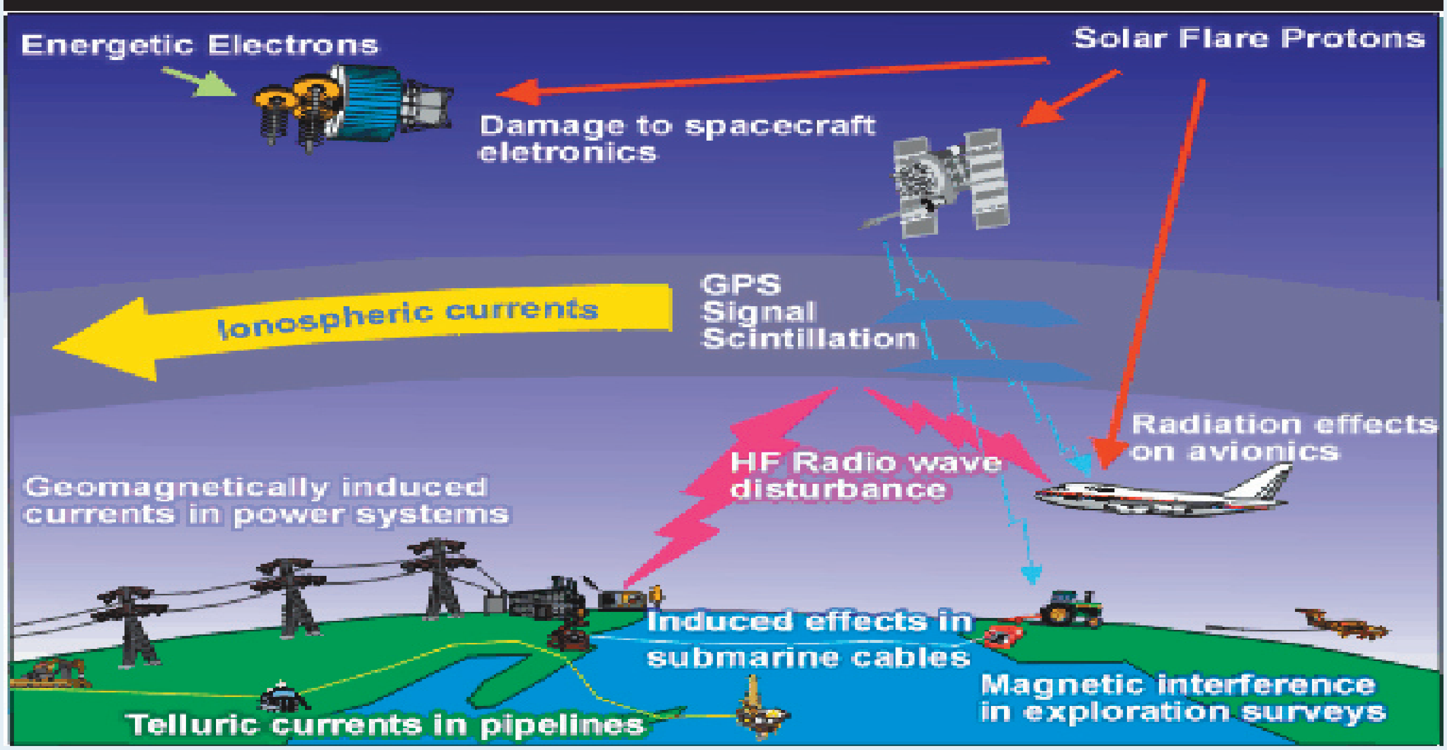
Includes all mechanisms related to the modulation of cosmic rays coming in from the galaxy, and those created at and within the heliospheric boundary and sheath regions. Heavy emphasis on the topology of the magnetic field, including effects of random walk of fieldl ines, Fisk field idea, reconnection, etc. Also, 22-year cycle effects, any variation in spectrum of cosmic rays as well as flux level (does high-Z content vary?).

Investigation 4. Understand how the properties of the heliospheric cavity evolve with time.

Over time scales of 10^4 years and more, the Sun in its motion through the Milky Way passes in and out of interstellar clouds. In each of these transitions, the environment of the heliospheric cavity is certain to change, perhaps substantially. It is important to ascertain the range of change and to assess the impacts upon our interpretation of the historical record, in light of the realization that heliospheric properties are inconstant over these epochs.

[how are NASA satellites going to answer this one?]





Energetic Electrons
Solar Flare Protons
Damage to spacecraft eletronics
GPS Signal Scintillation
Ionospheric currents
Radiation effects on avionics
HF Radio wave disturbance
Geomagnetically induced currents in power systems
Induced effects in submarine cables
Magnetic interference in exploration surveys
Telluric currents in pipelines

Objective H

Understanding the nature of our home in space

We will 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; we are intimately coupled with the space environment through our technological needs, the habitability of planets and solar system bodies we plan to explore, and ultimately the fate of Earth itself. Variability in the near-Earth space environment affects the daily activities that constitute the underpinning of our society, including communication, navigation, and weather monitoring and prediction.

This objective attempts to understand our place in the Solar System by investigating the interaction of the space environment with Earth and the effect of this interaction on humankind. There is necessarily overlap between this Objective and the other Objectives in this Roadmap. For example, the investigations under this Objective are dependent on the knowledge of fundamental processes investigated under Objective F. Furthermore, there is clear overlap with much of Objective J, "Safeguarding our outbound journey", devoted to assuring the safety of human and robotic explorers. Much of the same science, for example, is applicable to both Objectives. The focus of this Objective, however, is the impact of the space environment on us and on our home, Earth, either directly or by what can be learned about life on Earth by studying other environments in our solar system and beyond. Human life and society provide the context in which our investigations are conducted.

This context, however, is not meant to be a limiting one. For example, as we extend our presence throughout the solar system, we are increasingly interested in the planetary environments awaiting us and how the study of these environments can be applied to our home on Earth. A casual scan of the solar system is sufficient to note that habitability to life in general, and humankind in particular, is a rare congruence of many events. At least some of these factors, especially the role of magnetic fields in shielding planetary atmospheres, are a subject of immense importance. We think we understand some of the features that make planets habitable, but we need to understand much more.

Because of the intimate coupling of solar system processes, the interplanetary medium, and the near-Earth environment, a comprehensive study of this coupled system requires a series of investigations covering each of these regions. Specifically, investigations of impacts on humankind must start from the Sun, then follow propagation of solar disturbances through the interplanetary medium to Earth, and fi-

Priority Research Focus Areas

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

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

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

Apply our understanding of space plasma physics to the role of stellar activity and magnetic shielding in planetary system evolution and habitability nally investigate the interaction of the solar wind with Earth's coupled magnetosphere-ionosphere-thermosphere system.

To this end, four Research Focus Areas (RFAs) have been formulated seeking to understand the creation and evolution of solar disturbances from the Sun to the Earth, the response of the coupled near-Earth environment to these disturbances, the role of the Sun as the principal energy source in our atmosphere, and how magnetic fields affect planetary habitability. The first attempts to understand the Sun to the degree that we can predict solar variability and the evolution of solar disturbances as they propagate to the Earth. The second tries to understand the response of the near-Earth plasma regions and their impact on society. The third addresses the atmospheric responses over short and long times. The fourth places the Earth and planets elsewhere in context, through study of the solar wind impact on other solar system bodies, and of the evolution of solar and stellar activity over the age of planetary systems.

It is important to note that it is not enough to just study variability and change. Coupled systems have complex internal forcings, e.g. gravity wave breaking in the upper atmosphere. Even in the absence of solar variability, we still have to understand the internal dynamics of the near-Earth coupled systems that protect us. The RFAs outlined below therefore focus on both internal linkages and external forcing mechanisms.

RFA H.1 attempts to understand the sun to the degree that we can predict solar activity and the evolution of solar disturbances as they propagate to Earth. It focuses on short-term events such as coronal mass ejections that can create large magnetic storms at Earth and solar energetic particle events that can pose serious threats to technological assets and astronauts in near-Earth orbit. It also addresses longer-term changes in solar irradiance that can affect Earth's climate.

To provide this understanding, an investigation is designed to seek out the precursors to solar disturbances that can serve as predictive tools of disruptive events. Events such as coronal mass ejections can evolve significantly over their day or so travel time to Earth. Therefore, another investigation is devoted to studying how disturbances propagate and evolve from the sun to Earth. This RFA is not only devoted to short-term impulsive disturbances. Indeed, long-term variations in spectral irradiance or solar cycle variation can have much greater impact on society and Earth's climate. Thus, another investigation is targeted at studying the long-term (decades or longer) variations in the sun and the impact of these variations at Earth.

RFA H.2 tries to understand the response of the coupled near-Earth plasma regions (magnetosphere, ionosphere, and thermosphere) to solar disturbances. This complex coupled system protects Earth from the worst solar disturbances, but in this process it also redistributes energy and mass throughout the coupled plasma system. This near-Earth plasma includes space assets for communication, navigation, and remote sensing needs and can adversely affect their operations. Ground based assets can also be affected by ionospheric and upper atmospheric changes.

A key element of investigations under this RFA is the need to distinguish between response to external and internal drivers, as well as the impact of simple reconfigurations of environmental conditions, such as might be encountered when Earth crosses a magnetic sector boundary in the solar wind. Investigations thus seek to understand how Geospace (the near-Earth plasma environment) responds to external and internal drivers, how the coupled middle and upper atmosphere respond to external forcings and interact with each other, and the relative importance of internal versus external mechanisms on the upper atmosphere and ionosphere. Finally, because these investigations directly impact society, it is important to make these findings available to those people and organizations charged with protecting us and minimizing negative impacts of space weather. Therefore, an investigation is included to determine how best to transition this knowledge to an applied user community.

RFA H.3 investigates the role of the Sun as the primary energy source for Earth's atmosphere. It seeks to understand not only the atmospheric response to solar variability, but also the importance of steady-state processes in maintaining our atmosphere. It also investigates long-term climatic impacts of solar variability on humankind.

A fundamental question to be answered is to delineate what processes convert and redistribute solar energy within the atmosphere and how this is done. In concert with this investigation, other investigations seek to understand the relative importance of solar versus anthropogenic effects on Earth's climate, and how electrical coupling within and between the atmosphere, ionosphere, and the magnetosphere affect Earth's climate.

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.

RFA H.4 addresses the importance of understanding additional, vitally important topics such as the impact of solar wind on other solar system bodies and the advantages of studying stars other than our sun. In particular, it is intended to understand the role of plasmas and magnetic fields on planetary evolution and the ultimate habitability of planets to humankind. Such studies provide important opportunities for linkages with other NASA fields of study.

Investigations under this RFA seek to determine the role plasmas and magnetic fields play in the evolution of planetary systems and what the study of analogous processes in our solar system tell us about the evolution of planets within the solar system. A particular goal is to understand the role of planetary magnetic fields for the development and sustenance of life. One applied investigation that stems from these studies is to determine what the study of planetary interaction with the solar wind tells us about the implications of past and future magnetic field reversals at Earth

[NOTE: The RFA discussion below needs to be significantly expanded at both the RFA level and the investigation level.]

RFAs:

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

This RFA focuses on the solar part of the Sun-Earth system and includes the variability of the Sun and how this variability is transmitted from the Sun to Earth. However, it is not limited only to isolated disturbances or single events. Rather, it includes study of the impact of so-called quiet time changes, such as the passage of Earth through a solar wind magnetic sector boundary. While not nominally thought of as a disturbance, such a process will affect Earth and its inhabitants.

The research topics include short-term impacts from energetic particles, moderate-term impacts from coronal mass ejections (CMEs), and longer-term impacts from changes in irradiance. They also include study of the impacts on planetary space environments, in particular Earth's magnetosphere, but the details of this influence are captured in the following RFAs.

This RFA necessarily overlaps with RFAs J.2 and J.3, and much of the discussion there applies here as well. However, the emphasis in this RFA, and throughout Objective H, is to understand the impact of solar activity directly relating to human activities on Earth. This RFA highlights the fact that the Sun is the primary driver of the detrimental impact of the space environment on human society and technological systems. A solid understanding of the physical processes beyond the planetary environment is thus critical to understanding the physical processes within the planetary environment.

This RFA is important because solar disturbances are the energy source for almost all near-Earth activity. If we can show that our understanding of the solar and heliospheric physics is correct, then we can produce a predictive capability that works here at Earth as well as anywhere in the solar system.

Investigations [NEED DISCUSSION AND GRAPHICS FOR EACH]:

1. What are precursors to solar disturbances?

2. How do disturbances propagate and evolve from the Sun to Earth?

3. What are the long-term (decades or longer) variations in the Sun?

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 characterized by plasma processes of ionized gases.

The variability within geospace and the nearby interplanetary environment is generically termed space weather. Much of space weather is driven by the external processes addressed by RFA3.1. This RFA (3.2) focuses on the geospace consequences of those processes. In addition, internal drivers of the MIT region, such as the upward propagation of gravity waves, wave-particle interactions, and auroral current systems are equally important and must be investigated. This means that even in quiet solar wind condition, there can be significant variability within the MIT region.

Geospace is the location of most of our space activities. Communication, navigation, Earth weather and remote sensing, emergency location, defense reconnaissance, and NASA space science and astronomy missions are all affected by space weather. Space weather also causes disturbances of electric power grids and sensitive electronic systems on the ground. These include navigation systems used by commercial airliners.

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

Investigations [NEED DISCUSSION AND GRAPHICS FOR EACH]:

1. How do energetic particle spectra, magnetic and electric fields, and currents evolve in response to solar disturbances?

2. What role does the electrodynamic coupling between the ionosphere and the magnetosphere play in determining the response of Geospace to solar disturbances?

3. How do the coupled middle and upper atmosphere respond to external drivers and with each other?

H.3 Understand the role of the Sun as an energy source to the Earth's atmosphere, and in particular the role of solar variability in driving change.

Solar energy in the form of photons and particles drives the chemical and physical structure of the Earth's atmosphere. Ultraviolet and more energetic radiation is deposited globally and throughout the stratosphere, mesosphere, and thermosphere and is responsible for the formation of the ionosphere. Particles primarily deposit their energy at high latitudes but the resulting ionization, dissociation, and excitation of atoms and molecules can have a global effect as a result of dynamical processes occurring within the Earth's atmosphere that transport energy over the globe. Ultimately these processes combine to drive the temperature and chemical composition of the entire Earth's atmosphere. A key example of how solar modification of the atmosphere affects life is ozone in the upper atmosphere. Ozone provides a shield for humans from the effect of solar UV radiation. The presence of ozone is a direct result of solar energy deposition. Nitric oxide is created at higher altitudes by processes involving solar energy but may be transported to lower altitudes where it will destroy ozone.

Because life is dependent upon the atmosphere and its climate, studies of the modification of the atmosphere by solar energy are critically important. Solar energy and its variation are thought to have effects throughout the atmosphere including the troposphere where humans live. The magnitude and variability of the solar energy deposition remain poorly understood. In addition, the coupling processes that spread the effects of that energy deposition in altitude and latitude are also poorly understood. To resolve these issues, spectral measurements of the solar energy deposition which are resolved in space and time are required. Observation, theory, and modeling of the dynamical processes which distribute the effects of the solar energy are also crucial.

Investigations [NEED DISCUSSION AND

GRAPHICS FOR EACH]:**

1. Understand the processes that convert and redistribute solar energy within the atmosphere.

2. Understand the effects of energetic particles on atmospheric ozone and Earth's climate.

3. How does electrical coupling within and between the atmosphere, ionosphere, and the magnetosphere affect Earth's climate?

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 play an important part in the formation, evolution and destiny of planets and planetary systems. The only habitable planet we know is shielded by its magnetic field, protecting it from solar and cosmic particle radiation and preventing the erosion of the upper atmosphere by the solar wind. It is important to establish the extent that this is necessary for the formation of a stable planetary atmosphere that can sustain life. Planets without a shielding magnetic field, such as Mars, are exposed to additional physical processes (such as direct momentum transfer between the variable solar wind and their atmosphere) that may have a significant role in their evolution.

It is believed that planetary systems evolve from debris disks around young stars. Plasmas and magnetic fields are thought to play an important part in this process, both in the internal structure of the disk and its interaction with its parent star. The study of analogous plasma processes in the solar system (for example dusty plasmas in magnetospheres of Saturn and Jupiter) can lend insight into the significance of these effects. The coupling between planetary magnetic fields and their magnetospheres (e.g. Jupiter and its magnetodisc and Earth and the plasmasphere) will provide insight into the mechanisms that couple young stars to their debris disks.

Investigations [NEED DISCUSSION AND GRAPHICS FOR EACH]:

1. What role do plasmas and magnetic fields play in the evolution of planetary systems?

2. What can the study of analogous processes in our solar system tell us about the evolution of planets within the solar system?

3. What is the role of planetary magnetic fields for the development and sustenance of life?

4. What can the study of planetary interaction with the solar wind tell us about the implications of past and future magnetic field reversals at Earth?

Origins-Evolution-Destiny

SSSC Relationship to Aldridge Report Notional Science Agenda

The Report of the President's Commission on Implementation of United States Space Exploration Policy (the Aldridge Report) suggested organizing the Exploration Initiative's science research agenda around three broad themes:

• Origins – the beginnings of the universe, our solar system, other planetary systems, and life.
• Evolution – how the components of the universe have changed with time, including the physical, chemical, and biological processes that have affected it, and the sequences of major events.
• Fate – what the lessons of galactic, stellar, and planetary history tell about the future and our place in the universe.

How does the research of the SSSC community map into these themes? Here, we attempt to address this question.

Origins

• The Early Sun & the pre-biotic solar system environment

Was the early Sun rotating faster? Was it more active? A more active Sun would produce more ionizing (mutagenic) EUV radiation, more solar energetic particles, and possibly a significantly larger solar wind flux? All of these would affect pre-biotic solar system organic chemistry.

Understanding the relationship between solar rotation and magnetic activity is the central goal of helioseismology; this is a prime focus of missions such as **Solar Dynamics Observatory** and **Solar Polar Imager**. Understanding the relationship between solar activity and the solar wind is an important SSSC goal (Is this in our investigations?) that will be addressed by missions such as **Solar Probe** and **Doppler.** Exploration of the moon can test these theories by studying the fingerprints of the early solar wind in lunar dust samples.

• Formation of Planetary Systems

How did the planets form within the early solar nebula? How do planets affect the structure of a stellar system's dust disk?

Mapping the structure of the dust distribution near the planets and in the Kuiper Belt is one of the goals of the Interstellar Probe Mission. Clues to collisional evolution of the solar system can be found in the pristine dust distributions in the Kuiper Belt. Moreover, we can use infrared observations of dust disks around other stars to help look for solar- type stars with planets once we understand how planets affect the dust distribution.

Evolution

• Role of Planetary Magnetic Fields in Creating Habitable Environments

The presence of a magnetic field shields the atmosphere from the direct impact of the solar wind and dramatically affects the radiation environment of the planet. An unprotected atmosphere can be stripped away by the solar wind as may have happened on Mars. The evolution of life on a planet – and its fate – is critically dependent on its atmosphere and radiation environment.

One goal of the SSSC research is to understand the evolution of the Martian space environment. It has been proposed that the young Mars had a protective magnetic field, but, as the planet cooled, its magnetic dynamo ceased. With no magnetic field, the solar wind, which may have been stronger then, had direct access to the Martian atmosphere and may have stripped much of it away. Exploration of Mars may find clues to the evolution of its space environmetn in the dust and rocks. In addition, new missions such as Mars Aeronomy and ???? (Help here Jeff) will study the interaction of solar wind with the Martian atmosphere. Understandin current processes and interactions will shed light on the processes which determined the evolution of the Martian space environment.

• Comparative Planetary Magnetospheres and Atmospheres

How did the magnetospheres and atmospheres of *the various planets evolve? How was this affected by the changing Sun?*

Understanding the interaction of the solar wind with planetary magnetospheres and atmospheres is major thrust in SSSC research. We can learn about processes now and in the past by comparing magnetosphere, ionospheres, thermospheres and atmospheres of the different planets and how they are affected by solar variations in irradiance and space weather. Someone help with missions here.

Fate (Destiny)

Solar variability and space weather

Solar variability and solar activity cause disturbances in interplanetary space and in planetary environments known collectively as "Space Weather." Solar energetic particles are generated by solar storms; in addition, solar storms can also dramatically effect the radiation environment around Earth causing geomagnetic storms. How can we mitigate the effects of space weather on human and robotic explorers?

Mitigation of space weather effects is central to two of thethree SSSC high level objectives. One focuses on predicting space weather effects on Earth and the other on space weather effects in space and in other planetary environments. The specific investigations and missions are discussed at length in the sections on these objectives:

• Solar variability effects on climate change

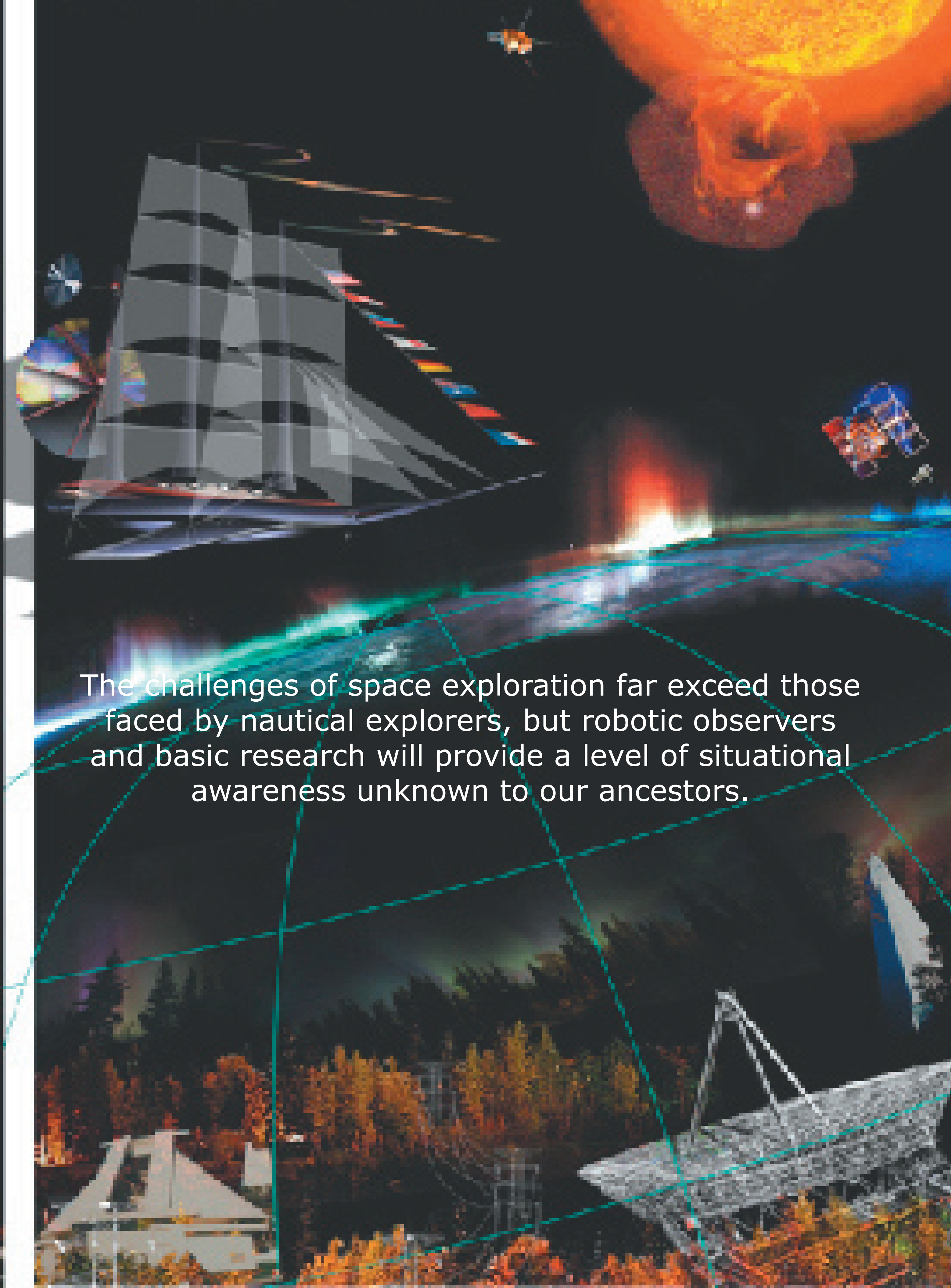
There are also important long-term (longer than a solar cycle, but shorter than stellar evolution time scales) variations in the Sun that may affect our climate and our radiation environment. For example, the period of low solar activity known as the Maunder Minimum is thought to have caused colder weather in parts of the world. Other Stars similar to the Sun show much greater variation in their total irradiance than the 0.1% observed for our Sun, suggesting much greater stellar activity. More activity implies more mutagenic EUV radiation as well as more solar energetic particles and space weather events in general. Is it possible that the solar irradiance will change dramatically in the future? How would this affect our fate?

One goal of SSSC research is to assess the role of solar variability in climate change and global warming. One specific goal is to understand how variations in solar irradiance, primarily in the EUV, affect Earth's climate (any missions?). At a more basic level, understanding the possible range of variations in solar activity and irradiance requires an understanding of the solar dynamo (see discussion under Origins) and, in addition, requires a knowledge of activity in other stars to constrain the models. One mission, the Stellar Interferometer, will try to image activity on other Sun-like starsfor this purpose.

• Long-term variations in the solar system's external environment

How does our local interstellar environment influence the solar system? Our solar wind and its magnetic field create a giant (hundreds of AU) bubble in interstellar medium known as the heliosphere. This magnetic shields us from some lower energy cosmic rays; however, the termination shock at the edge of the solar system is also thought to be a source of anomalous cosmic rays. Presently, our solar system is immersed in a relatively low density cloud of interstellar material. If our solar system encounter a region of hotter, denser plasma, the heliosphere would shrink and the flux of anomalous cosmic rays would increase dramatically.

Understanding the interaction of our solar system with the interstellar medium is an important goal of SSSC research. Controversial results from the Voyager spacecraft, now at approximately 100 AU, indicate that the first boundary of the heliosphere, the termination shock, is close by. IBEX, a recently selected Explorer mission, will study the structure and dynamics of the heliosphere remotely by imaging energetic neutral atoms created in the region beyond the termination shock by charge exchange of shock-heated solar wind ions with interstellar neutrals. It is also known that the galactic cosmic ray flux has changed significantly in the last century. Is this due to a change in our heliosphere or a change in the GCR flux incident on the heliosphere? The proposed Interstellar Probe mission would directly sample the interstellar medium and measure the GCR flux unaffected by the heliospheric magnetic field.



The challenges of space exploration far exceed those faced by nautical explorers, but robotic observers and basic research will provide a level of situational awareness unknown to our ancestors.

Objective J

Safeguarding our outbound journey

We will work to maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space.

There are many space environment conditions (i.e. energetic particle radiation, plasma and neutral particle environments, and electromagnetic radiation) that will have a significant impact on implementing the vision for exploration. This objective focuses on the science necessary for ensuring safety and maximizing productivity of all space explorers, both human and robotic, from low Earth orbit to the Moon, Mars and beyond. By characterizing the variability and extremes of the space environment, and ultimately developing the predictive capability to nowcast and forecast the dynamic conditions in space, we provide a key element in supporting the vision. This objective includes the near-Earth environment as well as the robotic and technological systems in space that support human space flight. The general issues addressed by this objective are the characteristics of various important environments, predicting the sources of deleterious variations, the amplifiers and modulators of perturbations, and understanding the effects on environments of interest.

Addressing these issues is necessary for optimizing spacecraft and instrument design, planning mission and operations scenarios and ultimately ensuring the safety and maximizing the success and productivity of both robotic and human exploration. Most, but not all, of the variability in the space environment is driven by solar activity such as flares and coronal mass ejections (CMEs). The underlying thread which links all three of the roadmap objectives is achieving the detailed understanding of the basic physical processes required to enable prediction (Objective F), with the emphasis here on the practical needs of supporting Exploration. The distinction between this Objective and Objective H (which focus on the science needed to understand how life and society are affected by the space environment) is the emphasis on understanding the variability of the space environment and its potential for violent change for the purposes of enabling and securing space travel

Priority Research Focus Areas

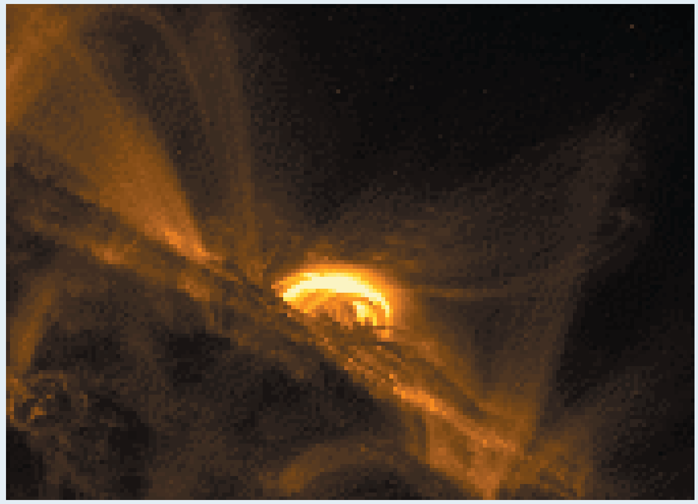
- Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.
- Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.
- Develop the capability to predict the propagation and evolution of solar disturbances (including shocks, and the acceleration and transport of energetic particles from solar, interplanetary, and galactic sources) to enable safe travel for human and robotic explorers.
- Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

There are fundamentally two ways in which understanding the dynamics of the space environment, the boundary conditions and sources which drive it, can assist future human and robotic exploration: 1) characterizing the variability and extremes, and 2) developing the predictive capability to nowcast and forecast transients (solar energetic particle events, CMEs, magnetic storms, etc.). Characterizing the likely or possible extremes of the space environment appears straightforward, yet requires understanding of the variables that modulate the conditions as well as their dependence on location within the solar system and the relevant boundary conditions that may influence the conditions. Predicting the variability and the extremes associated with this variability requires a more fundamental level of understanding of the entire system, and in particular, an understanding of the drivers and sources of the variability at the Sun. As a result, developing and applying an understanding of

"There are no such things as applied sciences, only applications of science."
- Louis Pasteur

the dynamic space environment (its boundary conditions which constrain it, and the interplanetary medium which modulates its extremes) is an important element of this objective.

In the LEO and geospace environment there are many conditions which effect robotic and technological systems that support human space flight. SEP events produce errors in navigation and commanding systems, spacecraft surface charging and discharging, location errors in GPS systems, single event upsets (SEUs) in spacecraft electronics, deterioration of spacecraft surface materials, sensors and solar panels, false star sensor readings leading to ACS problems, and difficulty in unloading "dumping" torque. Changes in the location of the auroral zone depends on geomagnetic activity, which can become disturbed in response to changes in the solar wind velocity, density, or direction. When the Earth's magnetic field is disturbed, the auroral zone expands to lower latitudes in proportion to the magnitude of the disturbance, and can produce errors in GPS systems and radar range errors which effect a wide range of systems. Enhancements in the trapped particle radiation belts or unexpected repeated passages through the radiation belts can also cause problems with spacecraft surface charging, single

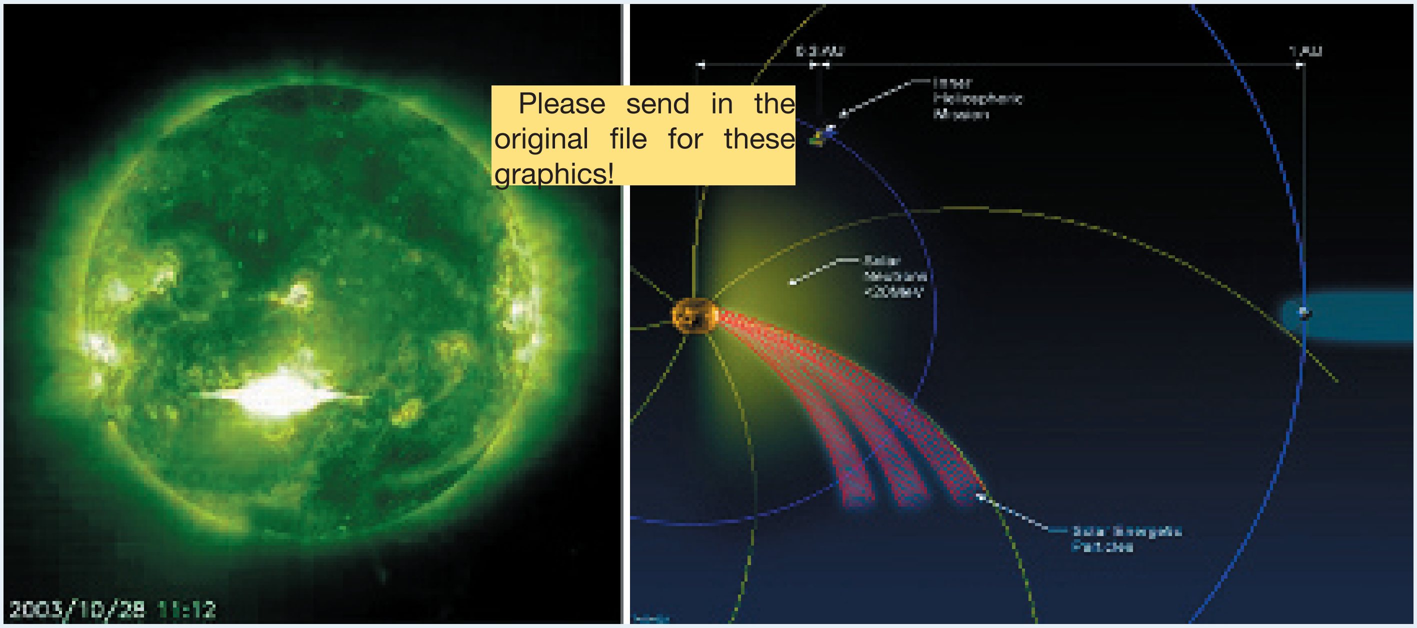


This solar X-class flare was observed by TRACE at 16:43UT on 22 November 1998. The flare heats up an arcade of loops at the edge of the disk that light up in the extreme ultraviolet.

event upsets, and deterioration of surface materials and solar panels. Planning for and mitigating these risks are all issues addressed by this objective. (This section needs to be flushed out in the RFAs!)

This objective is divided into four Priority Research Focus Areas (RFAs). The first RFA is focused on characterization of the space environment to be encountered by human and robotic explorers, including the current (?) conditions throughout the inner heliosphere, (characterize the system) the variations as well as the extremes to be expected. The second and third RFA build upon the first and are focused on developing the capability to predict the space environmental conditions throughout the heliosphere. RFA #2 is focused on the capability to predict the onset of solar activity and solar disturbances as the source of potentially hazardous space weather events, while RFA #3 is focused on the capability to predict the nature and severity of environmental hazards associated with the propagation of solar disturbances through the heliosphere. RFA #4 is focused on the characterizing and understanding the impact of space weather on non-terrestrial? planetary environments for the purpose of mitigating risk in exploration activities.

(Note: We could use help and input from the geospace folks to help flush out issues related to LEO, etc.)



(Left) SOHO Extreme Ultraviolet Imaging Telescope (EIT) image revealing flaring plasma (near the middle of the image) formed at > 2 million degrees Celsius. (Right) The energetic particles from this event propagate out along the magnetic field, impacting spacecraft electronics and human explorers in their path.

RFA #J-1. Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

Of the many space environment conditions (i.e. energetic particle radiation, plasma and neutral particle environments, and electromagnetic radiation) that will impact explorers, h the most significant is the space radiation environment. Understanding this space radiation environment, and mitigating future risk to long-duration space flight, translates into two elements that are required input for operational planning, the anticipated background (average daily) environment, and the worst-case scenario, transient event environment. Ultimate success in future risk mitigation, as well as optimizing both human and robotic performance, includes not only measuring and characterizing this environment, but understanding and predicting it.

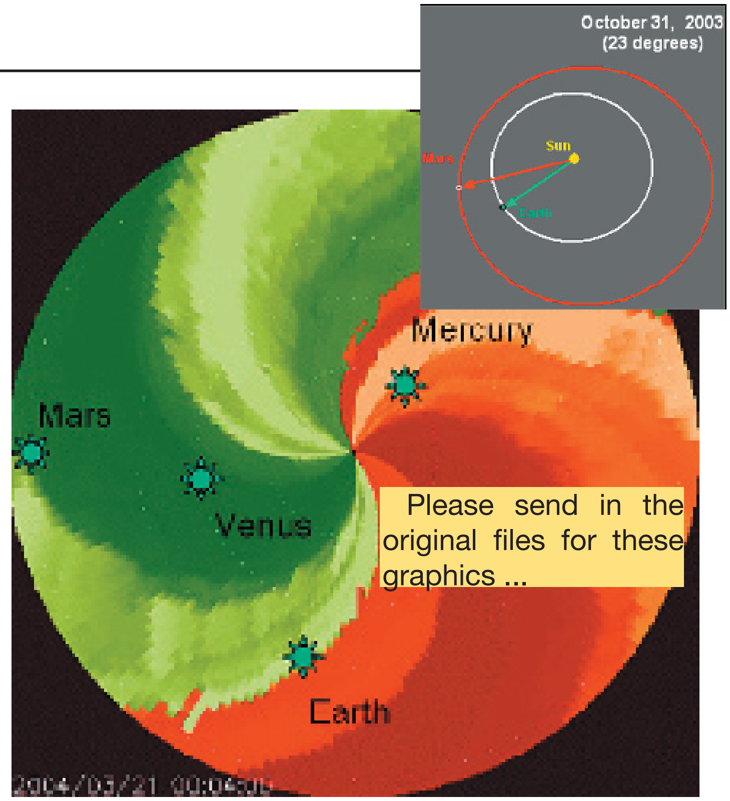
There are two major components to this radiation environment beyond Low Earth orbit (LEO), galactic cosmic rays (GCRs) and solar energetic particles . Galactic cosmic rays, at their most lethal energies, vary by roughly a factor of two throughout the solar cycle, and are strongly modulated by the solar wind and its variations. Solar Particle Events (SPEs) are sudden intense bursts of energetic particles associated with solar activity, which can add significantly to the accumulated doses and equivalent doses for both astronauts and robotic equipment. Both solar energetic particles and the charged plasma environment can disrupt communications and effect the electronic performance of satellites and spacecraft, increasing mission risk. SPEs can be roughly separated into two classes, impulsive and gradual, but the division is not sharp. Impulsive events originate near the Sun and have 1 AU transit times on the order of hours. The largest events are the gradual events whose particles are produced in shocks driven by large fast CMEs. One of the largest such events occurred between two of the Apollo moon landings. [Give facts about dose/effects from this famous event.]

One aspect of this problem that has recently become vividly apparent to the community is the variation of this radiation environment as a function of location throughout the solar system. Energetic particles produced by a flare or CME close to the Sun generally propagate roughly along the magnetic field embedded in the solar wind, approximating in the ideal case the path of an Archemidean spiral. However, this idealized case is routinely perturbed by CMEs and ICMEs which disrupt the field lines and solar wind flow, making modeling and prediction more difficult. Numerous measurements and monitoring across a wide range of latitudes, along with detailed monitoring will be required to accurately characterize, and ultimately predict the conditions throughout this region of the heliosphere.

A practical example of this is the space radiation environment en route to Mars, or at Mars, which can be significantly different than the radiation environment near Earth or at L1, purely for geometric reasons. Half of the time, Mars is on the far side of the Sun or significantly separated from the Earth sun line. The implication is that near Earth or L1 observations are not always sufficient to monitor or provide warning of the space environment for future Mars missions. In the case of the Oct./Nov. 2003 flare and CME events, which affected much of NASA's armada of spacecraft, Mars was in line with Earth and did experience 'our' space weather. This fortuitous alignment brought attention to the problem, but at other times we have observed energetic particle activity at Mars without any indication of cotemporal activity at Earth. For example, the MARIE instrument on Mars Odyssey (knocked out by the Oct./Nov. storms) showed previous increases in proton flux at Mars with no observed change in the GOES proton level at Earth. Future spacecraft in transit to Mars will undergo 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.

Complicating our understanding of this relatively straightforward view are recent GOES satellite observations which have detected significantly elevated proton events without any visible activity observed on the Earth-facing side of Sun! The current hypothesis is that solar activity on the far side of Sun of sufficient magnitude can have broad reaching effects throughout the inner heliosphere, with the radiation field becoming almost isotropic. Therefore, characterizing and monitoring the inner helisopheric space environment from all longitudinal vantage points is essential for understanding the nature and impacts of all levels of solar activity.

The primary goal of space environment characterization will be to establish the range of variability for both system design purposes as well as to develop and refine comprehensive models for predictive capabilities. This characterization therefore must be conducted over a sufficiently long time frame, over several solar cycles to properly experience and establish best and worst case scenarios of activities. Establishing this full range



Model of the inner solar system, illustrating the location of the planets superposed on the Archemidean spiral structure of the solar wind. Space weather forecasting is only valid in the local environment along a given spiral arm. In order to support continued exploration of the solar system, astronauts will need such forecasting capability from their own, remote location, independent of Earth-local forecasting.

of activity levels is a fundamental need for mission planning and execution.

In addition to planning for future missions, we also need to be able to characterize and monitor the space environment in real time, so astronauts can react to what is going on at the moment. An important objective from the point of view of planning, for example, future surface EVA operations on the moon, is the characterization required to provide real time forecasts and nowcasts of conditions and likelihood of events, above the nominal/normal baseline. For example, in-situ observations of the relativistic energetic electron environment can serve as precursors for, and nowcasting of, higher energy proton and solar energetic particle events , which have significant biological and astronaut safety ramifications. Therefore, in this particular case, real time observations are crucial for planning and implementing EVA and other surface activities.

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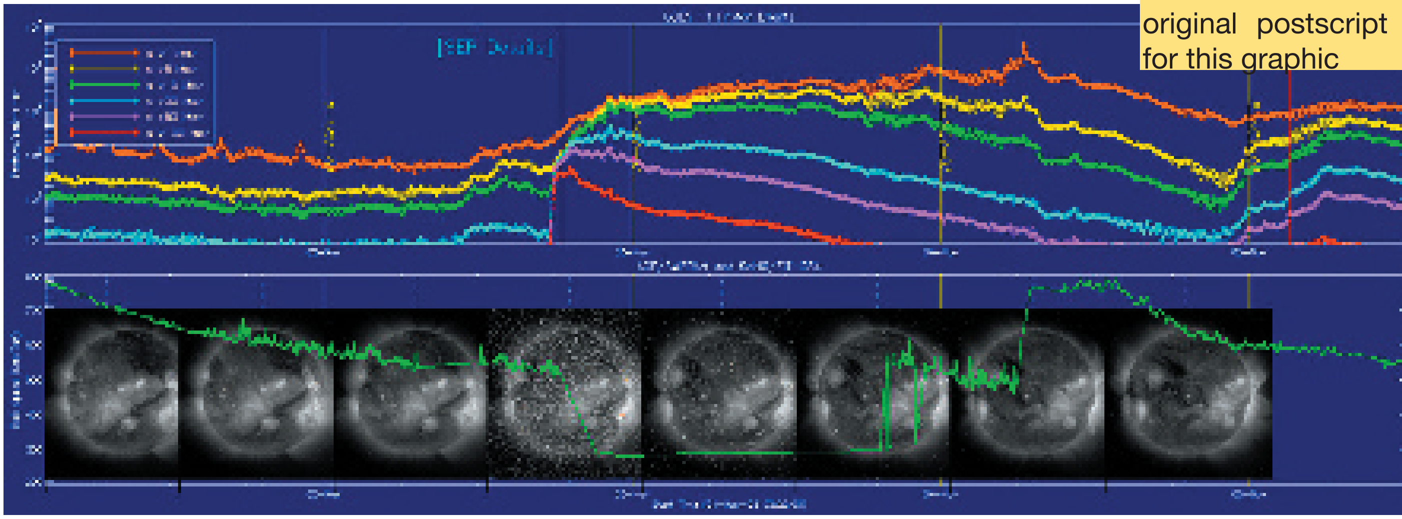


GOES proton fluxes and ACE/SWEPAM solar wind data superposed on SOHO/EIT images. Massive Solar Energetic Particle (SEP) events from October/November 2003 created havoc on satellites and spacecraft throughout the solar system. Earlier in the month, a similar SEP event knocked out the MARIE instrument on Mars Odyssey after recording radiation doses in excess of 1200 mrad/day. Remote sensing images, such as these, have been identified by the National Space Sudies Board as an important tool for predicting and forecasting space weather events. However, such instruments currently only exist in earth orbit and at L1 (SOHO).

Investigations:

Investigation J.1.1 What is the worst case space radiation environment that will be encountered by future human and robotic explorers, both in space and on the surface of target bodies?

- Relevant Missions: SWB, Sentinels, L1-Star, ACE, Mars GOES

Investigation J.1.2 How does the interplanetary radiation environment vary as a function of radial distance, heliographic longitude, latitude and time, and how should it be sampled to provide situational awareness for future human explorers?

- Relevant Missions: SWB, Sentinels, Solar Probe, Mars GOES, ACE

Investigation J.1.3 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?

- Relevant Missions: ACE, Sentinels, SWB, Mars GOES

RFA #J-2. Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

Successful space weather forecasting entails reliable characterization of impulsive solar disturbances as well as accurate knowledge of the global corona and solar wind through which they propagate.

The energetic particles in the impulsive SPEs produced near the Sun by flares or CMEs in the low corona have 1 AU transit time of minutes to hours whereas the gradual events associated with CME shocks have travel at the shock speed. It may be possible to use coronagraph observations of a CMEs leaving the Sun to give 1-2 day warning of the gradual events, but to give warning of the near-relativistic impulsive events, or to increase the warning time of CMEs and gradual events, it is necessary to develop the capability to predict the origin and onset of solar activity and disturbances from observations of the Sun itself. This RFA focuses on the onset of solar activity; the next RFA focuses on the propagation of the solar disturbances.

We now have some empirical understanding of the regions that generate solar activity. We know that large, complex active regions are likely to produce flares and CMEs. But current understanding of coronal stability is not sufficient to predict these flares or CMEs. Much work is needed to to develop this predictive capability, to understand when a flare or CME will occur and how large the event will be. 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 the magnetic configurations that lead to flares and CMEs and we need to understand what triggers a flare or CME. Why do some active regions produce multiple CMEs and other not? Both systems are thought to be driven by magnetic energy release, but neither the stabilizing mechanism allowing energy to accumulate, nor the release process are understood well enough to predict eruption reliably. Additional diagnostics and techniques are needed to identify precursors of CMEs. Measurements of motions and changes in nonthermal velocity distributions in the lower corona and chromosphere are crucial to separating the various models of CME onset. Depending upon the specific physical process, Dopplergrams and other derived data products are likely to be the most reliable indicators that a specific region is about to erupt. Even without advance warnings, "nowcasting" and the reliable characterization of near disk-center CME liftoff would represent a significant improvement in space weather modeling capability.

Another critical need for exploration will be the capability of predicting "all clear" periods when 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 in transit or on Mars.

On a longer time scale, we need to develop the ability to predict the when and where active regions will arise. This will require development of helioseismology techniques and also observation of the Sun from multiple view points. Research focus areas from Objective F provide the foundation for understanding the fundamental processes related to long term variations in solar activity.

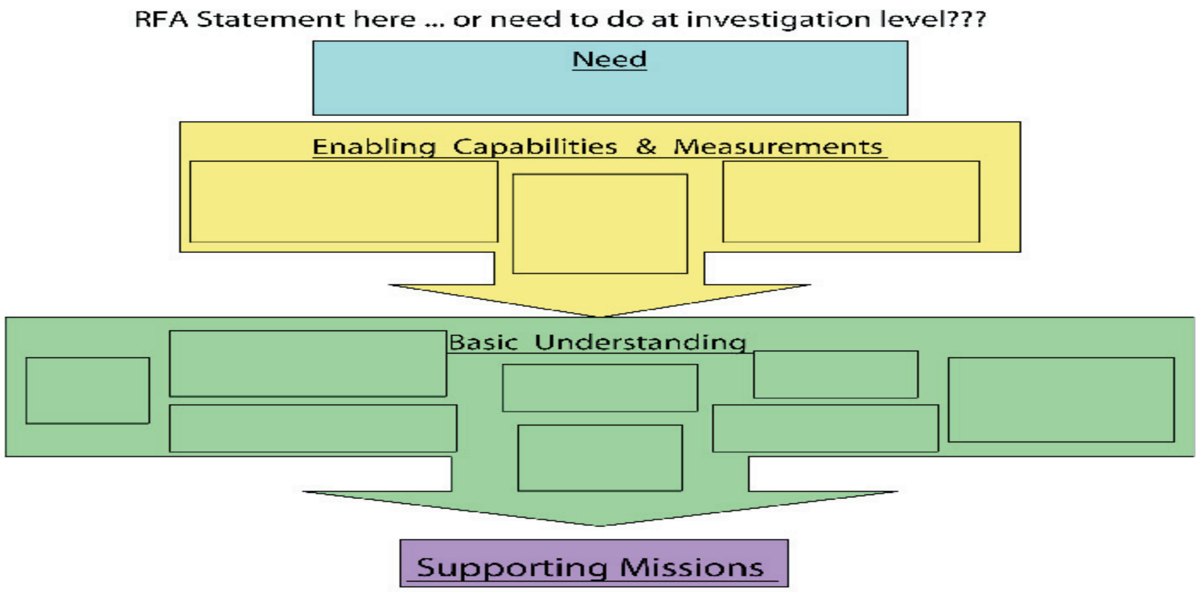
Investigation J.2.1 What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances and what determines their magnitude and output of energetic particles?

- Relevant Missions: IHS, DOPPLER, SHIELDS, RAM, PASO

Investigation J.2.2 What are the mechanisms that trigger CMEs and flares?

- Relevant Missions: IHS, DOPPLER, RAM, SHIELDS, SEPP

Current understanding of coronal stability is not yet sufficient to predict flares or CMEs. Both systems are thought to be driven by magnetic energy release, but neither the stabilizing mechanism allowing energy to



accumulate, nor the release process are understood well enough to predict eruption reliably. Existing indicators, such as magnetic field configuration and X-ray sigmoidal structure, do not provide precise prediction of CME onset. At present, the best indicators of oncoming geoeffective coronal disturbances are morphological: visible halo CME events, type II radio bursts, large flares, disappearing filaments, coronal dimmings, and "EIT waves". Although coronagraph image sequences in principle provide some velocity information, they cannot measure directly the speed of Earth-directed shock fronts.

New diagnostic observational techniques may hold the key to more reliable prediction. Measurements of motions and changes in nonthermal velocity distributions in the lower corona and chromosphere are crucial to understanding the structure of the inner heliosphere, and for separating the various models of CME onset. Depending upon the specific physical process, Dopplergrams and other derived data products are likely to be the most reliable indicators that a specific region is about to erupt. Even without advance warnings, the reliable characterization of near disk-center CME liftoff by means of Doppler imaging would represent a significant improvement in space weather modeling capability. Signatures that may be detectable up to hours before eruption include an early slow liftoff seen in Doppler shift, increased turbulent motions and/or heating, line asymmetries associated with prominence flows of 100 km/s or higher, sudden downflows in the vicinity of a prominence due to mass draining or reconnection, and sudden broadenings of chromospheric lines associated with energetic particle impacts due to reconnection high over the site of the potential eruption.

Investigation J.2.3 What observational data and models are needed to provide the predictive capability required by future human and robotic explorers?

- Relevant Missions: IHS, DOPPLER, SHIELDS, L1 Star, SEPP

VRFA #J-3. Develop the capability to predict the propagation and evolution of solar disturbances (including shocks, and the acceleration and transport of energetic particles from solar, interplanetary, and galactic sources) to enable safe travel for human and robotic explorers.

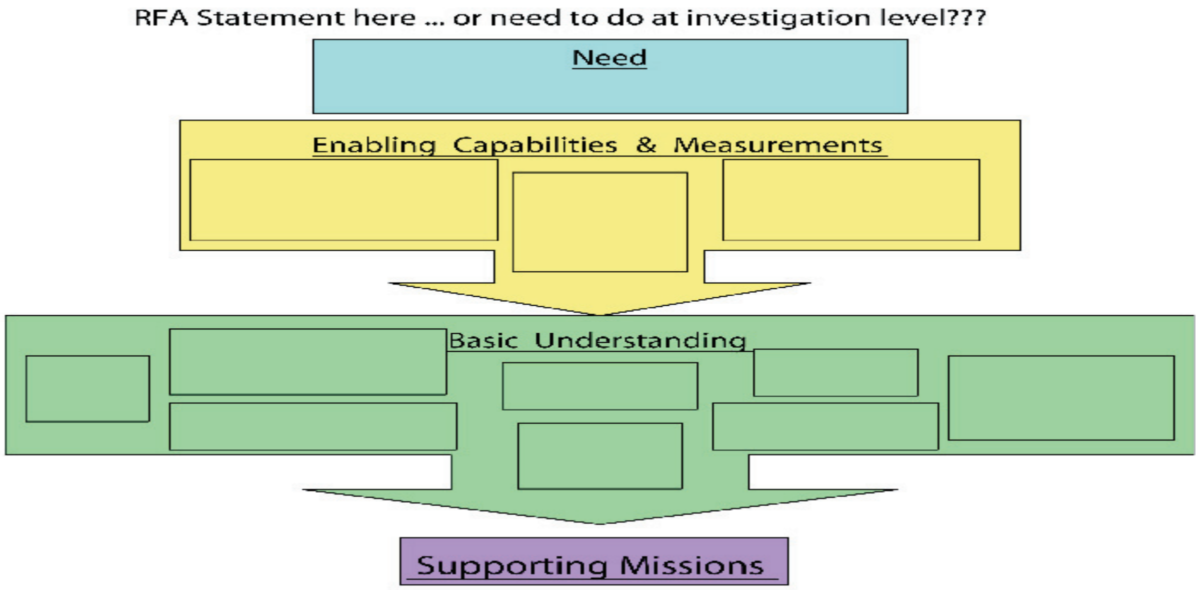
Energetic particles from CME shocks and galactic cosmic rays are a known radiation hazard to human and robotic explorers. In order to maximize the safety and productivity of these explorers, we need to develop the observational and modeling tools for more accurately predicting the arrival times, durations, and severity of impacts from these energetic particles. To a lesser degree shocks and plasma disturbances are also important since they can also damage space hardware. From a future operational point of view, an improved predictive capability will reduce the false-alarm rate and allow longer periods of extravehicular/lunar surface activity for human explorers. It should be noted that the emphasis for this RFA involves developing an understanding of the acceleration mechanisms and propagation of solar disturbances, and does not include understanding the triggering of solar events, which are included in RFA J.2. Both parts are needed for a complete understanding of these events. Research focus areas from Objective F provide the foundation for understanding the fundamental processes related to shocks and particle acceleration.

Models along with a comprehensive set of in situ and remote sensing measurements are needed to determine the energy spectrum, yield, duration, and composition of solar energetic particles (SEPs) from CME shocks and current sheets. The fastest 1AU transit time for the gradual event SEPs -- produced from CME shocks near the Sun -- are on the order of hours, which is the time constraint for which the information necessary for a confident prediction must be made. For energetic storm particles (ESPs) that are locally produced when the shock arrives at locations of interest, the lead time is the shock travel time (2-4 days to 1 AU). The highly relativistic SEPs from impulsive events arrive at 1 AU in minutes but they are constrained to follow the Archimedean spiral of the large scale solar magnetic field and so their impacts are more localized in space. By their nature the SEPs from shocks are of greatest concern for safety because they affect a larger volume of the heliosphere and can produces disturbances that last for days.

Theories for particle acceleration at shocks are reasonably well developed; however, questions about the source, injection, acceleration, and transport of the particles remain unanswered. A better understanding of the magnetic field line geometry and how the energetic particles, once created, escape along open field lines is also needed. These models depend on the shock strength, the configuration of the magnetic field and the turbulence in the vicinity of the shock, and the ambient energetic particle populations that are available for acceleration. Radio, white light imaging and EUV spectroscopic measurements of the extended corona have provided some information about shock properties in the extended corona but other new and more detailed measurements are needed to provide tight constraints for predictive SEP models.

Another possible source of SEPs is from CME/flare current sheets. As the main energy conversion region in the eruptive processes, the current sheet contains essentially most of the physics behind the eruptive phenomena observed. Information about the physical processes that occur is usually deduced indirectly by observing the dynamic behaviors of growth and separation of flare loops on the solar surface. However, indirect observations are not able to provide the information regarding the plasma density and temperature, the scale (mainly the thickness) of the current sheet, the rate of magnetic reconnection, and the magnetic field in the current sheet. This information is necessary for improving the understanding of how SEPs from impulsive events are produced and accelerated.

The galactic cosmic ray (GCR) background is a continuous source of particle radiation that is modulated by the disturbances in the heliosphere. Much of the GCR flux is shielded by the outer heliosphere and the remaining flux (approximately 10% at 100 MeV/nucleon) that enters the solar system is modulated by variations in heliospheric structure over the solar cycle and by sporadic events such as coronal mass ejections (CMEs). Substantial variability is observed in the differential fluxes of GCRs with energies below several hundred MeV/nucleon. So far ongoing intensive research has not achieved a complete physical



understanding of the processes responsible for factor of 10 or more solar cycle variation in the fluxes of these potentially hazardous particles.

Requirements for a predictive capability: Establishing a predictive capability for SEPs requires a program for obtaining the necessary set of measurements that will characterize the conditions where the disturbances develop. These critical parameters can then be used as inputs to forecasting models that predict the severity of radiation storms. During their development, the models can be tested by comparing their expected outputs with actual particle measurements at various locations in the heliosphere. Ultimately, the only definitive way to confirm models that describe the production and transport of solar energetic particles is to travel to the Sun, where they are produced, and to make the critical measurements of the plasma parameters, magnetic fields, particle source populations, and acceleration processes in situ.

The critical measurements that are needed for modeling CME shocks as they propagate from the Sun throughout the inner heliosphere can be obtained from both remote sensing and in situ measurements. Radio, white light and EUV (imaging and spectroscopic) measurements can constrain the important input parameters including the magnetic field topology at the Sun, orientation of CME magnetic field, background solar wind speed, shock speed inferred from plane of the sky CME speed, density of the shocked and upstream plasma (compression ratio), and magnetic field measurements (Alfven Mach number). Hard X-ray and gamma ray remote sensing measurements can be used to derive the SEP energies and identify their source regions. In situ measurements can determine directly that plasma and field parameters including the ion charge states and elemental composition of both thermal and energetic particle populations.

Further progress in understanding the SEPs from CME/flare current sheets can be made with a similar complement of remote sensing and in situ diagnostics discussed above for the study of shocks. Required measurements for the current sheet includes the thickness of the current sheet, the speed of reconnection inflow near the current sheet, as well as the magnetic field around the current sheet.

Remote sensing measurements provide an indirect means of studying the processes in the extended corona where the corona is heated to millions of degrees and the solar wind is accelerated to supersonic speeds. However, the best way to probe regions of the inner heliosphere is with a near-Sun in situ mission like Solar Probe in conjunction with remote sensing instruments to provide context. Understanding the physics of this critical region is ultimately necessary to produce the required models for predicting the radiation environment throughout the solar system.

Models to predict the severity of GCRs at different destinations in the solar system require the following measurements as inputs: galactic proton flux, magnetic field strength and size scale of the CMEs in the heliosphere, the latitudinal distribution of CMEs, and polarity of the ambient magnetic field. The propagating diffusive barriers used by models of GCR modulation need to be quantified in terms of CMEs and interaction regions.

Proposed investigations for RFA J.3:

Investigation J.3.1. What is the relationship between CME properties and the SEPs that they produce?

- Relevant Missions: SEPP, DOPPLER, IHS

Investigation J.3.2. What is the origin of the seed population for solar energetic particles?

- Relevant Missions: Solar Probe, IHS

Within a few solar radii of the sun's surface the solar wind is accelerated to speeds of several hundred km/s and heated to temperatures of millions of degrees. This region also is thought to be an important source region where solar energetic particles are produced and accelerated to energies as high as GeV/nuc. 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 measurements made outside this region to determine the physical mechanisms at work there. Remote sensing measurements can tell us much about the region nearest the sun – from the photosphere into the corona, however the regions of the outer corona that provide the interface between the surface and the heliosphere (solar wind) cannot be studied in this way. Understanding the physics of this critical region is necessary to produce models that can use remote measurements of the sun and sparse measurements in interplanetary space to characterize and predict the radiation environment throughout the solar system.

Investigation J.3.3. How do solar magnetic fields and solar wind plasma connect to the heliosphere?

- Relevant Missions:

Investigation J.3.4. What is the ground state of the solar wind through which heliospheric disturbances propagate?

- Relevant Missions: SWB, Sentinels, IHS

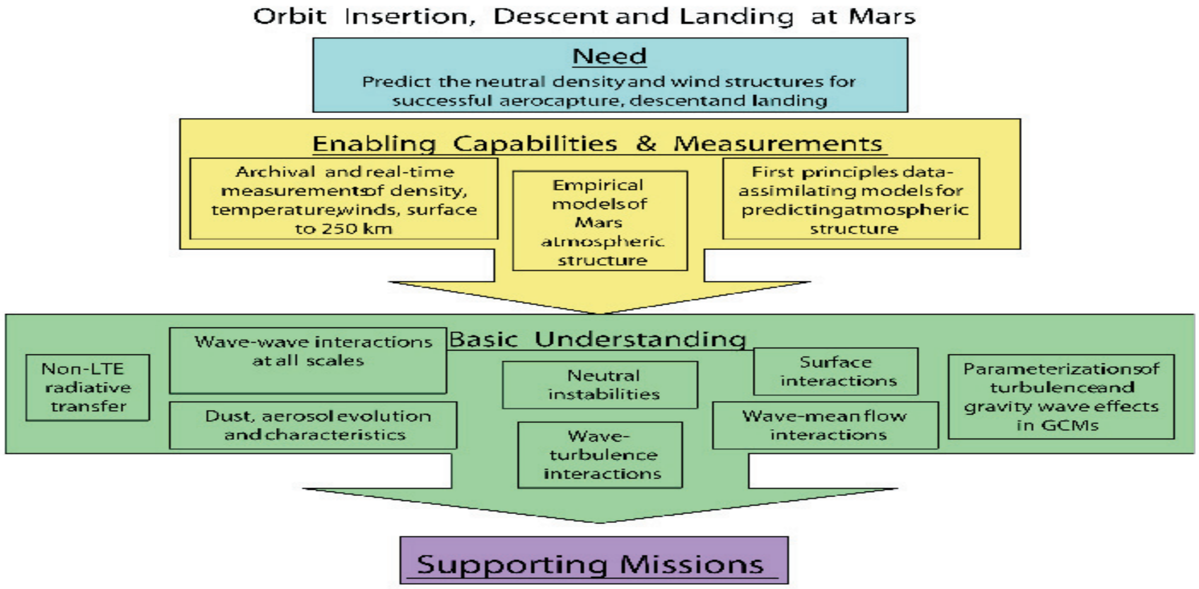
Investigation J.3.5. How are energetic particles modulated by the heliosphere and what determines the large variations observed fluxes of these particles?

- Relevant Missions: SWB, IHS, Sentinels, Solar Probe

RFA #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 and beyond will necessarily depend on planetary environments. Both the plasmas and neutral atmospheres of the planets, including Earth and Mars, impact the safety and productivity of exploration activities in a variety of ways. Surface-to-orbit and surface-to-surface communications depend on space plasma variability. Spacecraft control in low orbits and aerobraking parking orbits depend on the upper atmospheric density. Asset staging and operations, as well as astronaut health and safety, depend on planetary radiation environments.

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 are tar-



geted for the "near-planet" environments of both the Earth and other planetary systems. Because initial staging activities and transit of human and robotic explorers occurs in geospace, understanding of this environment is particularly important. 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 investigations/missions. In addition, comparison of other planetary environments to that of Earth will inform our understanding of the environment of our home planet. Understanding and characterizing the effects of near planet interaction and environments is essential to maximize the safety, productivity, and risk mitigation of hazardous conditions for exploration activities. A manned mission to Mars will require some combination of both orbiting and landing crews. Improved knowledge of Mars atmosphere for aerocapture and EDL (see Section J.1.x), 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.

In addition, reliable communications and navigation between orbiting and surface crews, and with Earth, are essential for crew safety, requiring improved understanding of the Martian ionosphere. Neutral density variability at aerobraking altitudes is predominantly controlled by dynamical influences from below, and can be addressed through the same basic connections and measurements delineated in Figure x, extended to higher altitudes. However, 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.

The implementation of the investigations described below will provide solutions to and establish key decision points for important questions that impact robotic and manned exploration program such as :

Investigations for J.4:

- What Level of Characterization and Understanding of the Dynamics of the Atmosphere is Necessary to Ensure Safe Aerobraking, Aerocapture and EDL Operations at Mars?
- To what extent does the ionosphere vary with season and solar flux, and how will this affect communication system requirements and operation?
- Do plasma instabilities and irregularities exist that can produce scintillations in navigation and commu-

nications signals?

• To what extent does radio wave absorption and fading occur in connection with solar particle events and x-ray flares?

• To what extend does solar irradiance and solar wind variability induce variations of practical importance in the neutral composition and density of the upper atmospheres and ionospheres of Earth and Mars?

• What is the distribution of energetic particle populations after transmission through Mars' atmosphere?

• How do Mars' magnetosphere and ionosphere respond to space storms?

• Are there particle populations at Earth or Mars that may be of concern for potentially hazardous spacecraft surface or deep dielectric charging?

Investigation J.4.1: What Level of Characterization and Understanding of the Dynamics of the Atmosphere is Necessary to Ensure Safe Aerobraking, Aerocapture and EDL Operations at Mars?

- Relevant Missions: Mars Dynamics, Mars Aeronomy

Aerocapture and EDL operations at Mars, particularly those involving human exploration, require accurate predictive knowledge of atmospheric densities and winds between the surface and 80 km altitude. The mean state and variability of Mars atmosphere is strongly driven by upward-propagating gravity waves and solar-driven thermal tides excited in the lower atmosphere, solar radiative forcing, CO2 cooling, and during some seasons, dust storms. The atmosphere of Mars is a strongly coupled system from the surface to the thermosphere, and consequently measurements in one part of the domain provide important information and constraints on other parts of the system. The accompanying diagram illustrates the connections between the operational need to predict the neutral density and wind structures for successful aerocapture and EDL by manned spacecraft at Mars, and the various applied science and research elements necessary to satisfy this requirement. First principles models will be needed, upon arrival of manned spacecraft at Mars, to assimilate real-time atmospheric measurements in order to specify and predict atmospheric state variables for accurate trajectory and spacecraft dynamics calculations. The precursors to these models are the existing GCMs, which, however, remain to be validated by simultaneous measurements of Mars atmosphere density, temperature, winds and dust from the surface to at least 100 km, but preferably to altitudes of order 150-200 km. It is critical that some measurements be performed as soon as possible so that the physics and parameterizations in these models can be tested and improved upon, and so that realistic empirical models of Mars' atmosphere structure can be developed for initial mission studies and perhaps even vehicle designs. The Mars Dynamics Mission is designed to provide many of the critical first measurements of Mars atmosphere required for decision points in the Mars exploration spiral.

A comparative planetary study of atmospheric dynamics on Earth and Mars is synergistic. Mars' upper atmosphere is driven by the same processes as Earth's mesosphere and lower thermosphere (MLT) region between about 60 and 150 km. Many key aspects of the upper atmospheres of both Earth and Mars are poorly understood, including energetics and dynamics. To understand the energy balance we need to measure the relative importance of various heating and cooling rates, including the role of dust. To understand dynamics, we need to quantify the effect of wave-wave coupling, wave-turbulence coupling, wave-mean flow interactions, the effects of radiative cooling on waves, etc. Our first insights into the dynamics of Earth's MLT region are provided by the UARS mission and the TIMED mission that is transforming our understanding of this region. However, our lack of knowledge of small-scale waves, their sources and sinks, and their interactions with larger-scale waves, the mean circulation, and turbulence represents a key pivotal link that must be addressed in order to enable further progress.

Thermosphere and Ionosphere of Mars. The upper atmosphere and ionosphere of Mars play important roles in programmatic aspects of the Exploration program. Aerobraking operations, and prediction of the lifetimes of orbiting spacecraft, require an understanding of the upper atmosphere of Mars in the 100-250 km region. Likewise, to ensure the ability to communicate and navigate requires knowledge of the ionosphere. In addition, the upper atmosphere mitigates the energetic particle and radiation environments that can affect humans.

A small subset of the issues can be addressed using ground-based observations from Earth, and a larger subset can be addressed by continuing to study the Earth's thermosphere and ionosphere through missions like TIMED and the planned LWS Geospace Ionosphere-Thermosphere Storm Probes and UV Imager. Some limited observations of the upper atmosphere at Mars are being made at present by several spacecraft, yet taken together they will not provide the understanding of the upper atmosphere structure, composition, dynamics, and variability necessary to address the pertinent risks to human exploration. Furthermore, the planned Mars Transponder Orbiter (MTO) mission has such a small payload available for instruments (~5 kg). There is no possibility that instruments on MTO will address the salient aeronomy issues. Therefore a dedicated mission to explore the upper atmosphere and ionosphere of Mars is needed, with the key goal of measuring key parameters simultaneously in order to provide a detailed understanding of the mechanisms that drive the variability in the thermosphere and ionosphere.

There are several existing first principles models of the Martian upper atmosphere and ionosphere, however there are insufficient data to validate the models except in an extremely rudimentary sense. These first principles models will be needed, upon arrival of manned spacecraft at Mars, to assimilate real-time atmospheric measurements in order to specify and predict atmospheric state variables for accurate trajectory and spacecraft dynamics calculations. Neither the model nor data components are ready for this challenge.

The Thermosphere-Ionosphere of Mars (TIM) mission will transform our knowledge of Mars upper atmosphere and will help prepare the way for exploration of the planet by humans. The parameters that must be measured are dictated by operational requirements. For aerobraking activities, the neutral density and winds must be measured in the 100 - 250 km region. The ionospheric plasma can only be understood with a knowledge of the neutral composition, neutral winds, temperatures, electric fields and magnetic fields that produce the electron density structure. A comprehensive dataset containing these variables is therefore required by TIM. On Mars, neither the upper atmospheric winds or electric fields have been measured, so TIM will be an exploratory mission. In addition, the neutral composition and temperature, and the ionospheric electron density have only been sparsely measured, so there is much still to be discovered about this region of Mars' atmosphere. For example, it is vital to discover whether the closed loops of the remnant magnetic field threading the ionosphere produce electron concentration peaks like the Appleton peaks found at low latitudes on Earth. On earth, these peaks are the location of maximum radiowave scintillation, and the cause of communication losses at all frequencies. If numerous similar structures exist in Mars complex magnetic topology, they could be problematic for human exploration.

The measurements proposed for TIM are a core subset of required parameters.

Investigation J.4.2 Radiation Hazardous of Planetary Systems

Relevant Missions: MSL, Mars Aeronomy, Mars GOES

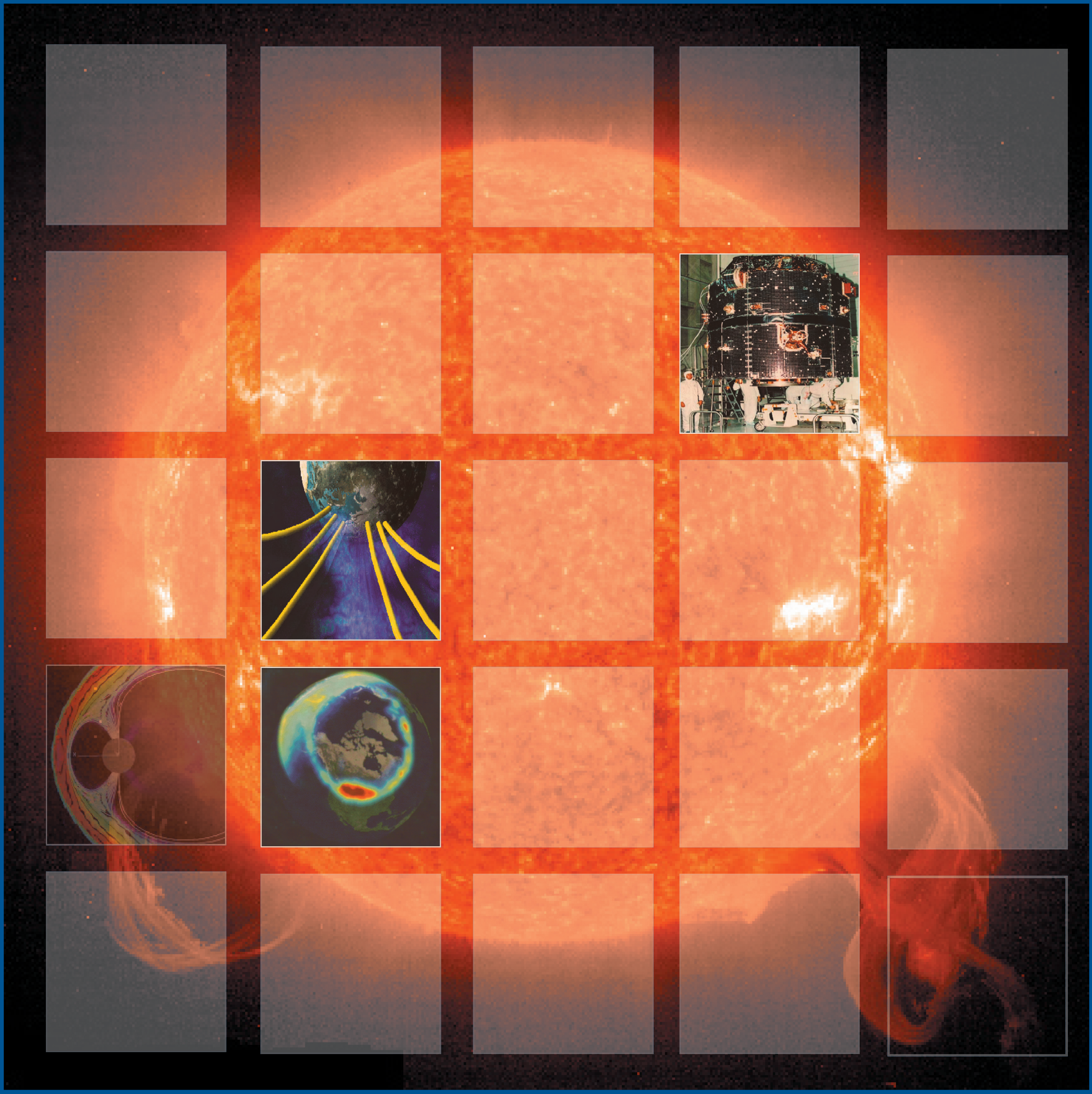
All robotic and human exploration activities will traverse the radiation environment within the Earth's magnetosphere. Assets involved in near earth staging processes will be exposed the radiation environment over prolonged periods of time. Predicting the behavior of the hazardous radiation environments within the Earth's magnetosphere is required in order to safeguard our outbound exploration activities. The current state of knowledge of the formation and evolution of radiation belts cannot predict observed behavior. Previous missions such and SAMPEX and CRESS have provided key information on the behavior of radiation belts that has led to the key decision point of developing the LWS Geospace Radiation Belt Storm Probe (RBSP) mission. A mission such as the RBSP is essential in order to predict the radiation environment of the near earth radian environment. In addition, the increase of knowledge resulting from this investigation is applicable to other magnetized planetary environments.

SSSC activities outlined in this roadmap provide an excellent match with the Exploration Initiative through their studies of the physical processes of our Sun, the impact of these processes on the solar system, and the nature of the interaction between the Sun and solar system bodies. Understanding all these processes is vital to safe exploration of the solar system.

The Sun is the central driver of all physical processes throughout the solar system, whether through direct illumination, emission of highly energetic particles, or the constant stream of solar plasma called the solar wind that interacts with the planets, including Earth. This interaction determines the nature of solar effects and varies between the solar system bodies.

The impact of the solar wind at Earth (and the Moon to a degree) is modulated by a strong terrestrial magnetic field that interacts with the solar wind in complex ways that are not well understood. Jupiter has a massive magnetic field that we are only beginning to understand. Mars, on the other hand, has essentially no internal magnetic field so the solar wind interacts directly with the Martian atmosphere. This interaction is directly relevant to the question of what has shaped the Martian atmosphere and what became of any water that was present in the past. It is also directly relevant to the safe exploration of Mars. The absence of a protective magnetic field requires thorough understanding of potentially dangerous events originating at the sun and a need for operational forecasts of both dangerous periods and 'all-clear' periods.

Mars exploration missions that employ aero-braking or aero-capture require knowledge of the Martian atmosphere and dynamics. While some robotic missions have successfully used these techniques, the state of our knowledge is insufficient to insure the safety of human explorers. Significant progress must be made in the understanding of wave dynamics, in general, and specifically in the Martian atmosphere. The fact that we do not fully understand these processes in Earth's atmosphere underscores the amount of fundamental research that must be performed before we can safely support Mars exploration.



Section 2: Strategies for Program Implementation

The SSSC Great Observatory

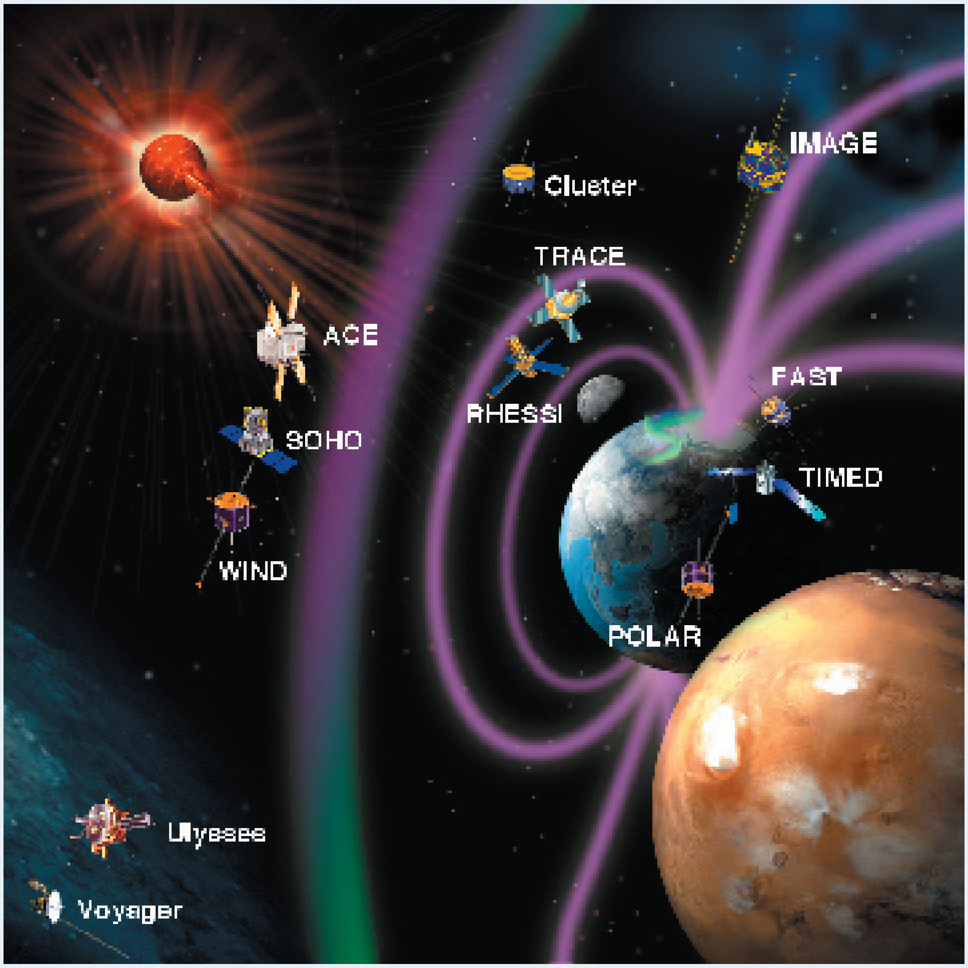
Our Great Observatory is a great fleet of solar, heliospheric, Geospace, and planetary spacecraft working together to help understand solar activity and its interaction with planetary systems throughout the solar system. Like NOAA's system for observing and predicting terrestrial weather, this observatory utilizes remote sensing, in situ measurements, data analysis and models to provide physical understanding and predictive capability. The diverse measurements across distributed spatial scales are linked with a variety of models that serve to fill in the gaps in the observations and help predict tomorrow's space weather. Much of the observatory is supported by our Mission Operations and Data Analysis (MO&DA) program, but vital information comes from instruments on other spacecraft as well in order to link together our understanding of the coupled Sun-Solar System.

Story F on the "Halloween Solar Storms" series gives an example of the unique and powerful capability of the Great Observatory to view a system of systems. The effects of the solar storms from the Sun to the Earth and beyond were observed simultaneously in key regions and from specific vantages. It would not have been possible to link the consequences of these superstorms at Earth to the solar drivers without this collection of satellites and the human and computational resources to interpret the data. Data from a single mission is rarely used in isolation. The greatness of our Observatory comes from the combination of multiple operational assets, focused and large-scale models, and associated data analysis.

The Great Observatory also helps us explain fundamental physical processes of the Sun-Solar System Connection. For example, magnetic reconnection between the interplanetary and Earth magnetic fields is the critical physical process determining the size of a geomagnetic storm. We have greatly increased our understanding of this process by relating upstream solar wind measurements to both data near the dayside reconnection site and to satellite-based images of the corresponding ionospheric airglow emissions. These discoveries about the foundational physics of our solar system were made possible by the combined resources of our Great Observatory: the coupled observations, the detailed data analysis, the extensive modeling efforts, and the knowledge of the underpinning theory.

The figure below shows spacecraft of the Great Observatory that provided key observations of the coupled system response to the large 2003 "Halloween Solar Storms". The measurement capability of the Great Observatory covers a broad range of methods including imaging the Sun, in situ and remotely sensing the disturbances in interplanetary space, measuring particles, fields, and radiation in Geospace remotely and in situ. With the SSSC portion of the Great Observatory, we are able to see disturbances moving out from the surface of the Sun all the way to the outer edge of the solar system (beyond 80 AU) and observe the effects propagating through the magnetosphere and ionosphere to the atmosphere. Additional "observation posts" for space weather were provided by spacecraft such as Mars Global Surveyor (MGS), Cassini and the Hubble Space Telescope; these provided important information on the effects of the Halloween superstorms on the space environment throughout the solar system. For example, from MGS, we learned that the fluxes of solar energetic particle radiation caused by the superstorms were quite different at Mars than at Earth. Therefore, our Great Observatory will need to evolve and expand to fully understand why these responses were different in order to meet the needs of the Vision for Space Exploration.

Our Great Observatory continues to develop as new spacecraft join and old ones retire or change their operating modes. Missions in their prime phase are generally focused on particular science objectives and systems; missions in extended phases (supported by MO&DA) provide the variety of observation posts needed to study the system of systems as demonstrated by the October Storms. One great strength of the SSSC Great Observatory fleet is that it is regularly evaluated and reviewed by the community to maximize the return on our investments. The Senior Review process determines which spacecraft are most necessary to meet the needs of the Sun-Solar System Connection program as defined by the community-developed Roadmap document. It is clear that there are some obvious gaps in this Observatory if it is to meet the new needs of the Vision for Space Exploration. New missions will be needed to characterize, understand and predict the dynamic environmental conditions in space to maximize the safety and productivity of both human and robotic space explorers.



Note: do we include "soon to launch" missions, like STEREO, Solar-B, TWINS, and CNOFS? Probably not, but this is a question to answer, like the inclusion of NOAA, DOE, and DOD satellites in this table.
Spacecraft in Our Great Observatory

Explorers and Other Mission Lines

There are three satellite lines that provide the elements of the 'Great Observatory' described in Section **, the Explorer program, the Solar-Terrestrial Probe line and the Living with a Star line. Operational and selected explorers and the operational and planned strategic missions will contribute critical input to achieving the goals set out in the three scientific objectives. In addition, this roadmap describes the crucial results obtainable from a set of satellites that are outside the scope of these three existing spacecraft lines. It is the connected nature of the Sun-Earth system that allows each element to expand the capabilities of the others.

The Role of the Explorer program:

The Explorer program has long been critical to maintaining the strength of the Sun-Earth Connection (now Sun-Earth System) science program. It affords a regularly recurring unique opportunity to fly exciting new missions, selected by peer-reviewed science with a relatively short response time, utilizing state-of-the-art instrument development. In addition, the program provides the opportunity for instrument teams to participate in missions-of-opportunity provided by other agencies (DOD, etc) or international programs. These missions-of-opportunity allow the space physics community to obtain the data necessary for specific strategic goals at a fraction of the cost of a dedicated mission. SEC Explorers are responsible for major scientific achievements that have profoundly transformed our understanding of the Sun-Earth system. Some highlights include: visualization of the global dynamics of the geospace system by IMAGE, the first gamma ray imaging by RHESSI, discovery of coronal magnetic complexity by TRACE, discovery of trapped anomalous cosmic rays in Earth's magnetosphere by SAMPEX, and discovery of small-scale size parallel electric fields in the auroral acceleration region by FAST. Many of these science discoveries provide direct input to the RFAs and therefore have already significantly contributed to the Vision for Exploration initiative. Examples include studies of particle acceleration via parallel electric fields by FAST (RFA 1.2), reconnection on the Sun by TRACE and in the Earth's magnetosphere by IMAGE (RFA 1.1), and variability of radiation belts over a solar cycle by SAMPEX (RFA 2.4 and 3.2).**NEED ACE result** Upcoming explorers will also enhance our understanding questions raised in the RFAs. An example is AIM, a smex that will quantify the connection between polar mesospheric clouds and the meteorology of the polar mesosphere and will provide the basis for study of long-term variability in the mesospheric climate and its relationship to global change. This study will contribute to solving RFA 1.3 and 3.3. The five spacecraft THEMIS will elucidate the mechanisms of transport and explosive release of solar wind energy within the magnetosphere and will provide important science results for RFAs 3.2 and 1.2. It is also a technology precursor to future 'constellation' missions by providing an example of mission operation and data analysis from large numbers of satellites. This dual role has often been played by explorers. The recently selected IBEX mission to examine galactic cosmic rays and particle acceleration at the heliopause will advance our understanding of RFA 1.2, 2.1 and 3.4.

There are two mission-of-opportunity instruments that will be part of the SSSC operations: CINDI, which will fly on the DOD Communication/Navigation Outage Forecasting System (C/NOFS) satellite and TWINS, which will fly on DOD satellites. The CINDI investigation provides data that are not available from other C/NOFS instruments - continuous measurements of the neutral wind, important for understanding the stability of the nighttime equatorial ionosphere, and the vector ion drift. The scientific goals of the mission, to elucidate the physical mechanisms that result in ionospheric irregularities that can impact communication and navigation systems, are part of those described in RFAs 1.3 and 3.2. TWINS is a two satellite mission in which identical energetic neutral imagers will provide the first stereoscopic imaging of the magnetosphere to study the 3d configurations and dynamics of large scale structures including the ring current. The results will contribute to RFAs 2.1 and 3.2.

The Explorer line exemplifies the ability of the science community to respond rapidly to 'decision points,' which is an important element in the strategy put forth in the Vision for Exploration initiative. Such decision points can be based on a new scientific discovery that suggests the need for a new mission, on new instrumentation development that provide the opportunity to address questions previously not accessible to an explorer class, or new technologies or analysis techniques that enable a less expensive mission. The rapid response of the SSSC community to such promising scientific opportunities insures that science goals are met in the most cost and time effective manner. Results from such missions in turn may lead to development of new strategic missions or modifications of existing ones, a 'spiral' approach to meeting the goals put forth in the roadmap.

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

The Explorer program provides one of the four key elements (Explorers, strategic missions, LCAS investigations and SR&T) that are necessary to insure the continued vitality of Sun Solar System Connections science and its effectiveness in contributing to the goals of the Exploration initiative. Although the roadmap can not plan that an Explorer mission will be selected in a particular timeframe that will address a specific RFA or investigation, history shows that the SSSC community responds to the high priority questions called out in the Roadmap with many innovative and unique mission concepts that have often been successful in the peer-review selection process, resulting in significant progress on the RFAs. The Explorer is an essential part of the SSSC science strategy, providing opportunities that cannot be anticipated in strategic mission lines. Interrupting or dramatically slowing the cadence the Explorer program would cause a loss of innovative science, as well as a future shortage of scientists and engineers with the necessary expertise.

The Role of the Solar-Terrestrial Probe Line:

The Solar-Terrestrial Probe Line is one of two strategic lines for the Sun-Solar System Connection. Strategic mission lines afford the space physics community the opportunity to plan specific large missions to address one or more of the RFAs and thus make significant progress in elucidating the fundamental processes of the coupled Sun-Earth system. In addition, such capable spacecraft missions often result in unexpected new discoveries. Many such examples are provided by the strategic line, ISTP, which was a precursor to the STP mission line and focused on flow of energy and momentum in the Sun-Earth system. For example, although not focused on microphysics, the ISTP missions have made numerous contributions to our understanding of plasma microphysics, such as direct measurement of the parallel electric fields in the auroral acceleration region (Polar), measurements of the electric field and electron motions in the electron diffusion region in magnetopause reconnection (Polar), ****need other examples from SOHO, Wind** discuss transformative science resulting**.

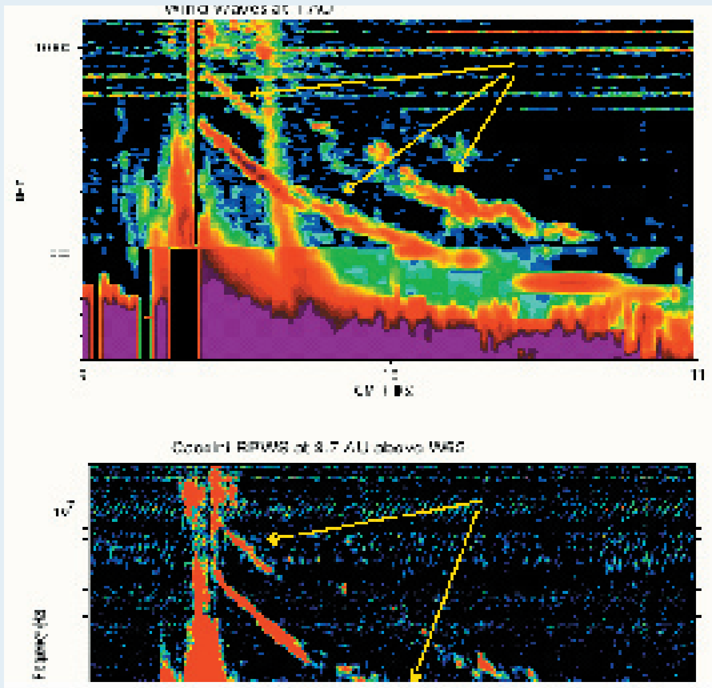
The first STP was TIMED, which is providing the first determination of both the energy input to the Earth's upper atmosphere and the response to that energy, a focus of RFA 1.3 and 3.3. TIMED has shown dramatic global thermal, chemical, and dynamic responses of the upper atmosphere to high latitude auroral energy inputs. During the storms of April 2004, TIMED observed a major NO enhancement in the upper stratosphere with evidence that it descended from the mesosphere (UARS also observed the largest NOx enhancement seen since its launch in 1993). This is an amazing event providing new evidence on atmospheric pathways that link solar variability to climate. Modeling suggests that the source of this perturbation is actually the superstorms in late 2003 in combination with a stable northern polar vortex. TIMED has also shown that the atmospheric response to high speed streams and coronal holes is more complicated than previously thought in a study of the impacts resulting from very large polar coronal holes and the geoeffective high speed streams of 2003. The interaction of atmospheric cooling and chemical changes due to large (30%) decrease in solar EUV with the effects of recurrent magnetic storms resulted in atmospheric effects of magnetic activity that extended deeper in altitude and lower in latitude and had significant effects on the chemistry of the MLTI. Other studies have addressed the formation of storm enhanced density (SEDs) plumes that cause major problems for communications and navigation systems. These and many other important new results of TIMED are the groundbreaking efforts towards obtaining the goals outlined in RFA 1.3 and 3.3.

STEREO, scheduled for a 2006 launch, will provide the first stereoscopic images of CMEs, thus elucidating the 3d structure of CMEs, and will examine the associated acceleration of solar energetic particles (SEP). In addition to the remote imaging of the Sun, a primary goal of STEREO is to triangulate the location of solar radio sources, making use of simultaneous measurements from the two spacecraft, thus examining particle acceleration and the structure of CMEs. The two main types of solar radio emissions observed from space are the very commonplace bursts associated with solar flares and the much rarer bursts associated with shocks driven by coronal mass ejections (CME). Although many observations have indicated that the flare-related bursts are emitted into a very broad beam so their position can be easily triangulated by widely space satellites, for the CME-related emissions, the beam width was not well known. The beam width is very important for understanding the relationship between 'space weather' near the Earth and elsewhere in the solar system. The figure below shows one example from many observed during the 'Halloween events' of 2003, where the radio receivers onboard the Wind spacecraft near Earth and the Cassini spacecraft in route to Saturn both measured radio emissions from one of the CME-driven shocks. The two spacecraft were approximately 62 degrees apart as seen from the Sun, equivalent to the separation of the two STEREO spacecraft 1.5 years into the mission. The ability to forecast the occurrence and spectra of SEPs is critical for the Vision for Exploration. STEREO will provide vital input for obtaining closure on RFAs 1.2, 2.3 and 3.1.

Need words on Solar-B

The next mission in the STP line is Magnetospheric Multi-Scale (MMS), which is a four spacecraft mission designed to study the microphysics of magnetic reconnection and particle acceleration in reconnection. This mission is critical to providing the answers to RFA 1.1 and 1.2.

Obtaining closure on the science questions described in this roadmap and their application to the needs of the Vision for Exploration initiative will be negatively impacted by the current slow-down in the cadence of these missions. In many cases, the science is dramatically enhanced by having missions operational during the same time intervals. When satellites are not simultaneously operational, the ability to directly map causal chains may be compromised. An example is that simultaneous observations by STEREO and MMS will allow the direct connection between specific types of CMEs and the way in



which reconnection occurs at the Earth's magnetopause in response to these varying solar wind conditions. Coincident measurements by MMS and GEC will facilitate understanding the impacts of energy input via electromagnetic fields and particles due to reconnection on the ionosphere and thermosphere and feedback of the ionosphere on the reconnection process. In addition, the opportunity for serendipitous discoveries resulting from the overlap is lost.

The Role of the Living with a Star Mission Line

The goals of the Living with a Star program are to understand the physical processes in the Sun-Solar System connection that directly affect life and society. The complex needs of this program led to the development of a dedicated line of missions to further these important goals and lead in the long term to operational missions and predictive capabilities. The LWS missions, which build on the fundamental knowledge gained by the STP missions, will very directly address the needs of the Vision for Exploration and Objective 2 and 3 of this roadmap.

Solar Dynamics Observatory, the first LWS mission, will examine the mechanisms that drive the Sun's 11 year cycle of variability, the magnetic field configurations that are precursors to CMEs and solar flares, and the variations is solar irradiance. These science questions exactly address RFAs 2.2, 3.1 and 3.3. The next set of LWS missions are the Geospace Storm Probes, which examine the effects of solar variability on the Earth system, including the radiation belts and the ionosphere-thermosphere, contributing directly to RFAs 2.1, 2.4, 3.2 and 3.3.

Mission	**Location**	**Primary function in GO**	**Phase/ funding**
Solar			
RHESSI	Low Earth orbit	imaging flare events	Prime, SEC
SOHO	L1	solar EUV and coronagraph observations	Extended, MO&DA
TRACE	Low Earth orbit	solar EUV observations	Extended, MO&DA
Heliospheric			
ACE	L1	upstream monitoring of SW	Extended, MO&DA
ULYSSES	Heliopolar orbit to 5 AU	heliospheric monitoring	Extended, MO&DA
Voyager 1-2	80 & 90 AU	outer heliosphere monitoring	Extended, MO&DA
WIND	L1-L2	SW measurements	Extended, MO&DA
Magnetospheric			
IMAGE	High Earth orbit	Auroral and magnetospheric imaging	Extended, MO&DA
POLAR	High Earth orbit	Mag.-Ionos coupling, reconnection, radiation belts	Extended, MO&DA
Cluster	High Earth orbit	Magnetopause and cusp	Extended, ESA and MO&DA
Geotail	High Earth orbit	Magnetotail and SW observations	Extended, Japan and MO&DA
LANL sats	Geosynch. orbit	Inner magnetosphere radiation environment	DOE
GOES	Geosynch. orbit	Magnetic field and radiation environment	NOAA
GPS	Medium Earth orbit	Total electron content, radiation belt monitoring	???
Ionospheric and Atmospheric			
TIMED	Low Earth orbit	MLTI physics and coupling	Extended, MO&DA
FAST	Low Earth orbit	Mag.-Ionos transition region	Extended, MO&DA
POES	Low Earth orbit	Particle precipitation obs.	NOAA
DMSP	Low Earth orbit	Particle precipitation, upper ionospheric measurements	DOD
Planetary			
Mars Global Surveyor	Mars orbit	Mars radiation monitor	Extended, Mars Program
Mars Express	Mars orbit	Mars plasma observations	Prime, ESA and Mars Program
Cassini	Saturn orbit	Monitor response of Saturn magnetosphere	Prime, SSE

Spirals/Stages/Pathwayas/Milestones/Decision Points

Each goal of the SSSC roadmap has a unique and compelling role in fulfilling the mission of NASA. The strategy employed to achieve the three goals maximizes the effectiveness of path-finding processes where clear decision points are based on discovery and new knowledge, and of developmental spiral or staged processes where recognition of needed Agency capabilities defines the activity.

SSSC Roadmap Goal	Strategic process
#1 – Fundamental Science	Pathway
#2 – Exploration Science	Spiral
#3 – Societal Impact Science	Spiral + Pathway

To understand (or know?) is at the core of what the word 'explore' means in its most fundamental expression. To understand how the Solar System and the Sun are connected, to understand how that influences the ability to explore beyond our home planet, and to understand how that impacts society are statements that define the content of the Sun-Solar System Roadmap. The processes that best enable the fulfillment of these statements will be implemented. The existing Sun-Solar System Great Observatory, comprised of existing missions and associated MO&DA programs, is the foundation for the strategic processes that are adopted. Decision points are defined as moments when the state of knowledge has progressed, as a result of previous activities and discoveries, to the point that an informed decision can be made with respect to what the next step should be in furthering the understanding of the relevant investigation or in achieving a goal.

Goal #1

The strategic progression for achieving the 1st goal of the road map is to pursue fundamental measurements in a stepwise fashion where the direction of the path is determined by the state of knowledge at the point of decision. Descision points Some decision points may dictate the end of a pathway if there are no compelling or urgent reasons to pursue that course. Other decision points may branch into multiple pathways that develop due to unexpected discoveries, or they may confirm a path that had been predicted. An example that demonstrate this process is the pursuit to understand the fundamental process of merging of magnetic fields or reconnection. The Magnetospheric MultiScale mission (MMS) has this as its primary objective. The results of this mission will mark the decision point and determine the path for future missions such as the Magnetospheric Constellation, Auroral Acceleration Probe, and the Magnetospheric Link mission (or whatever the better name for MiLiMII is).

The missions of heritage for the Sun-Solar System science and the processes by which they were selected provide strong evidence that the pathway progression has, in effect, been implemented in the past. The evolution of the Sun-Solar System Great Observatory is a testament that the pathway progression can be successfully utilized.

Need to flesh this out:

Solar Heliospheric Pathway

Heritage - SkyLab solar telescope, the Solar Maximum Mission (SMM), and Solwind led to SoHO; SoHo led to SDO and STEREO

Future - The results of SDO and STEREO with those of TRACE and RHESSI will lead to a decision whether we need a large aperture solar telescope in space such as SEPP or MTRAP, or ground or 360° 1AU ring - to provide predictive capability.

Geospace Pathway

Branch pathways have developed from heritage missions that can be described as a System Science path and Fundamental Science path.

fundamental path:

Heritage – Cress, IMP, Wind and Polar led to Cluster and MMS

Future – The results of MMS, Cluster with those of THEMIS will led to decision point regarding Magnetospheric Constellation or a radio sounding mission

system path:

Heritage – DE, FAST, Polar

Future –: The results of these missions along with the results of IMAGE and THEMIS lead to the complimentary Auroral Acceleration Probe mission and Magnetospheric Link missions

Goal #2 – Exploration Science

Need to develop capability to predict and characterize space environment. This is what is needed (1) predictive capability of Source of solar variability, (2) predictive and characterization of evolution of solar wind in interplanetary space, and (3) predictive and characterization of the effect of solar wind and solar variability on planetary environments. Therefore a developmental spiral process in each of these areas will be implemented; the solar-source spiral, the inter-space spiral and the planet-system spiral. With the Sun-Solar System Great Observatory as the foundation for each spiral, the process of developing the capability of characterizing and predicting the environment for exploration has already begun. The solar-source spiral is will develop based on the results of TRACE, RHESSI, SDO and SoHO to establish the predictive ability of existing models and measurement requirements for additional missions such as SEPP. The inter-space spiral will use the measurements of SoHO, Wind, ACE, and those of STEREO to define drive the solar wind evolution models and energetic particle environment and the requirements of future missions to Mars and the Moon that will spend so much time in interplanetary space. Part of the staged process will likely require additional measurement capability with missions such as the Space Weather Vanes and L1. The Solar Probe mission will provide a key ingredient in the predictive capability of energetic particles. The planet-space spiral will use the results of Polar, Fast, Cluster and MMS with the discoveries of the Radiation Belt Storm Probes to develop the predictive and characterization of the environment for the mars exploration missions and the associated staging in the near-Earth environment. The Ionosphere-Thermosphere Storm Probes, GEC and the global FUV imager will contribute to the knowledge of Mars global circulation models and to the requirements for the Aeronomy and Mars Weather (Dynamics) missions as well as define and predict the Mars environment in which aero braking/capture will occur.

Goal #3

A combination of strategic processes will be used to meet Goal #3. A spiral process will be implemented to develop the capability to predict the interplanetary space and its impact on the Earth's environment where space and ground assets operate. This may consist of measurements at L1 and those closer to the Sun, with the aide of solar sail technology, and global observations of the Earth's ionosphere/ther mosphere system. A strategic process incorporating pathways and decision points will be realized to determine the impact of radiation and EUV on the Earth's climate and space environment. The resulting knowledge of the SDO solar EUV measurements, the IT Storm Probes, and FUV global imager will determine the path to global circulation modeling efforts that impact communications/navigation and atmospheric/ionospheric coupling. The RB Storm Probes will investigate the evolution and variability of the near-Earth radiation environment and provide direction for subsequent measurements.

New Initiatives:

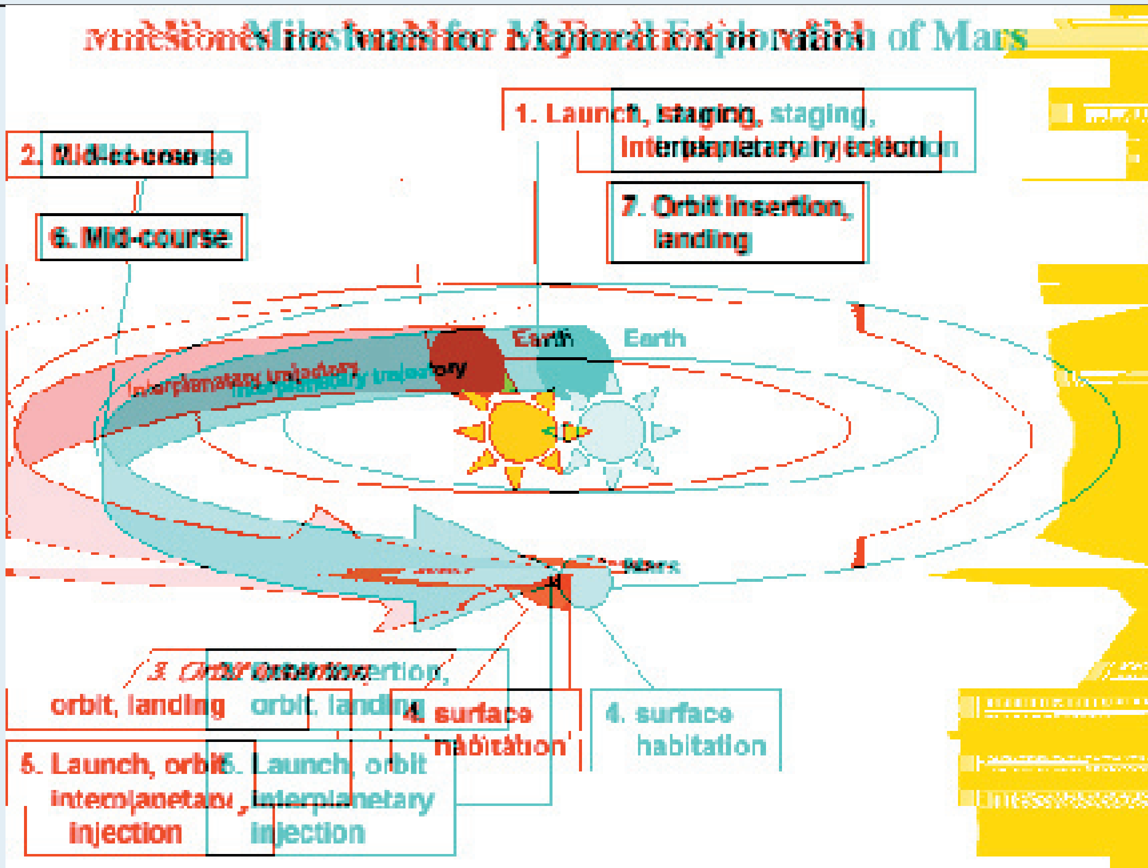
The SHMEx (Space Hazards Mitigation for Exploration) Program, and Solar Probe

1. The SHMEx (Space Hazards Mitigation for Exploration) Program

The space environment poses a number of threats to the productivity and safety of both robotic and manned exploration missions. With the miniaturization of electronics comes increased susceptibility to deep dielectric discharge and to soft and hard upsets by single-event and cumulative-dose energetic particle deposition. Spacecraft or habitat elements including life support systems, thermal coatings, solar cells, etc., require knowledge of the energetic particle environment to serve as a basis for proper design and perhaps corrective action. The energetic particle spectrum, including the secondary particles generated by irradiation of a spacecraft or habitat, can also be hazardous to humans in space. The radiation environments of concern for the VSE include geospace, the lunar environment, the interplanetary medium, and the Martian space environment and planetary surface.

The external environment of a spacecraft also consists of the neutral atmosphere that it encounters during aerocapture or atmospheric entry. Accurate knowledge of density, particulates, winds, and the variability of these parameters, including turbulence, is important for accurate specification of spacecraft trajectories and heating.

The basic and applied research agendas of the SSSC Roadmap address the above concerns at several levels, ranging from understanding basic physical processes to the development of predictive models that assimilate (ingest) observational data. The VSE has set goals of manned missions to the moon by xxxx and to Mars by yyyy. It is possible to delineate the SSSC elements that support the VSE by anticipating the operational needs of nominal lunar and Mars missions, deriving the enabling technologies, measurements and models required for mission success; and then to identify the basic physical understanding that must underly the above. An example is provided in the Mission-Enabling Flow Chart xx and accompanying Figure yy. The figure delineates the critical space environments to be encountered in the manned exploration program: geospace environment and lunar transfer orbit; the moon; the interplanetary medium; and the Martian environment (orbit, aerocapture & entry, habitation).



In going through the above process, the SSSC community has found that much of what we already do, and what is planned within the STP line and LWS program, can be traced through a flow diagram such as xx, leading to demonstrable connectivity with one or more operational needs. However, significant shortcomings have also been identified. These shortcomings include accurate empirical knowledge of the radiation environments of geospace and the moon; real-time (during Mars transit and habitation) 360° coverage of low-energy plasma, magnetic fields and energetic particles emanating from the Sun; the aerocapture, entry and descent environments of Mars; and real-time assimilative models of the above environments. It is proposed to address the above shortcomings through a proposed initiative, the *Space Hazards Mitigation for Exploration (SHMEx) Program.* The main elements of SHMEx include:

(N.B. I don't what the exact missions would be, but I am thinking one "radiation belt", one "solar/heliosphere" and one "Mars atmosphere" – I don't think we can credibly argue for more than 3 of these between now and 2035)

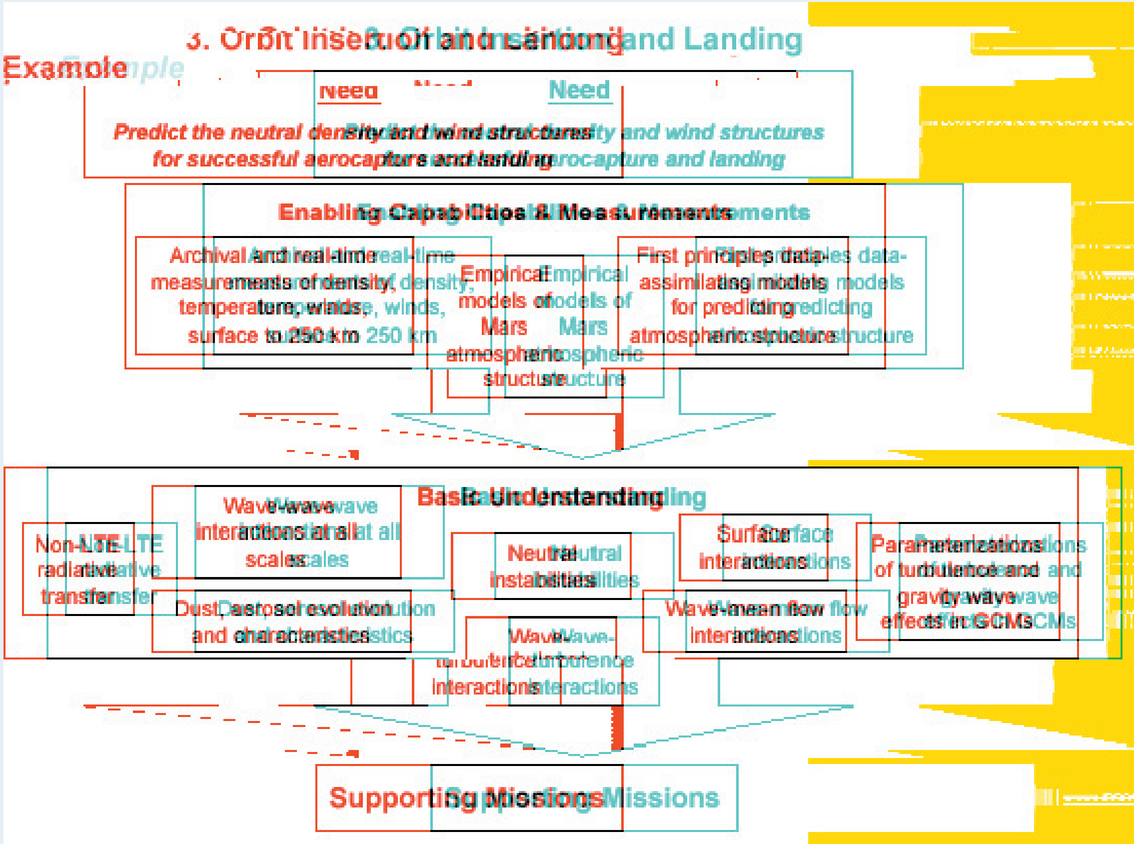
• Characterization of the geospace and lunar energetic particle environments, allowing for separation of spatial and temporal variability. This would be accomplished in part by a mission similar to one currently known as MagCon, supplemented by other missions of opportunity (secondary payloads, etc.).

• Characterization of the temperature, density and wind structure of Mars' atmosphere from the surface to ~200 km. This would be accomplished in part by the mission currently referred to as Mars Dynamics,

• Characterization of the interplanetary and Martian energetic particle environments through mission of opportunity payloads on various Mars missions.

• A real-time system (during manned mission to Mars) for measuring the spatial-temporal structure of disturbances emanating from the Sun. This would be accomplished by a system of "space weather buoys" surrounding the Sun at L1, measuring CMEs and SEPs, and providing other key data for ingestion into data assimilation models.

• A comprehensive theory and modeling program, with the ultimate goal of producing first-principles data-assimilative models of the geospace and heliosphere particle environments. This program would consist of large multi-institutional grants (~1 $M/year)



that aggressively tackle the difficult problem of accurate specification and prediction needed for supporting manned missions to the moon and to Mars.

- SR&T and GI Programs in support of the above.

2. Solar Probe

Solar Probe is the SSSC flagship mission. Using both in-situ and remote sensing instruments approaching as close as 4 solar radii from Sun, Solar Probe will visit one of the last unexplored regions of the solar system. Measurements will provide the first 3-dimensional view of the corona, high spatial- and temporal-resolution measurements of the plasma and magnetic fields, and high-resolution helioseismology and magnetic field observations of the solar polar photosphere. The primary science objective of Solar Probe is “to understand the processes that heat the solar corona and produce the solar wind”. In addition, Solar Probe will expand our knowledge of physical processes on the Sun responsible for the formation of active regions and the eruptive release of energetic particles, EUV and UV radiation, and indeed, the long-term evolution of solar output driving Earth’s climate and weather.

According to the report of the 1999 science definition team the fundamental science questions to be addressed by Solar Probe include:

- What is the physics of the flow of energy through the Sun’s surface and into the solar atmosphere (corona)?
- What causes the slow solar wind? What causes the fast solar wind?
- What are the properties of the smallest structures in coronal holes and streamers?
- What are the magnetic fields and solar rotation like near the poles of the Sun, beneath the polar coronal holes?

Solar Probe is cited as the highest priority mission for Solar and Space Physics in the **Decadal Research Strategy in Solar and Space Physics (“Decadal Survey”)** published by the National Research Council in 2003. Solar Probe is technically feasible now, and remains a very high priority mission in the SSSC Roadmap.

Programmatics, Partnerships, & Links

Because of the extensive nature of research in space plasmas, the Sun Solar System Connection has a broad set of links to and partnerships with other organizations and science disciplines. Partnerships and links are made at multiple levels, from individual collaborations between scientists to national and international agreements between agencies. While many of the partnerships that contribute to SSSC goals are not planned strategically (they are the result of competitive mission selection or mission implementation decisions, for example), they form an important part of the SSSC infrastructure and, in fact, make significant contributions to strategic goals. Some examples of successful partnerships that benefit both SSSC and our partners are given below.

Scientific links exist between research efforts in SSSC and a number of other discipline areas; for example, the SSSC community has an ongoing relationship with the planetary science community. One common goal is the study of Mars: Mars Global Surveyor, which reached the red planet in 1997 and is still returning high-quality data, is equipped with an instrument to measure the magnetic field in the space environment around Mars. This sensor transformed our understanding of Mars, detecting strong magnetic fields emanating from the crust of the planet. The intensity of the fields are ten times stronger than Earth's crustal fields, and their pattern and placement around Mars have changed our thinking about the geologic history of this planet. A similar instrument flew on Lunar Prospector, detecting very faint crustal magnetic field signatures on the Moon.

In recent years, it has become increasingly clear that solar variability has an effect on the evolution of the Earth's climate. Attempts to explain this influence via the small (4%) variability in solar irradiance over the solar cycle have been unsuccessful, however, the UV output of the sun varies by as much as 20% over the cycle, providing a potential source of climatic influence. In addition, it has been proposed that cosmic rays can seed the production of atmospheric aerosols and their variability could affect climate. Unraveling this mystery requires understanding the coupling of two complex systems: the nature of the sun's long-term variability and the coupling between solar variability and earth's climate.

The results of scientific research in SSSC are also applied outside the solar system. For example the study of the formation of planetary systems from debris disks is strongly influenced by the presence of plasma and magnetic field within these disks. Fundamental processes that are influenced by stellar magnetic fields and winds include the formation of an inner disk 'magnetospheric cavity', accretion flow along field lines and what factors affect planetary migration through the disk and momentum transfer between the disk and star. Stellar winds and magnetic fields also play an important role in the dynamics of older systems, from Vega-type debris disks (e.g. Vega, Fomalhaut, Epsilon Eridani, Beta Pic) through mature disks like our own zodiacal cloud.

Programmatic links within NASA also provide fruitful partnerships that help accomplish SSSC goals. The Explorer Program has flown multiple high-return missions that have added substantially to the study of the Sun-Solar System Connection. The IMAGE mission, a MIDEX explorer satellite launched in early 2000, has dramatically changed the way we think about the inner magnetosphere. It is the first mission dedicated to remotely sensing the plasmasphere, ring current, and auroral oval globally and simultaneously. These data have revealed how the global structure of these different plasma regimes dynamically evolves during geomagnetic disturbances. It has also provided a wealth of understanding on the interplay between these disparate charge particle populations of geospace.

To pursue the ambitious missions required to fulfill SSSC objectives requires partnering with other parts of NASA to develop the necessary technology. A number of planned SSSC missions require high delta-V propulsion, for example, to achieve high inclination solar orbits, to station-keep upstream of the L1 libration point or to leave the solar system completely. One potential technology to enable these missions is solar sail propulsion. Solar sails offer the promise of inexpensive high performance propulsion for low-mass payloads and NASA's In-Space Propulsion Technology Program (ISPT) has pursued their development. The complex problem of storing and deploying the large gossamer films required for solar sails has been solved, with 10m sail quadrants already successfully tested on the ground and full 20m sails systems will be tested in the near future. The ISPT program is also developing the control systems and tools that will allow precise attitude control and trajectory determination. Because of these developments we are in a position to fly a flight demonstration solar sail mission in the near future, thus enabling several future SSSC missions. Such a demonstration mission has been solicited by the New Millennium Program, and may fly as early as 2009.

SSSC partnerships also benefit other parts of NASA; for example, knowledge of the space radiation environment is critical to mitigating the risks of exposure to astronauts. The Space Radiation Analysis Group at Johnson Space Center addresses this need for NASA's manned space flight missions. It provides radiological support during missions, crew exposure projections via space weather predictions and comprehensive exposure modeling, and operation of in-flight radiation instruments to characterize the environment in and around the spacecraft (i.e., the shuttle or the ISS). This group is a conduit for the SSSC science results to be operationally applied to maximize the safety and enhance the productivity of human space explorers.

There are also significant partnerships between SSSC and outside agencies. One such partnership is with NOAA's Space Environment Center (SEC). The SEC continually monitors and forecasts the Earth's space weather conditions, providing alerts and advisory notices to commercial and governmental spacecraft operators around the world. The SEC staff also conducts research and development programs to improve their predictive capabilities. This includes operating space-based instruments for detecting solar and geophysical disturbances, as well as enhancing their modeling and theoretical capabilities. SEC also provides a critical link in transitioning research tools into operational use through the Rapid Prototyping Center. The RPC staff works with SSSC space scientists to convert their data sets and numerical models into streamlined, readily usable tools that enhance the predictive capabilities at SEC.

International Partnerships also play an important role in the pursuit of SSSC research. One of the most spectacular examples is the SOHO mission, a partnership between NASA and ESA. SOHO has revolutionized our understanding of the sun, probing its internal structure and sub-photospheric flows, the energization of plasmas and the explosive release of energy in Coronal Mass Ejections. The Ulysses mission is also a successful partnership between NASA and ESA that has had a transformational impact on our understanding of the solar wind. As the first mission to orbit the sun at high latitude, Ulysses is providing enormous insight into the structure, composition and energetics of the global heliosphere over the whole solar cycle.

Technology

NASA is intimately connected with technology, both in terms of enabling and enhancing technologies that are at the heart of NASA mission concepts, but also because of the impact of space weather effects on the global technological infrastructure. One of NASA's main goals is to understand the effects of solar disturbances on society, i.e. technology.

In furthering the study of the Sun Solar System Connection development in a number of technology areas is required. Future SSSC technology needs are driven by the requirement to sample space plasmas at multiple points simultaneously (with missions such as MMS and Magcon), to achieve high delta V orbits (to escape from the solar system or enter a polar heliocentric orbit for example) to visualize and analyze ever more complex data sets and assimilate them into sophisticated models. Technologies that enable or enhance our efforts to study the Sun Solar System Connection will be pursued as part of our strategic plan.

Future SSSC technology needs are broken down into several focus areas: Enabling high delta-V propulsion, enabling the development of compact low-cost spacecraft, enabling the visualization, analysis and modeling of solar system plasmas and enabling the development of the next generation of SSSC instrumentation and enabling the return of large data sets from throughout the solar system.

Enabling high delta-V propulsion

A number of SSSC missions will study solar system plasmas from unique vantage points (examining the sun from over its pole, or leaving the heliosphere to study the interaction between plasmas in the solar system and the interstellar medium). To enable such missions we need to develop propulsion systems that can supply a larger delta-V than conventional rocket engines. Studies have shown that for the combination of low payload mass and orbit requirements being considered, solar sails are an ideal choice. Ground based demonstrations of solar sail subsystems have taken place over the last few years, and plans are being made to undertake a flight demonstration of a 40m solar sail flight system that would provide all the necessary data to enable solar sails to be used operationally. Following this flight demonstration the first science missions (e.g. Heliostorm and Solar Polar Imager) would require sails in the 100m 150m class.

Enabling the development of compact low-cost spacecraft

Because of the complexity of solar system plasmas, it is often necessary to study them with clusters or constellations of spacecraft making simultaneous multi-point measurements (for example, Inner Heliospheric Sentinels, MMS and Magcon). For multi spacecraft missions enabling and enhancing technologies include the development of low power electronics and low mass, economical spacecraft.

Enabling the visualization, analysis and modeling of solar system plasmas

One of the most exciting technological advances is in the field of advanced supercomputing for model development and innovative new technologies for data analysis and visualization. Examples include NASA's Information Power Grid, a joint effort between government, academia, and industry to provide large scale, distributed computing resources to the scientific and engineering community. Another noteworthy example, the Columbia supercomputer, named in honor of the astronauts lost on the space shuttle, uses 10,240 Intel Itanium 2 processors and provides an order of magnitude increase in NASA's computing capability.

One of the great challenges faced by current and future NASA missions is visualization of multiple vector and scalar quantities measured by many spacecraft in a simultaneous, coherent fashion. The VisBARD project, funded by NASA's Applied Information Systems Research Program was developed to meet this need.

Space science data are displayed three-dimensionally along the orbits which may be presented as either connected lines or as individual points. The data display allows the rapid determination of vector configurations, correlations between many measurements at multiple points, and global relationships. Events such as vector field rotations and dozens of simultaneous variables that are very difficult to see in traditional time-series line plots are easily visualized with this tool.

An example of this is shown in the figure with data from the Helios 2 spacecraft orbiting the Sun. The symbols on the orbit show that the plasma becomes colder (smaller symbol) and denser (blue and green) where the wind slows (colored arrows) and the magnetic field changes direction (blue arrows). The change in the field direction in this "sector boundary" region is quite complex, and is very difficult to visualize using line plots.

Enabling the development of the next generation of SSSC instrumentation

Many of the missions needed to pursue future SSSC goals will require the development of new scientific instrumentation. While most required measurement types can currently be made by flight instruments, these instruments are often more massive and power hungry than can be easily accommodated by future missions. There are also important advances needed in, for example, large focal plane arrays and large scale optics.

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

External Drivers Beyond SSSC Control

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

FREE MARKET AND SPACE LAUNCH COST

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

The commercial space market represents approximately half of the worldwide demand for space launch vehicles. The 2004 FAA/COMSTAC forecast is the most recent summary of commercial demand. That report shows that the launch rate has been and will remain static at 22 per year from 2000 until 2013. The principal change has been the growth in demand for very large satellites. The average mass per satellite has grown from 2,400 kg in 1993-94 to 4,100 kg in 2003-04. The demand for larger satellites drives the move to new, larger launchers.

The recent development of EELVs by the DoD suggests that their needs are similar to those of the commercial market. Some of the other Federal space activities, including NASA, also need large spacecraft and launchers. Taken together, the manufacturers of space launchers have good reason to focus on larger vehicles. The constant, small numbers of launches prevents economies of scale. To recoup the high development costs of new launchers, it is desirable to stop the production of older, smaller vehicles. With only large, expensive vehicles available, the opportunity for small, simple, inexpensive, risky payloads is absent. Only large, expensive spacecraft make economic sense.

Yet, many NASA science missions can be accomplished with much smaller, less costly spacecraft. The SMEX, MIDEX, Discovery, ESSP, and New Millenium mission lines are all highly productive and depend on smaller vehicles. Fiscal responsibility, scientific and technological opportunities are strong arguments for working to maintain a range of launch vehicles, both large and small.

PUBLIC TRUST AND RISK TOLERANCE

NASA provides the visible demonstration of the value of American technological society to solving grand problems. The inspiration provided by a great success such as the Mars Rovers is matched by the disappointment and concern attached to failures such as the Mars Climate Orbiter loss. Success and failure are all visible and are owned by the American public.

Personal freedom is one foundation of American society. We accord individuals the right to pursue activities that have significant risk of injury or death as a price of that freedom. These private risks, taken voluntarily, are accepted.

In contrast, risk in systems supported or controlled by tax funds is not accepted. Public safety and fiscal responsibility require detailed investigation to determine causality and future improvement. Examples include airline or other controlled transportation accidents, military accidents, and NASA accidents.

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

Yet risk is a critical part of the process of learning to succeed. NASA fosters future success by offering broad range of projects and missions to permit new generations to learn through trial and error, and help the best progress to larger projects. The desire to minimize risk must be tempered by a desire to maximize success. Scientists and the public are inspired by spaceflight, in ways that they are not by many other activities, because its challenges bring us to the edge.

NATIONAL SECURITY

Space technology provides unique contributions to national security, in reconnaissance, navigation, and communication (and space weather effects on such systems). American technological advantages over potential adversaries drives restrictions on civilian space interactions with foreign collaborators. Recent increases in these restrictions, founded in the International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR), apply even to interactions with friendly nations. One result is decreased opportunities for the cost-sharing of space missions. NASA has accorded Principal Investigators (PI) freedom to involve foreign collaborators. Foreign contributions, such as the Huygens lander on the Cassini mission, have improved the quality of many science missions. The costs of these positive foreign interactions are increasing, to insure the required compliance with ITAR/EAR restrictions. This problem affects both facility and PI-class missions.

RECOMMENDATIONS

1) NASA should find ways to keep a broad range of launchers available, both large and small.

2) NASA should work with all its communities to develop the most cost-efficient methods for appropriate risk management of complex space projects. NASA should engage the public in the challenges and inherent risks of pioneering spaceflight and exploration.

3) NASA should aid its projects to achieve cost-effective compliance with ITAR rules. NASA should continue dialog and negotiation with the relevant agencies to develop and clarify more appropriate rules, to facilitate valuable foreign collaboration with America’s space goals.

EDUCATION AND PUBLIC OUTREACH (E/PO)

Sun-Earth System E/PO programs share the excitement of science discoveries with the public, enhance the quality of science, mathematics, and technology education, and help create our 21st century scientific and technical workforce. These efforts align with NASA's Science Mission Directorate's education goals and priorities to inspire and motivate students to pursue careers in science, technology, engineering and mathematics (STEM), and to engage the public in shaping and sharing the experience of exploration and discovery. In addition, E/PO programs has focused on the development of tools for evaluating the quality and impact of Sun-Earth system science education and outreach programs, in order to identify and disseminate best practices in E/PO.

Strengths

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

The Sun-Earth Connection Education Forum (SECEF; a partnership between NASA Goddard Space Flight Center and the University of Berkeley) combined with the regional Broker/Facilitator institutions work to establish strong and lasting partnerships between the Sun-Earth system science and formal and informal education communities. These centralized efforts seek to

- facilitate the involvement of Sun-Earth system scientists in E/PO activities; to develop a national network to identify high-leverage education and outreach opportunities and to support long-term partnerships, to
- provide ready access to the products of Sun-Earth system science education and outreach programs, and to
- promote the participation of underserved and under-utilitzed groups in the Sun-Earth system science program by providing new opportunities for minorities and minority universities to compete for and participate in Sun-Earth system science missions, research, and education programs.

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

[The following texts are for sidebars that highlight two programs – one is the result of centralized efforts and the other directly associated with an observatory]

Sun-Earth Day

Sun-Earth Day is an annual national event that was created and coordinated by SECEF. Since 2001 opportunities have been provided to share the science of the Sun with educators, students, and the general public via informal learning centers, the Web, TV, etc. Webcast technology is used to bring NASA science into the classroom and to the museums in real time. Support materials are made available to registered users and through NASA centers. While the emphasis is on the Sun-Earth connection, a specific theme is created each year to continue to engage the public:

2001 - Having a Solar Blast
2002 - Celebrating the Spring Equinox
2003 - Live from the Aurora
2004 - Venus Transit, and
2005 - Ancient Observatories: Timeless Knowledge.

Sun-Earth day activities include telescopes on the Web, Webcasts, Web chats, teacher training workshops, museums activities, and the sharing of data collected by various audiences. Scientists participate through classroom and museum presentations, and answering questions during the Webcasts and Web chats. The 2004 annual event directly engaged 60,000 participants and indirectly several millions. For example, the Sun-Earth Day website received 40 million hits in 40 hours. There were 1000 news reports on various TV channels, including 40 interviews with NASA scientists. More than 12,000 packets of educational materials were distributed to teachers, museums, and amateur astronomers.

(Images can be selected from: http://sunearth.gsfc.nasa.gov/sunearthday/2004/vt_gallery.htm)

As part of the 2005 Sun-Earth Day programming, in fall 2004, the Ancient Observatories Timeless Knowledge website (sunearthday.nasa.gov) and the Traditions of the Sun website (www.traditionsofthesun.org) were launched to allow users to explore Chaco Canyon and other areas. These websites also highlight NASA research on the Sun and Native American solar practices within a larger historical and cultural context. The culminating event for Sun-Earth Day 2005 is a bilingual webcast live from Chichen Itza, which will reach many Hispanics and Native Americans.

The Solar and Heliospheric Observatory (SOHO)

SOHO has produced many products for the informal audience and media outreach: for example LASCO and EIT images on the web and in many popular magazines including the National Geographic; and the lanticulars (3-D cards).

For the formal education audience, the English and Spanish presentations on the Dynamic Sun CD, and building your own spectroscope poster have been very effective. SOHO's collaboration FiMS (Fellowships in Mathematics and Science), a partnership grant with the Pa. Department of Ed. (in 3 school systems) is a strong example of the power in working directly with the local formal education system. SOHO educators and scientists work with their local teachers to increase content knowledge and support their ability to develop and implement inquiry-based lessons that are tied to state standards and the current curriculum. The Endeavour program, a collaboration between SOHO/NASA and 18 school systems, gives teams of students real-life NASA problems to research with the support of their teacher team leaders that have been exposed to the content and training through professional development. [Image of spectroscope poster; images of SOHO educators working with their kids from the Pa. Dept of Ed., images of Endeavor teachers and student teams]

SOHO is bringing the science and exploration of our Sun to the visually impaired through their groundbreaking "Touch the Sun" book. [Image of Book]

Opportunities

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

The articulation of the scientific objective for the Sun-Earth system scientific community presents tremendous opportunity to expand and invigorate E/PO efforts looking ahead. The relevance of Sun-Earth system science to our daily lives has never been in doubt, and current E/PO efforts successfully emphasize the importance of the Sun in the Earth System (Sun-Earth Day programming and SOHO), and the impact of Space Weather on our technological systems. In addition, E/PO efforts can and do take advantage of the connection between research and understanding of the processes that govern our Sun and those that govern stars in general ('Living with a Star'). In addition the highly visual and data-driven nature of Sun-Earth System science makes it very powerful for image-rich, dynamic E/PO products and programs.

The new articulation of the Sun-Earth System science objective also emphasizes human exploration of space, and this will galvanize public interest in NASA's activities in general. In particular, the public will be very interested in the essential role of Sun-Earth system science in ensuring the safe transit of our astronauts as they explore the solar system. Developing the capacity to predict radiation conditions and other hazards in the space environment anywhere in the Solar System that humans may be traveling will be high priority for this community. E/PO efforts will benefit greatly from a focus on exposing this exciting science to a full range of audiences both to enhance STEM efforts and keep the public informed of NASA's progress towards its goals.

Unification of the scientific enterprise into the Science Mission Directorate presents opportunity for science education efforts in both the formal and informal arenas, as well as for purposes of public outreach from across NASA, including the Sun-Earth System community. Moving forward, while each Division, mission, and individual scientist and engineer within NASA will have unique content and experiences to contribute to E/PO; overall, the result has the potential to be more effective in terms of message– it won't matter if it's Space Science, Earth Science, Fundamental Physical and Biological Research, etc. – the 'brand' can be exciting, relevant NASA science. In addition, the opportunity exists to marry the integration of the sciences with an integrated E/PO effort across the scientific missions and activities. The best strategies of each of the different former enterprises can be integrated to create the strongest possible suite of product/program.

Challenges

Mission and individual PI based education efforts. As indicated above, commitment of substantial funding levels for E/PO that derive from the ongoing scientific and mission-based activities is a very strong attribute of NASA's programs. Also, while the challenges indicated below to reflect the general sense of the community, there are many examples of successful supplement and mission-based E/PO programs. However, design, development and implementation of E/PO on the mission and/or individual PI basis results in several challenges.

Scientists and engineers are overburdened. On the small scale (i.e. E/PO supplements attached to funded research), the resources are not sufficient to cover PIs time needed to design, develop and deliver quality E/PO. While the Broker/Facilitators are charged with facilitating this process, the support provided is uneven, and not accessed by many individual PIs. On the larger scale of missions, where substantial resources are committed, relying on PIs to conceive of effective ways to invest these resources for maximum impact results in uneven outcomes, and is frustrating for PIs and the E/PO community.

Variable E/PO products and programs don't consistently best serve target audiences. NASA's partners in E/PO – whether in schools (teachers) or in informal settings (Museums and Science Centers, youth-serving community based organizations, libraries, etc.), or various media outlets, need of tested programs and products. Professional development and training is essential to maximize use of products and programs; and consistent formats, strategies, and approaches, to these programs will best enable effective, sustained professional development efforts. In essence, while educators and others involved in public outreach will always benefit from personal contact with NASA scientists and engineers, they need the 'One NASA' approach to effectively take advantage of NASA's wealth of resources in the E/PO arena.

"If you build it, they will come" mentality. Resources invested in E/PO should correlate strongly with impact; and thus broad dissemination is typically expected, particularly if the E/PO program involves the creation of a product of some type; or the reach of a message geared towards the general public. However, effective dissemination is a big burden to place on individual researchers and even larger scale missions. Well established channels that can be relied upon for new, relevant, resources and information, are key to success in working with partners to achieve E/PO goals. Education Resource Centers have long been the strategy for getting NASA products to educators, however these operate with mixed success; in New York City, for example, the ERC is located on a college campus where it is not typically open after 3:00 in the afternoon meaning that teachers have little opportunity to access it, and it is not open for museum educators.

Web dissemination has tremendous potential; and NASA's site is in one of the top 3 most visited sites for educators, however centralized planning and maintenance is key to sustaining investments. The former OSS Educators Resource Directory is a powerful tool for educators, although ongoing maintenance of the Web sites accessed through that portal is always a challenge. The former ESE Education Product Review is another strategy that addresses the challenge of promoting strong educational resources to educators.

"NASA speaks with one voice". As indicated above, the "One NASA" approach is key for achieving strong E/PO. NASA has embraced this goal already for public affairs, and thus, by extension, for public outreach. To achieve this, NASA is increasingly articulating "Look and Feel" as well as editorial messaging for public affairs. This raises the challenge of coordination with Public Affairs which is separate from E/PO. In addition, it has been a challenge to discern between outreach and advertisement. There have been many EPO products that really only served to advertise a mission, rather than keeping the public informed about what NASA is doing, which is the goal for outreach.

Recommendations

Strong opportunities exist to further extend the power of Sun-Earth System science and related mission activity to engage and inspire students in the formal setting of schools and institutions of higher education, the audiences at informal learning centers (Museums, Science Centers, etc.) and other informal venues; and general public audiences across the nation via the press and other communication outlets.

Informal Education

In the informal arena, onsite exhibitions geared towards the general public, programs that target various segments of the public including families, children, adults, etc.; as well as school groups and educators, and high-production media programs take advantage of Sun-Earth System science content to promote public understanding of science, science learning and teaching and building the nation's scientific and technological capacity.

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

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

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

Formal Setting

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

Provide a consistent and coherent set of formal education resources and professional development for K-12 science education that derives from across the NASA enterprise. For educators to take advantage of Sun-Earth System science to engage their students from K-12 in the mastery of these essential concepts, however, NASA needs to centralize its outreach to the formal system. Sun-Earth System science is one aspect of the ongoing NASA enterprise. The entire enterprise could, for example, be mapped to the Benchmarks for Scientific Literacy. The result will be a roadmap for integrating NASA science and engineering activities into science curricula across the nation. Standards-based educational resources (e.g., an informational website, an animated simulation, a set of data visualizations, a teaching guide, a set of standards-based curriculum activities, a professional development seminar, online course or videoconference, an interactive module, a poster, a set of opportunities to interact online and by video with scientists, engineers and technicians, an opportunity for student research, regular updates, etc.) and professional development offerings created in the context of this roadmap, that tap ongoing NASA missions, will provide a constant stream of fresh, current, authentic scientific discovery and engineering practices that will ensure that educators will always have NASA in their tool-kit for effective science education.

This is equally relevant for the informal arena. Sun-Earth System and other NASA missions and activities are a wonderful springboard for learning. But educators and exhibit planners in the informal settings find each NASA opportunity requires a significant effort, simply to ramp up, since there is little consistency in what NASA produces, from center to center, from mission to mission. It would be tremendously helpful to know that for each NASA activity, there will be a standard set of resources (e.g., an informational website, an annotated simulation, a set of opportunities to interact online and by video conferencing with scientists, engineers and technicians, activities for out-of-school settings, regular updates, etc.) with common interfaces and similar formats that are fairly constant from activity to activity. It is understood that flexibility is essential - unique opportunities and requirements of each activity should be exploited, technologies will evolve, and evaluation inform revision – however, to be able to count on a standard package would likely reduce the learning curve for users and increase the usability and use of the resources. SECEF is a good example of the value of a coordinated national effort to develop and support E/PO activities; emphasis on standardized packages will strengthen this approach.

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

Public Outreach/Affairs

New communication initiative already in development. A new initiative coming out of NASA Headquarters has set up a process in which NASA communications, which includes most of the traditional EPO products, will be reviewed and accepted by a new Communication Review Team (CRT). More details can be found at http://communications.nasa.gov, but the bottom line is that this is a reaction to the diverse messages that NASA has traditionally set out. One consequence is that new materials will have to conform to a NASA "Look and Feel", although that "Look and Feel" has not been worked out yet. The CRT will also be regulating content, insisting that one of NASA's main messages (as determined by them) be a part of all communication. Scientific papers are exempt as are scientific presentations, but there is talk of requiring NASA funded scientific presentations to use a standard powerpoint format. The initial phase will only pertain to communications coming from the NASA centers, but it is expected that all NASA funded communications will eventually require approval under this initiative.

• Develop better coordination with Public Affairs

The overlap between Public Outreach and Public Affairs (PA) should be much higher than most missions currently plan for. Public Outreach from SSSC can cover a very large range of topics and is targeted directly to the public, and Public Affairs is typically new and current results targeted to the media for dissemination to the public. However there is great similarity in the style of writing and the visuals needed to make our science interesting and exciting. We are not recommending that EPO funding be used for Public Affairs, but rather that new missions have a separate PA budget and plan, and that Public Affairs team up with the EPO group early on in order to work from the same core messages and visual assets.. This will facilitate getting better media coverage of scientific results and publicizing exciting EPO events.

• Focus on outreach, not advertisement

We discourage the use of EPO funds for lanyards, pins, etc., that are solely designed to advertise a mission or product instead of instructing or informing. While it is true that these can be very popular with the public, it is not acceptable for EPO to fund them. They may not be able to pass scrutiny by the Communications Review Team, anyway.

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

Overarching E/PO recommendations

Enhance existing and create new distribution channels for E/PO efforts: products, programs, and messaging. Do not make individual Sun-Earth system PIs responsible for building and sustaining these relationships. This is not to say that individual PIs should not be encouraged to into classrooms, make public presentations, appear in the media, etc.– but it needs to be understood that these are choices in a spectrum of dissemination options sanctioned and supported by NASA.

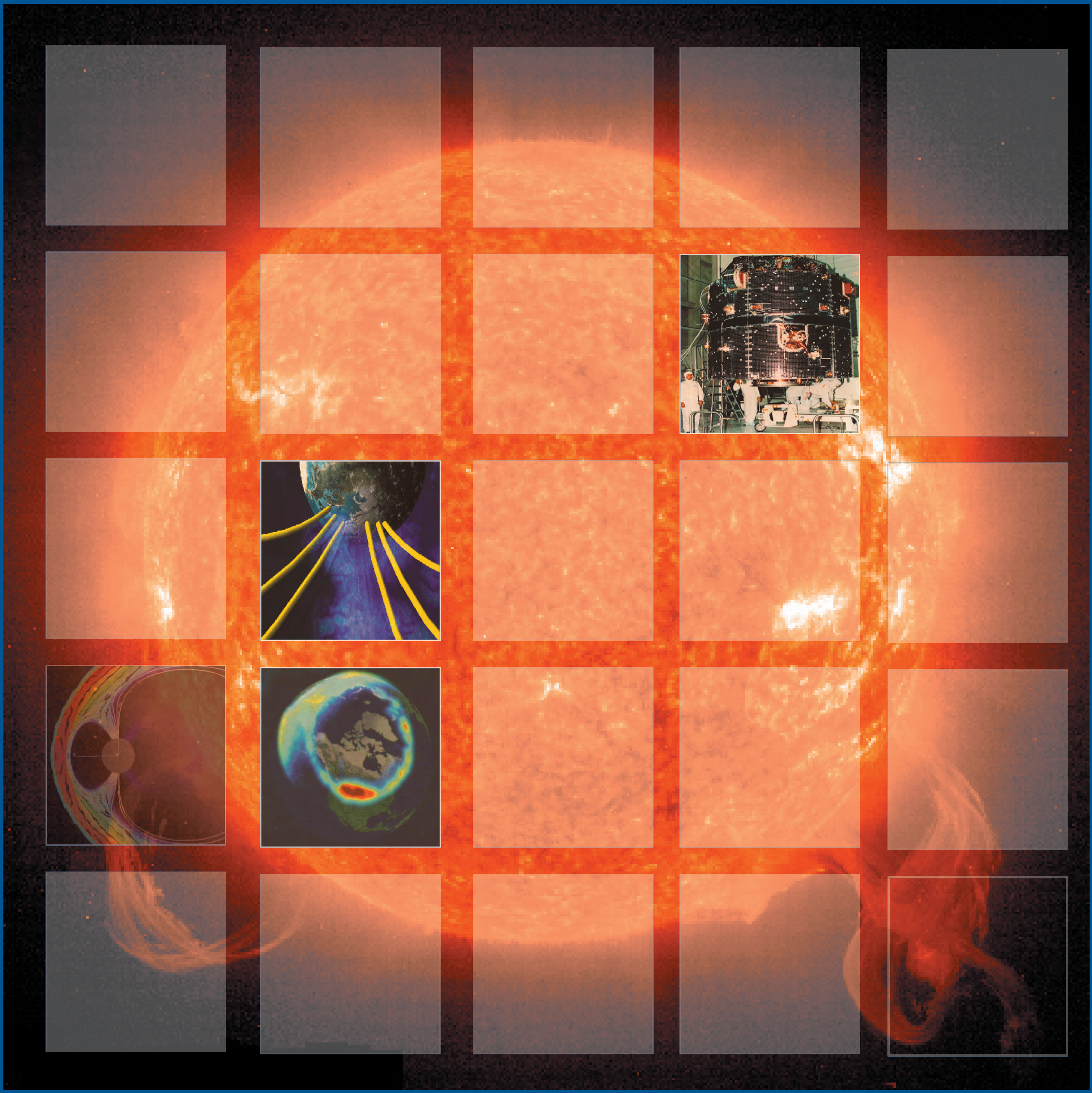
Shift funding model for E/PO (but not level of funding). It can't be stressed too highly the impact NASA has had through commitment of substantial funds for E/PO efforts over the past decade or so. In addition, the value of having the scientific community intimately involved in the development and implementation of E/PO products and programs can't be over emphasized.

At the smaller scale NASA should continue to use the model of supplements for which individual PIs can apply to encourage their participation in strong E/PO efforts. Rather than rely on the PIs to invent their own E/PO activities, link allocation of these funds to a portfolio of approved E/PO strategies that guide choice of program and product templates from which the PI can select; and require dissemination activities through one or more of NASA's approved and maintained channels as appropriate.

At the mission scale – again, require that each mission select from range of approved product and program suites coupled with appropriate dissemination strategies prior to approval/release of funds. While individual PIs with particular interest and commitment to developing new types of E/PO should be encouraged and supported, as a general case, do not burden PIs with inventing E/PO program as they are putting their mission proposals together. In essence, science proposals funded by the Science Mission Directorate should be selected on the basis of their scientific merit. Funding for E/PO derived from these scientific missions and programs should then be set at agency approved levels. The E/PO funds should then be allocated to selections from the portfolio of approved programs and strategies as described above.

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

Science in Common with Earth Science



Section 3: Critical Elements of the SSSC Program

Community Health

Summary:
STRENGTHS
World leaders...
Strong EPO
Diverse spectrum of sizes and specialities
Infrastructure
∑ Computing, e.g. Columbia, AISRP, CCMC
NASA Summer Faculty Fellowship program

NASA's goals depend on a strong scientific and technical community to envision, develop and deploy space missions, and to apply results from these missions for the benefit of society. This community currently exhibits a diverse spectrum of sizes and specialties, based at universities, government and industrial labs, and is a world leader in space physics research.

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

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

Nonetheless, our research community faces significant challenges in the immediate future, challenges which directly affect our ability to meet NASA's goals and support national objectives. The most significant challenges are those of training new researchers while maintaining the corporate memory of an experienced work force. By way of illustration, NASA and its supporting contractors will soon have large portions of its work force eligible for retirement. By some estimates the services of as much as two-thirds of the most experienced scientists, technicians, and managers could be lost in the near future. As another example, consider that the United States, with a population of 300 million, produces about 60,000 engineers annually (2 per 10,000), while China and India, with a combined population of nearly 2 billion, produces 3,000,000 engineers annually, which is almost an order of magnitude more per capita than in the US. [THESE FIGURES NEED TO BE VERIFIED.]

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

[Potential Vignette: UMich hiring marketer from operating budget to reach new students]

Training opportunities at the graduate and undergraduate level provide an introduction to all aspects of space missions, including instrument development, mission operations, data analysis, and theory and modeling. These are often the first opportunities for students to experience the excitement of working in space physics and provide the primary means of recruiting these students into the space physics community. NASA programs that provide low-cost access to space such as rocket, balloon, and airplane missions, are especially useful for training in that students can contribute to mission design and operations while obtaining data in a timely fashion for analysis. This is particularly important in light of the long development times for complex missions that can exceed the normal tenure of graduate education. In such cases, students working on these projects may not see the fruits of their work before their graduation.

The maintenance of existing research teams and investigators is also of paramount importance to a healthy and robust scientific community. There is a real danger that the loss of 'critical mass' of research teams will begin to impinge on NASA's science and exploration goals.

NASA's SR&T, TR&T, and Guest Investigator programs are the traditional underpinning of most research teams and individual investigators and have been repeatedly recognized as such in community strategy documents such as the Decadal Survey. In this role, they have provided a significant contribution to the vast body of knowledge needed for direction and implementation of NASA's initiatives and are envisioned as continuing in this role in the future.

Continuity of funding opportunities is especially important to maintaining technical excellence, more than ever for hardware development teams which have a high startup investment and have difficulty in keeping technical expertise in uncertain funding cycles. NASA support for low-level hardware development is generally deemed insufficient to support truly innovative instrument development. Only the largest teams are perceived as capable of competition for hardware development Paradoxically, the opposite can be said about modeling support, in that large-scale modeling are not sufficiently funded for the tasks they face. In all cases, there must be a balance between large and small research efforts, as well as between pure and applied science.

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

The recommendations in this Roadmap chart a course of steady, uninterrupted progress towards NASA's goals that provide ample opportunity to inspire, recruit, and train the next generation of space scientists and engineers while insuring the robust health of a community in support of NASA initiatives.

The Supporting Research Infrastructure

It takes a substantial investment in basic research and technology development to provide the infrastructure to NASA's scientific community needed to achieve NASA's goals. The term infrastructure is often used in the context of hard assets, such as launch facilities and communication networks such as the Deep Space Network (DSN). However, in addition to investing in hard assets and flight missions, NASA also invests heavily in the scientific community through its programs of research grants (SEC SR&T, LWS TR&T, SEC Theory, AISR, etc.) and its support of computing and data analysis infrastructure.

These investments in the science community are critical to the execution of a program to understand the Sun-Earth System and the solar system. In particular, a robust research infrastructure provides the underpinning for large, strategic NASA missions. However, long before large missions are selected, there is an extensive development program starting from first generation 'brass board' instrument concepts, followed by near-Earth testing under the Low Cost Access to Space (LCAS) opportunities. More mature concepts are tested in Explorer-class missions. Two excellent examples of this process are the IMAGE and STEREO mission concepts, both of which are based on SR&T funded research.

NASA also benefits from research funded by other agencies, such as NSF's CEDAR, GEM, and SHINE programs. In light of the importance of non-NASA research to NASA's research infrastructure, it is important that intra-agency cooperative programs be supported. (See, for example, the recommendations of the NRC Decadal Survey.)

New mission are formulated to answer questions arising from basic research and from the analysis of data from previous missions. To carry out this basic research and data analysis, the scientists need the data analysis tools and the computing facilities that are also a part of this infrastructure. Moreover, this R&D infrastructure supports the training of the students and post docs who will become the next generation of scientists.

Research and development activities cover a broad spectrum of activities in basic and applied research. As an example of most basic research, solar physicists supported by NASA grants study fundamental physical processes such the generation of solar magnetic fields. For example, Fig. 1 (beautiful color picture from Cattaneo's dynamo simulations) shows results from a three-dimension simulation of solar magnetic fields created in the solar convection zone by the solar dynamo (Cattaneo et al, ApJ 588:1183-1198, 2003 May 10).

Scientist use data from existing missions to constrain their theory and models; the results then tell us what measurements on the next mission to test the theory. Large scale numerical calculations such as these which give the temporal evolution of fundamental equations in three dimensions require massive supercomputers such as the new Columbia parallel computers at NASA Ames. Without the support of the computing infrastructure, such computations would not be possible. A strong computing structure is needed to support data analysis as well.

One challenge of current and future NASA missions is the large quantity and complexity of the associated data sets. This challenge is driving new research efforts, funded by programs such as NASA's Applied Information Systems Research (AISR) Program, to develop software tools to enable the analysis of the ever larger data set resulting from the existing NASA SEC missions. Moreover, new missions such as STEREO and SDO will provide even greater challenges: STEREO, because of its need to utilize data from both STEREO spacecraft as well as from SDO, ACE and ground based instruments; and SDO because of its TBS daily telemetry requirements.

One of the great challenges faced by current and future NASA missions is visualization of multiple vector and scalar quantities measured by many spacecraft in a simultaneous, coherent fashion. The Visual System for Browsing, Analysis, and Retrieval of Data (ViSBARD) Project, funded by NASA's AISR Program was developed to meet this need.

Space science data are displayed three-dimensionally along the orbits which may be presented as either connected lines or as individual points. The data display allows the rapid determination of vector configurations, correlations between many measurements at multiple points, and global relationships. Events such as vector field rotations and dozens of simultaneous variables that are very difficult to see in traditional time-series line plots are easily visualized with this tool.

An example of this is shown in the figure with data from the Helios 2 spacecraft orbiting the Sun. The symbols on the orbit show that the plasma becomes colder (smaller symbol) and denser (blue and green) where the wind slows (colored arrows) and the magnetic field changes direction (blue arrows). The change in the field direction in this "sector boundary" region is quite complex, and is very difficult to visualize using line plots.

The next concept in data analysis and visualization is the concept of Virtual Observatories, in which all relevant data is collected into a unified data set with appropriate tools for access and display. The original concept, pioneered by the astronomy community, is being applied to solar and space physics data. An initial example is the Virtual Space Physics Observatory (http://vspo.gsfc.nasa.gov/websearch/html/VSPO.html).

LCAS & Instrument Development

The Low Cost Access to Space (LCAS) program, with key elements of the sounding rocket and balloon (suborbital) programs, is a critical component of the NASA space physics research program, providing cutting-edge new science discoveries utilizing state-of-the art instruments in a rapid turn-around responsive environment. Many rocket and balloon investigations do stand-alone science, while others are flown in conjunction with satellite missions and/or ground observations. Although these missions are selected solely on the basis of the importance and probable significance of their science goals, they play two other important roles that are not available in any other flight programs-training of experimental space physicists and engineers and the development of new instruments and instrumental approaches which are verified by actual spaceflight.

A recent example of this three-pronged role of the suborbital program is the new understanding of auroral physics and the structure of parallel electric fields obtained in a series of rocket flights that both developed the state-of-the-art instrumentation and the pathfinding science discoveries leading up to one of the first NASA small explorers, FAST.

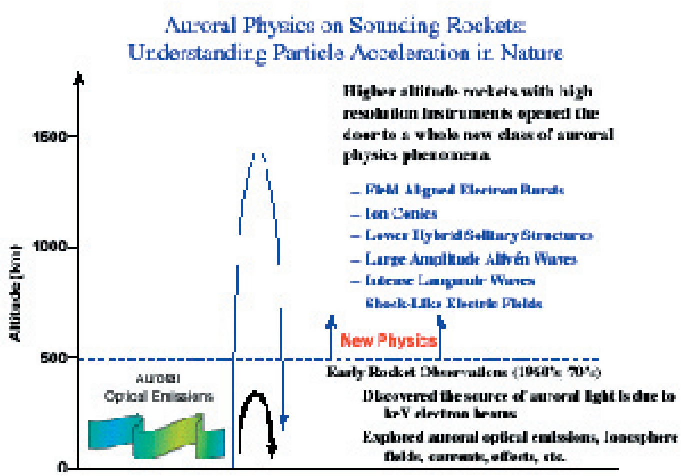
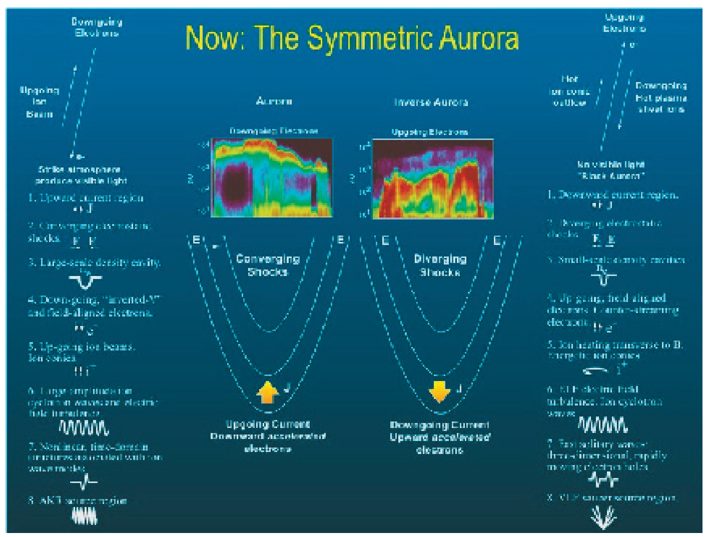


Figure 1. Sounding rocket impact on auroral science showing how ever improving rocket capability has increased science return.

Figure 1 shows how new rockets with higher altitude capability than previously available demonstrated the importance of microphysics, the need to make extremely high time resolution measurements and time domain electric fields to elucidate the acceleration processes. The 'top hat' plasma detectors, developed by C. W, Carlson for this series of rockets, are now utilized on almost all space plasma missions to provide 3D, high time resolution electron and ion measurements. The program provided Dr. Carlson (who became the FAST PI after a long association with the sounding rocket program) with the opportunity to develop project management skills and also provided the hand-on training of graduate students who became the instrument leads on the FAST satellite. As Figure 2 shows, FAST has made many new discoveries, important both for understanding aurora on earth but also for aurora on other planets, and particle energization in collisionless plasmas.



Although the LCAS program is often emphasisizes the suborbital sounding rocket component, the balloon flight program contributes strongly to NASA's strategic objectives. Recent and currently proposed solar physics flights are relevant to NASA's strategic objectives and research focus areas. These balloon missions, utilizing solar physics research instruments, have an outstanding record of scientific discoveries. For example, the LASCO coronagraph on board the SOHO spacecraft enabled systematic studies and arrival time predictions of coronal mass ejections aimed at Earth (1.3 Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere). The solar telescopes on the RHESSI Explorer mission used hard X-ray imaging spectroscopy, high-resolution nuclear gamma-ray line spectroscopy, and gamma-ray line flare imaging to reveal the energy release process in solar flares in greater detail than ever before. RHESSI has shown that flare-accelerated ions and electrons are physically separated on the sun (5.7 Discover how charged particles are accelerated). The RHESSI results have implications not only for solar flare theory but also in other astronomical contexts where charged particle acceleration occurs. These achievements can trace their heritage to balloon-borne instruments flown in the continental U.S. and in Antarctica.

Besides the coronagraphs and high-energy flare spectrographs, the balloon program supported development of the active-cavity radiometers that detected decadal solar irradiance variations (1.3 Understand the role of solar variability in driving global climate change), and it supported flights of high-resolution optical telescopes that revealed the convective nature of solar granulation and the serpentine structure of magnetic fields emerging from beneath the photosphere (5.6 Understand the origins and dynamics of solar magnetic variability). Today, the ballooning program is supporting the development of new instruments for high-resolution solar imaging. For example, the Flare Genesis Experiment, an 80-cm diameter solar telescope recently made the first near-space observations of vector magnetic fields in sunspot groups.

The balloon program is enabling pioneering high-resolution imaging with big telescopes and the concomitant development of lighter, cheaper optics for eventual use in space. The Sunrise consortium of European and American investigators is assembling a 100-cm telescope to measure the vector fields in intergranular spaces. The resolution will be high enough to study the origins and properties of the intermittent magnetic structures (5.7 Discover how magnetic fields are created and evolve). In another new program, the balloon-borne Solar Bolometric Imager recently mapped the sources of irradiance variations on the solar disk. Another flight is planned at the next sunspot minimum to establish the baseline for irradiance variations in the absence of magnetic fields. It is the first step in a program to discover the physical mechanisms of the Sun's long-term brightness variations (5.6 Understand the structure and dynamics of the Sun). The SBI will also test new technology for eventual flight in a decade-long space mission to map all possible sources of solar brightness variation.

Solar physics continues to benefit enormously from the ballooning program through new and unique observations and through the development of future space instrumentation. Projects under consideration include a new approach to high-energy X-ray imaging and a telescope to operate in the near infrared for high-resolution studies of the magnetic transition zone between the photosphere and chromosphere. . New balloon-borne flare instrumentation could provide 50 times RHESSI's sensitivity to gamma-ray lines and at least twice RHESSI's angular resolution for ions. This could be accomplished in a budget of only a few million dollars. With a ULDB platform and the addition of new neutron detection technology, the science return for a high-energy flare mission will be comparable to that of a small Explorer at a tiny fraction of the cost.

Another program that may be undertaken in the near future calls for further development of coronagraphs, especially those with features that can be implemented in the Terrestrial Planet Finder mission (5.9: Find out how common Earth-like planets are).

LCAS – Responsive to evolving science needs

Several recent developments in the LCAS sounding rocket program have evolved specifically in response to needs articulated by the science community. One of these is the capability (now demonstrated by a successful launch in 200?) to fly flat trajectories by igniting the final stage after reorienting the payload and motor in a nearly horizontal attitude. The first successful flat trajectory launch was performed in a study of neutral atom responses within the auroral region (Conde). Representative examples of other science focus areas that benefit from this new capability include studies of joule heating, E-region layering phenomena, and large scale waves and instabilities in the electrojet. To date this flat trajectory capability has only been utilized in flights from Alaska because of safety considerations, but it may be possible to utilize this approach from other launch sites.

A second example of LCAS responsiveness and flexibility is the development of an exciting new rocket technology called the High Altitude Sounding Rocket (HASR). (Note: This development effort was recently halted to conserve financial resources). This vehicle could carry 1000 lbs to 3000 km and afford more than 40 minutes of observing time above 100 km. It would support payload of the order of 1 m in diameter . The increased diameter and increased observing time (compared to 6-12 minutes presently) would provide a substantial leap in observing opportunities for space science payloads. The longer observing time is important for solar and space physics payloads that track events on the sun or examine longer period phenomena in space. Lighter payloads could attain even higher altitudes (4000 km or more) opening up possibilities for in-situ space physics investigations of the inner radiation belt at mid-latitudes and auroral acceleration regions. Wallops Flight Facility has carried out a preliminary study to show that this can be done with existing hardware. The estimated price tag is about ~5M per launch, at least for launches out of Wallops.

LCAS – The Importance of Developing Human Assets

As the Exploration Vision goes forward, an essential ingredient is a continuing source of well-trained engineers and scientists who understand the demands of building and delivering spaceflight systems and hardware for implementing this vision. The suborbital program provides an important training ground for experimental space physicists and engineers with hands-on experience. It provides the opportunity for a graduate student to participate in the complete life cycle of a scientific space mission, from design, construction, testing to flight, and data analysis. No other flight programs have time scales commensurate with that of a Ph. D. thesis. The success of this program in doing this is statistic that more than 350 Ph.D.s have resulted from the rocket program. In addition, the lower cost allows for higher risk, so that graduate students and postdocs can be allowed to take substantive roles in the program. A rocket project offers the chance for young scientists to gain the project management skills necessary for larger missions (explorers,etc).**discuss numbers of sc and instrument Pis have come from rocket background.

The roadmap committee strongly endorses the importance of the suborbital program and, in addition, the continued development of these new capabilities.

Random Notes:

Rob Pfaff's new physics above collisional ionosphere picture

Other science: weather wind shears etc or ionospheric (impacts on communication, etc)

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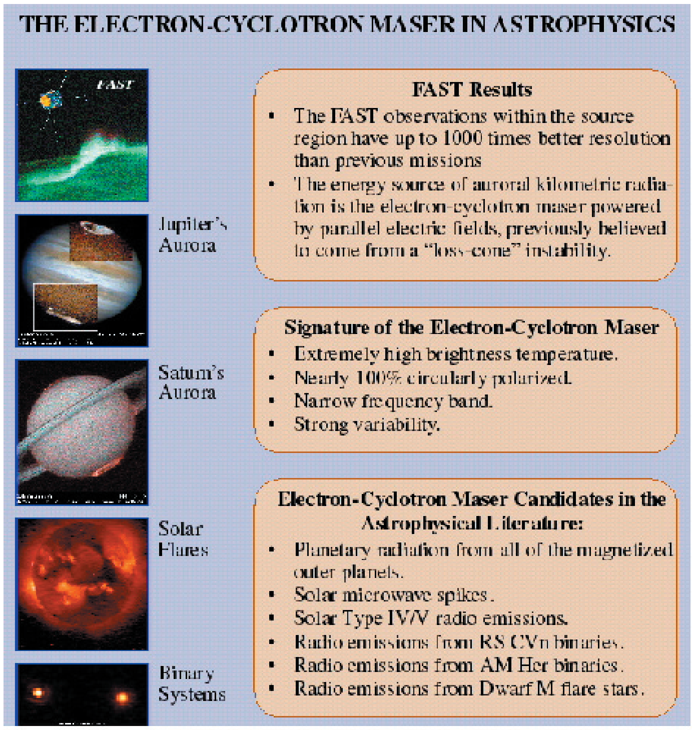
EELV Adaptor for piggy-back payloads on a regular basis.



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**include another vignette on solar science, instrument development leading to SC and include balloon examples. (BARRY).

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Should this emphasize science more?

Modeling & Theory

The interplay among observation, modeling and theory is necessary for the vitality of space science. In some cases, a model may have specific predictions that spur the development of new techniques that are required to obtain the necessary data. In other cases, unexplained observations may lead to changes in an existing model or the creation of entirely new models.

Two examples that illustrate these connections are discussed below. In the first example more accurate data has been used to fine-tune dynamo models and in the second example models for SEP acceleration drive the quest for improved observational tests at the production sites.

Helioseismic data has provided much more accurate information on the solar radial rotation profiles, latitudinal shears, and meridional flows, which are crucial to developing realistic solar dynamo models. This information is important for understanding the evolution of the solar magnetic field which has a profound influence on the dynamic structure of the Sun's outer atmosphere including the production of flares, CMEs and the solar wind. Prior to the use of helioseismic techniques, it was believed that the magnetic dynamo action occurred in the solar convection zone. Now using the high precision data from SOHO observations and ground-based observatories, it is believed that the dynamo action may be at the base of the convection zone and also possibly at an unexpected sheared layer just below the photosphere. Concurrent with the improvements in the quality of helioseismic data, flux-transport dynamo models have become increasingly more sophisticated so that the length of quasi 11-year period of the solar cycle can be now be modeled. The new models are still not able to reproduce the strength of the magnetic field over the solar cycle but these efforts continue.

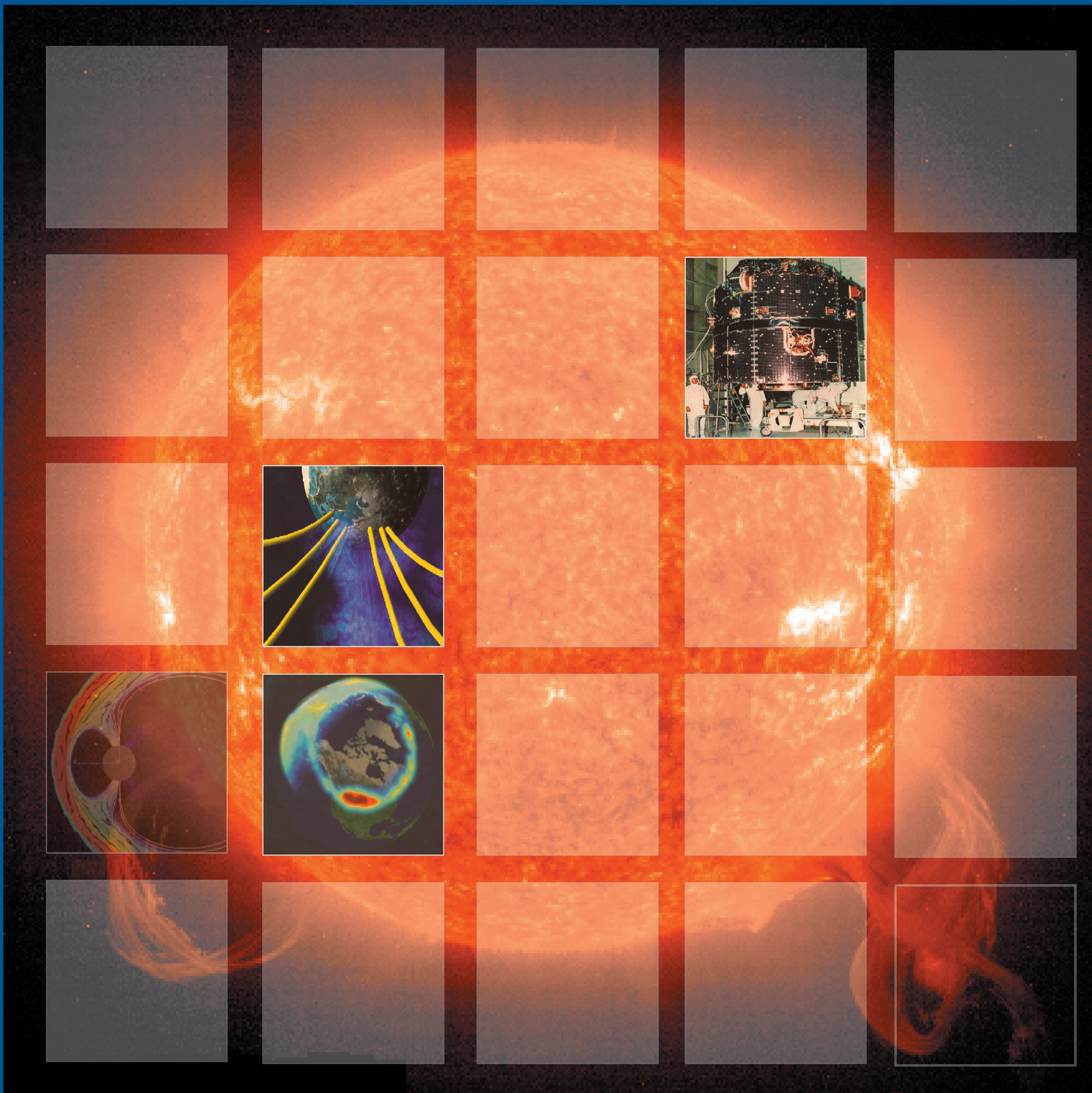
Another example shows how models can be used to address the problem of predicting solar energetic particles (SEPs), a known hazard to astronauts and their equipment in space. At the present, we do not have a satisfactory model for predicting the energy, yield, duration, or composition of SEPs from coronal mass ejections (CMEs), flares, and current sheets. Separate models that describe the production, and transport of energetic particles exist but many of these models cannot be adequately tested because of the lack of the necessary measurements of the conditions at the Sun and in the inner heliosphere. Remote sensing measurements of plasma and magnetic field parameters at the SEP production sites can provide the necessary model inputs while in situ measurements can be used to characterize the output particle properties. Models that can predict the particle properties starting from a known set of initial conditions will be the most useful. End-to-end predictive models based on physical processes are preferred to models based on statistical inferences alone. The next step in advancing these models is to identify the most useful input parameters.

Systems-View Modeling Story

Viewing the Sun – Heliosphere – Planet systems as an integrated whole is not just a challenge, but rather a critical next step toward understanding. Scientists have spent much of the past few decades investigating isolated regions in the heliospheric system. The surprises and rewards will lie in fitting these isolated regions back together to capture the "system" behavior. Critical to this effort are the use of high performance models of the regions and a software framework to couple them together.

The systems that link the Sun with the planets in the solar system are extremely complex natural systems that involve many different interacting elements. A major goal of the near future is to unify our understanding into a more comprehensive framework that can specify and predict the properties of these systems (solar system weather). Significant progress in the unification and expression of this understanding has been accomplished with the development of the Space Weather Modeling Framework (SWMF) and the physics codes that are fully coupled within this it. The SWMF is a NASA-funded endeavor, and is available to the community through the Community Coordinated Modeling Center (CCMC). Other framework efforts are also underway, e.g. the Earth System Modeling Framework (ESMF) and the Center for Integrated Space Weather Modeling (CISM).

A major focus for the Vision for Space Exploration must be the extension of the software framework to the entire solar system and the objects within it. Further development of the models of the physical domains of the various planets, moons, comets, asteroids, etc. will be required. Much of this development will be extrapolations of what we have learned and modeled in the Sun-Earth system, and some will be new development based on our understanding of physics and the data from exploratory spacecraft. The effort to integrate and fully couple models is a considerable challenge that will require a sustained effort from multidisciplinary teams with expertise in high-performance computing, software design, information technology, and all of the physical domains to be modeled, validated, and integrated.



Section 4: Vignettes to enrich earlier sections

Science Accomplishments

SCIENCE HIGHLIGHTS:

Solar, Heliospheric, and Magnetospheric Mission Results

Solar:

S1) First imaging of MHD Waves and oscillations in solar corona (EIT, TRACE)

S2) Mapping of the backside of the Sun with helioseismology (MDI/SOHO)

S3) Spectroscopic detection of CME-driven shocks in type II events (UVCS, LASCO, radio) - Raymond

S4) Global waves (EIT waves) and coronal dimming after launch of CME (EIT) - Thompson

S5) Radio signature of interaction between overtaking CMEs (WIND, SOHO/WAVES) - Gopal

S6) Polar magnetic polarity reversal linked to high-latitude CMEs (SOHO/LASCO) - Gopal

S7) Correlation between CME rate and galactic cosmic ray modulation (IMP-8, SOHO) - Lara

S8) Deceleration of CMEs in interplanetary space (SOHO/LASCO, WIND, HELIOS/PVO) - Gopal

S9) Detection of current sheets behind CMEs (UVCS/SOHO) - Ciaravella

S10) First imaging of gamma-ray emission from energetic protons in solar flares (RHESSI) – Hurford

S11) Acceleration of relativistic electrons by CME-driven shocks in corona (ACE, WIND)

S12) Puzzles in isotopic and charge-states of energetic solar ions (ACE)

Heliospheric:

H1) Triangulation of interplanetary type III radio bursts (WIND, ULYSSES) – Reiner, MacDowall

H2) Propagation of solar energetic particles to solar polar latitudes (ULYSSES) – Reisenfeld, Lario

H3) Voyager 1 exits the solar wind at 85 AU (termination shock) (Voyager 1) – NYT

H4) Interstellar pick-up ions–samples from the interstellar medium (Ulysses, WIND, ACE)– Gloeckler

Magnetospheric:

M1) Observations of electron diffusion region in magnetic reconnection (POLAR)

M2) Imaging of continuous reconnection at the magnetopause complementarity of in-situ and remote measurements (IMAGE, CLUSTER)

M3) Ballistic acceleration of oxygen and hydrogen in the ion diffusion region in geotail (CLUSTER)

M4) Direct observation of parallel electric fields and structure in auroral acceleration region (FAST, POLAR)

M5) The role and dynamics of plasmasphere within a strongly coupled system (IMAGE, POLAR, CLUSTER)

M6) Particle acceleration by kinetic Alfven waves (rockets, FAST, POLAR)

M7) Energetic neutral atom (ENA) images of dynamics of trapped magnetospheric ions at Earth and Saturn (IMAGE, Cassini)

Energetic Particles

Gamma ray observations with the RHESSI spacecraft have determined that the source regions for solar energetic particle (SEP) hazards during solar storms are located well above the solar surface. One of the most likely locations of SEP production are current sheets near 1.5 solar radii, where magnetic energy is released and electricpotentials of up to 500 billion volts are induced. The other site is near the leading edge of coronal mass ejections (CMEs) where shock waves can accelerate protons to velocities near the speed of light (see Figure). Instruments on the SOHO spacecraft have measured the current sheet and CME shock characteristics that are needed as inputs to theoretical models aimed at predicting the production of SEPs for specific solar storm events.

The current sheet is the place where the conversion of the magnetic energy that drives the flare and CME through a process called magnetic reconnection occurs. Magnetic fields of opposite polarities and plasma are successively brought into this region to maintain the continuous energy conversion. In this process, the anti-parallel magnetic fields annihilate one another and induce a strong electric field inside the current sheet where the electric field can reach 5V/cm and sometimes as much as 50 V/cm. Such a robust electric field can accelerate charged particles, especially electrons and protons, to very high speeds in a few minutes. Turbulent modes inside the current sheet are expected to accelerate charged particles as well. Spectroscopic observations by UVCS/SOHO in concert with SOHO's EIT and LASCO instruments have provided a robust diagnostic approach to analyzing and studying the properties of the plasma and the magnetic field of the current sheet before and during the eruptions. These properties include the electron density, plasma temperature, magneticfield strength, magnetic reconnection inflow and outflow, and thusthe rate of magnetic reconnection. They are guiding the development of theoretical models that will ultimately forecast the production of energetic particle hazards.

The physics of particle acceleration in shocks is fairly well understood, in that models predict reasonable shapes for the particle spectra. However, the prediction of the number of particles accelerated is still under debate. Shock fronts in the neighborhood of 2 solar radii have been detected with UVCS/SOHO. The UV spectra have made it possible to derive shock wave parameters (pre-shock density and composition as well as shock speed), and to measure the partitioning of thermal energy among various particle species.

Figure Caption:

New theories of solar flares and coronal mass ejections treat them asa single dynamic system called a solar storm. This picture consists ofa two dimensional image of a coronal mass ejection (CME) superimposed on a theoretical model of the magnetic field configurations of the solar storm. The footpoints of an arcade of magnetic field loops (f) near the solar surface trace out the two ribbon flare (g) shown in the image of the coronal base. As the event unfolds, instabilities in the coronal magnetic field stretched and pushed the fields upward until opposite polarity magnetic field came in contact forming a current sheet (e). Enormous electrical potentials are induced across the current sheet accelerating protons to relativistic speeds, and magnetic energy is transformed into thermal and kinetic energy that drives the flare and heats and accelerates the CME. A shock front (d) forms above the leading edge of the CME (c) heating the coronal gas and accelerating solar energetic particles. The CME core (a) and void (b) are also shown.

Figure Credit: Alexander Panasyuk and the SOHO UVCS, EIT and LASCO
Consortia.

Voyager Exiting the Solar Wind

Abstract

Beginning in mid-2002, Voyager 1 observed an extended period of field-aligned flows of low energy ions and electrons that was unlike previous observations, suggesting that the spacecraft was in the vicinity of the solar wind termination shock. However, the observations differed from expectations and have resulted in differing interpretations as to whether or not Voyager 1 crossed the termination shock and entered the subsonic flow in the heliosheath for a seven month period. The puzzling aspects of the observations suggest that the shock is more complex and dynamic than generally expected and that there could be more surprises as Voyager 1 will likely encounter the shock several times before durably entering the heliosheath sometime in the next few years.

Two Voyager spacecraft were launched in 1977 on a journey of exploration of Jupiter, Saturn, Uranus, Neptune, and the outer heliosphere. We were fortunate that this alignment of the giant planets was such that the Voyager spacecraft are headed in the general direction of the nose of the heliosphere where the solar wind and the interstellar wind meet

(see Figure 1). In July 2002 Voyager 1 was at 85 AU and Voyager 2 at 68 AU, with radial speeds of 3.6 and 3.1 AU per year. The size of the heliosphere is determined by the pressure balance between the outward supersonic expansion of the solar wind and the pressure in the local interstellar cloud that surrounds the Sun. The distance to the termination shock will vary by _10 AU as the dynamic pressure of the solar wind varies over the solar cycle. Because of uncertainties in these pressures, the distances to the termination shock and heliopause are not precisely known. However, a summary of recent estimates [2] suggests that the termination shock may be at 90_10 AU, indicating that Voyager 1 may now be in the vicinity of the termination shock.

ADD FIGURES & ADDITIONAL TEXT

Reconnection

Reconnection in space and astrophysical plasmas is the rapid conversion of the energy stored in stressed magnetic configurations into ion jets, magnetic field-aligned electrons, and radiated wave energy. Reconnection is the primary process driving almost all of the energy intensive processes operating in the Earth's magnetosphere. Despite the importance of this process, until recently, there have been very few direct in-situ observations of the spatial structure of the electric and magnetic fields along with simultaneously measured accelerated particle distribution functions. Observations from the ESA/NASA Cluster Mission have provided the first evidence for very thin bifurcated current sheets (100 km or ~3-5 electron inertial lengths) with intense shock-like electric fields (60 mV/m) coinciding with/and directed normal to the current sheets. The potential drop across the current layer is ~6 kilovolts. These electric field structures form potential wells, which are sufficiently thin that it is expected that incident ions are ballistically accelerated across the electric field structures. Observations of H+ distribution functions in the reconnection separatrix region between the shocks provide evidence for counter-streaming monoenergetic ion beams directed along the shock normal with energies of ~5 keV. The data indicates that a similar larger scale potential structure (15-30 kV) coincides with large-scale portions of the cross tail current sheet and results in the formation of O+ beams. This acceleration may be regarded as the first step in the creation of reconnection jets. The second is ejection away from the x-line. Simultaneous observations by separate spacecraft moving through the reconnection structure near the x-line al soprovide the first evidence in a space plasma for the diverging standing wave structure reminiscent of the Petchek geometry. The three-dimensional structure of the small scale potential well is that of an electrostatic nozzle.

ADD FIGURES

Cluster observations near a reconnection x-line in the Earth's geomagnetic tail of an electrostatic well and associated shock-like acceleration of ion beams between thin current sheets

Plasmaspheric Dynamics

A breakthrough in our understanding of the plasmasphere was achieved through the convergence of remote sensing by the IMAGE mission, with in situ observations from Polar and Cluster. IMAGE showed us for the first time that the plasmasphere is every bit as dynamic as suspected, in response to geospace storms. In quiet times the plasmasphere is a relatively featureless corona-like extension of the ionosphere. But when dayside and nightside reconnection occur simultaneously, they create a strong sunward flow of the entire magnetosphere. The outer part of the plasmasphere is swept sunward into a plume that is vividly illustrated by EUV imaging of resonantly scattered solar Helium emissions. The Polar spacecraft substantiated this observation, showing that cold plasmaspheric material is routinely present in the subsolar magnetopause region, at highly variable density, and is subject to sporadic sunward flow bursts approaching Alfvén speed, indicative of reconnection regions. The Cluster spacecraft, with its active spacecraft potential control, was able to sample plasmaspheric plumes in transit from the inner magnetosphere to the magnetopause, further establishing this phenomenon and calibrating the EUV images. Taken together, these observations demonstrate the power of coordinated imaging and in situ measurements to enhance our understanding of space plasmas and their response to solar wind disturbances

Raditation Effects

Radiation is a concern for Exploration Science from two perspectives; Astronaut safety and performance of the hardware component of space systems. The direct radiation effects on Astronauts include cancer, degenerative tissue diseases, damage to the central nervous system, cataracts, and hereditary risks. However, the performance of space hardware is also related to Astronaut safety because it involves the performance of the crew vehicle plus all auxiliary space systems they rely on. Failures or malfunctions of these systems can endanger Astronauts. The space environment can endanger robotic missions that support Exploration Science. In addition, space environment effects are a concern for all space technologies that we as a species depend on, here in near Earth space.

The particulate radiation component of space environments consists of the plasma, energetic ions and electrons and cosmic rays (both galactic and solar). These particles can also generate secondary radiation in systems and within planetary materials that are of concern to both Astronauts and technology.

Table 1, shows examples of radiation components and their effects on humans. This table addresses the direct impact of radiation on Astronauts. The Q factor indicates the relative ability of energetic particles to cause biological damage. It is a function of a particle's Linear Energy Transfer (LET) which is itself a function of the particle's mass, nuclear charge and energy. Most of the sources and effects are related to primary energetic particle and secondary radiation to be found in interplanetary space and on planets without magnetospheres. The galactic cosmic rays (GCR) represent the highest energy component of interplanetary radiation. Their average flux is low but their persistence is an important factor in estimating the relative dose equivalence and biological effect. There is little to nothing that can be done to protect against the energetic GCRs.

The solar energetic particle (SEP) component of interplanetary radiation is significantly higher in flux but of short duration. It may be possible to predict the occurrence of SEPs. In any case, the onset of SEPs can be detected and estimates of the severity of a SEP event may be possible with continued study. Shielding can be effective against the lowest energy, high flux component of SEPs. Prediction and early detection of SEPs allows for management of that component of Astronaut radiation exposure using the concept of ALARA (keeping radiation exposure As Low As Reasonably Achievable).

As is noted in Table 1, for protons, electrons and the secondary sources, magnetospheres can be very inhospitable places for Astronauts. Magnetospheres energize the entrapped particles and build their fluxes to levels that exceed average interplanetary levels by many orders of magnitude. At Earth, the worst radiation occurs in the inner proton belts (generated via GCR interactions with the atmosphere). These protons have lifetimes of order 103 years so weak the source builds to high flux levels with hard spectra. Humans could not survive in such regions. Magnetospheric electrons are energized as they are transported inward from the outer boundaries. Internal process raise the fluxes and energies to high values such that during a traversal of the electron radiation belts dose levels can reach a few rads/hour behind 2-3 mm Aluminum (for a few hour traversal of the belts) with 0.1% being from Bremsstrahlung radiation. The trapped radiation at weakly magnetized planets is not known and could be of concern, especially for close orbits. It would have to be measured in advance.

Table 2 shows space radiation effects on technologies. When considering the safety and effectiveness of Exploration endeavors, both direct effects on Astronauts and the impact on their support technology must be addressed. Failures and operational anomalies of space systems caused by particulate radiation have been well documented. Total dose is a lessor concern than other impacts of space radiation primarily because parts can handle higher dosage than people. Space vehicle charging and related malfunctions have been a dominant source of operational anomalies and failures for systems orbiting in near Earth space (i.e. in a magnetosphere; ref. Fig 1). SEE related malfunctions, which occur both in interplanetary regions and inside magnetospheres, are the second most likely environmental cause of malfunctions. Given the effects shown in Table 1, significant care has to be taken in designing systems that must transport and shelter Astronauts for extended missions. An equivalent "ALARA" needs to be used for these technological systems.

[Triboelectric charging is a non radiation effect that has occurred under some atmospheric conditions (e.g. launch vehicles passing through clouds) and should be a consideration for any planetary exploration during entry and escape through the atmosphere.]

Table 1: Requirements for Complete Characterization of Radiation Environment for Astronauts

Particle Species	Quality Factor	Relevance (Biological Importance and Need for Measurement)
Protons	1-7	Largest flux, large contributor to total dose outside magnetospheres (>90% of GCR, >98% of SEP); High flux inside magnetospheres in GCR albedo-neutron generated trapped proton belts
He (alphas)	2-30	Large flux, high Q at low energies
C, N, O	5-30	High Q with large probability of reaction in body tissue
Fe	6-30	High Q factor with high probability of of reaction in body tissue
Neutrons	3-10	High Q factor, relevant near regolith and in high intensity high energy proton belts (secondary production within crew compartment)
γ-rays	1	SEP indicator and a secondary radiation from activated materials

Table 2: Technology Requirements for Characterization of Radiation Environments

Particle Species	Relevance and Effects
Protons	Large contributor to total dose and SEE effects outside magnetospheres ; High flux inside magnetospheres in GCR albedo-neutron generated trapped proton belts and regions of entrapped SEP protons. Source of SEE, directly in low LET threshold electronics or via nuclear interactions that generate high mass fragments
Other Ions	Lower flux than protons but more effective in generating SEE effects (LET threshold dependent) in microelectronics and control logic. High mass ions, such as Fe, have relatively high LET. SEE is a major contributor to space vehicle malfunctions
Neutrons	Source of SEE and secondary radiation (through activation) especially within high flux trapped proton radiation in magnetospheres.
γ-rays	SEP indicator and a secondary radiation from activated materials
Electrons	Significant source of total dose within most magnetospheres. Responsible for space vehicle charging effects that can damage or "scramble" systems.

ADD Figure 1. Percent of satellites that experienced anomalies from specific environmental causes

Halloween Storms

The solar eruptions late October and early November 2003 are the best observed outbreak of intense solar activity to date. The violent solar eruptions occurring from 18 October to 8 November 2003 can be considered as extreme events in terms of both their source properties at the Sun and their heliospheric consequences. The eruptions were accompanied by intense solar flares and coronal mass ejections (CMEs) of very high energy. The plasma, particle and electromagnetic consequences of these events were detected by various instruments located throughout the heliosphere.

A series of shocks were launched into the heliosphere, some of them accelerating particles to unprecedented intensities.

Earth's ionosphere and atmosphere were severely affected by these eruptions. The impact of these eruptions was felt not only in the near-Earth space environment, but also in the far reaches of the heliosphere: Spacecraft located much beyond Earth's orbit such as Ulysses, Cassini, and Voyagers felt the shocks from these eruptions. Disturbances associated with two of the eruptions arrived at Earth in less than a day, providing bench mark data for space weather purposes. Historically, there were only 12 eruptions with less than 1-day shock travel time to Earth including the Carrington event of 1859 September 1. Several aspects of the solar eruptions including active region size and potential energy, flare occurrence rate and peak intensity, CME speed and energy, shock occurrence rate, SEP occurrence rate and peak intensity, geomagnetic storm intensity displayed extreme behavior. Shock transit times for the Oct-Nov 2003 events and documented historical cases suggest a minimum CME Sun-Earth transit time of about half a day. This minimum transit time (maximum CME speed) is consistent with the free energy available from active regions.

About 59% of the reporting spacecraft and about 18% of the instrument groups experienced some effect from the episode of solar activity between mid-October and early November 2003: electronic upsets, housekeeping and science noise, proton degradation to solar arrays, upper atmosphere-induced changes to orbit dynamics, high levels of accumulated radiation, and proton heating were observed. The spacecraft affected were in low-Earth orbit (LEO), Geostationary (GEO) and interplanetary regimes.

The largest solar energetic particle event occurred on October 28, 2003 and resulted in a significant ozone depletion due to the production of high levels of hydrogen oxide constituents in the mesosphere and upper stratosphere. Ozone depletion was observed between 50 and 80 km with a maximum value of 75% around 65 km. North American GPS receivers found more than ten times of total electron content enhancement over the US mainland during the October 30-31 superstorm. The severity of the October geomagnetic storms marked by the day-time aurora reported in Boston in response to the 30 October 2003 storm. Extraordinary density enhancements in both the magnetosphere and ionosphere coinciding with intervals of southward IMF and high-speed solar wind were observed.

By the time the disturbances reached Voyager 2, about 180 days after leaving the Sun, the multiple events observed at 1 AU had formed a single merged interaction region (MIR). The MIR was associated with an unusually large (about 450 days) and fast (about 560 km/s) stream following a forward shock, with a sheath-like region between the shock and the stream. The MIR was associated with a large depression in cosmic ray intensity, lasting more than 70 days.

Although it is not unusual that such solar eruptions occur during the declining phase of a solar cycle, these events bench mark the level of understanding we have on the behavior of the sun over different time scales. Understanding these events will help us assess the extremeness in terms of the free energy available at the Sun and the geospace and heliospheric consequences.

ADD FIGURE + CAPTION

Detecting Activity on the Far Side of the Sun

Productive Teaming of Exploration and Science

Space Weather

Temporally variable conditions in the Sun, solar wind, and planetary space environments (magnetospheres, ionospheres, and atmospheres) are known as Space Weather. These conditions are measured by the plasma speed and density, the solar magnetic field and the radiation density. Space weather can damage space-borne or ground- based technological systems and may threaten human health and life. Space explorers need to mind space weather, which is likely to be different at different destinations.

Most of the space weather drivers can be traced to the Sun, in the form of sunspot groups, filament regions and coronal holes. Flares and coronal mass ejections originate from these activity centers that dump huge amounts of energy in the form of energetic particles, plasmas and electromagnetic radiation. Solar wind streams from coronal holes can press against each other creating interaction regions with shocks, which also accelerate charged particles. High speed streams can also lead to energetic particle population in Earth's magnetosphere. Our galaxy and the interstellar medium also contribute to the space weather in the form of cosmic rays. There are also effects related to the interaction between these two sets (solar and non-solar) of drivers.

X-rays and EUV radiation generated at the time of flares can modify Earth's ionosphere over a matter of minutes by enhancing the ionization. Radio communication systems depend heavily on the conditions in the ionosphere and hence can be severely affected by these prompt solar-flare effects.

An example of how the normal functioning of space instrumentation is affected by a solar event. Two SOHO/EIT images taken less than half an hour apart. The 07:14 image is seriously degraded by SEPs arriving at the spacecraft at L1. The SEPs were released from the Sun due to an eruption in the northwest quadrant of the Sun.

Coronal mass ejections (CMEs) and the shocks driven by them result in more prolonged and severer effects. During their journey into the interplanetary space, CME-driven shocks accelerate charged particles to dangerously high energies and hence pose a radiation hazard. Astronauts' career limits for radiation exposure can be exceeded during a single solar energetic particle event (SEP). The first particles can arrive almost as fast as light can. The bulk of SEPs arrive in tens of minutes. The shocks are most potent when they are near the Sun and release the highest energy particles when they are within the first 10% of the Sun-Earth distance. The shocks arrive at spacecraft in the vicinity of Earth within a day or two, continuing to produce high levels of charged particles. It takes longer for the shocks to reach farther locations such as Mars. Even though the shocks are considerably weakened at these distant locations, they do produce hazardous SEPs.

Energetic CMEs and shocks sweep through the entire solar system in about six months. High energy particles can cause single event upsets in spacecraft electronics. When they pass through humans, they ionize molecules along their track creating free radicals that can break DNA strands leading to cancerous cells.

CMEs contain hot plasma with enhanced magnetic field, so they can stir up the planetary magnetospheres on impact causing intense magnetic storms. At Earth, they can cause intense geomagnetic storms and lead to the production of another population of charged particles within the magnetosphere. The geomagnetic storms can also result in current surges in the ground, transmission lines, rail roads and pipelines leading to large disruptions with potential economic impacts.

CMEs with southward interplanetary magnetic field disrupts the shielding currents in the inner magnetosphere and allows solar wind electric fields to penetrate all the way to the equator, lifting up and redistributing ionospheric plasma in a strong equatorial fountain, while allowing dense plumes of plasma to be drawn from mid-latitudes up over the polar cap. The SEPs can also penetrate into the magnetosphere and reside in new radiation belts for months, thus posing additional hazard to satellites. SEPs have been shown to affect the atmospheric chemistry and the ozone layer in particular: SEPs combine with the energy inputs from the auroral storms to break up nitrogen and water molecules, creating nitrogen and hydrogen oxides (NOx and HOx), which react with atmospheric ozone and deplete it significantly. The stratospheric ozone distributions at lower altitudes remain disrupted possibly for months.

The impact of SEPs and CMEs on other planetary atmospheres depends on the prevailing physical conditions and chemical compositions. For example, the lack of global magnetic field in Mars minimizes magnetic storms and the related processes. However, the patchwork ionosphere at the locations of regional magnetic fields may be affected by CME/shock impact. The thinner atmosphere makes it easy for the penetration of charged particles. The solar wind has eroded the atmosphere of Mars considerably, and CMEs represents gusts of enhanced solar wind that modulate the continued erosion.

Magnetospheres are regions where internal processes enhance solar-variability driven space weather responses and generate their own space weather effects. Two examples of such responses are the enhancement of radiation belts and substorms. Both cause the phenomena of satellite charging (internal and surface) which can damage space platforms. These phenomena are uniquely magnetospheric. They are driven by magnetospheric processes which convert the solar wind energy into particle energy enhancements. These processes occur in planetary magnetic fields such as at Earth, Jupiter, Saturn, etc. The danger to space platforms and their occupants exists to a significant degree independent of whether CMEs or SEPs have occurred or not. Within the Earth's magnetosphere space platform charging has been the major cause of space weather related malfunction and failure. Chart 1 shows the result of a study that identified number of space platforms that had anomalies and the cause of those anomalies. The second most likely cause of anomalies was single event effects from GCR, SEPs and energetic ions trapped in the magnetosphere.

Chart 1: Number of space platforms that have experienced anomalies of different types caused by the space environment. Other includes effects such as meteor strikes and atmospheric drag. (after Koons, e. al. 1999)

During magnetic storms, electric fields, currents and energetic particles of magnetospheric origin induce extreme modifications of the ionosphere-thermosphere system. Energetic particles ionize the conducting layer of the high-latitude ionosphere, and deposit energy that heats the neutral and ionized gases and produces the aurora. The electric fields and currents drive an ionospheric current system that also dissipates heat (Joule heating), leading to global modifications of thermosphere temperatures, densities, composition and winds. These effects are manifested in significant increases in the drag experienced by satellites. Electric fields penetrate to low latitudes, and are also induced by the dynamo effects of storm-time winds. The electric fields, winds, and composition changes modify the global state of the ionosphere, leading to changes in radio propagation conditions including scintillations produced by small-scale plasma irregularities.

The upper atmospheres of Mars and Earth are significantly modified by upward-propagating gravity waves, tides and planetary waves that originate in the lower atmosphere and propagate to upper levels. These disturbances of meteorological origin induce density variations relevant to re-entry and orbital drag concerns, and at Earth induce electric fields (via the dynamo mechanism) that map along magnetic field lines and redistribute ionization. The latter mechanism is responsible for a large fraction of Earth's ionospheric variability at low latitudes.

There are two sources of space weather external to the solar system: (1) the galactic cosmic rays (GCRs) thought to be produced by supernova shocks in our galaxy. The GCRs are of very high energy and present everywhere in the heliosphere. The effects of GCRs on astronauts on long duration missions beyond the Earth's magnetic field depend on when and to what destination the travel is made. (2) Neutral atoms from the inter stellar medium enters the solar system, get ionized by solar energetic photons or charge exchange with solar wind ions to be ultimately accelerated by the termination shock as anomalous cosmic rays (ACRs).

The solar wind turbulence and CMEs modulate the cosmic rays over 11 and 22 year cycles of solar activity. During solar maxima, the intensity of the GCRs is reduced to a minimum, while it reaches a maximum during solar activity minima. The duration of peak GCR intensity is alternatively higher and lower for successive solar activity minima because the heliospheric magnetic field flips its polarity during every 11 years. Thus both SEPs and GCRs are controlled by CMEs in a time dependent fashion.

Space missions in general need to mind the space weather caused by CMEs, shocks, flares and the solar wind. Space Exploration in the future will extend to Mars, so monitoring Earth- and Mars-directed solar events is of crucial importance. Monitoring of cosmic ray intensity variation over different timescales at Earth and Mars is also very important. Unmanned spacecraft venturing into the far reaches of the solar system need to be safeguarded against GCRs.

Empirical and physics based models with good computational resources are needed to monitor space weather at several locations within the sphere of human exploration. These models need to be constantly tested and updated using observations from existing and future assets in space and on the ground.

Chronology of an SEP Event

The SEP event of August 4, 1972 remains one of the bench mark events of radiation hazard to astronauts and dramatically illustrates the need for space weather forecasting. The impact time scale is similar to the Indian Ocean Tsunami of Dec 28 2004!

At 06:20 UT, the flare starts.

At 13:00 UT, the astronauts' 30-day skin and eye exposure limit exceeded

At 14:00 UT, yearly limit for eyes and 30-day limit for blood-forming organs exceeded

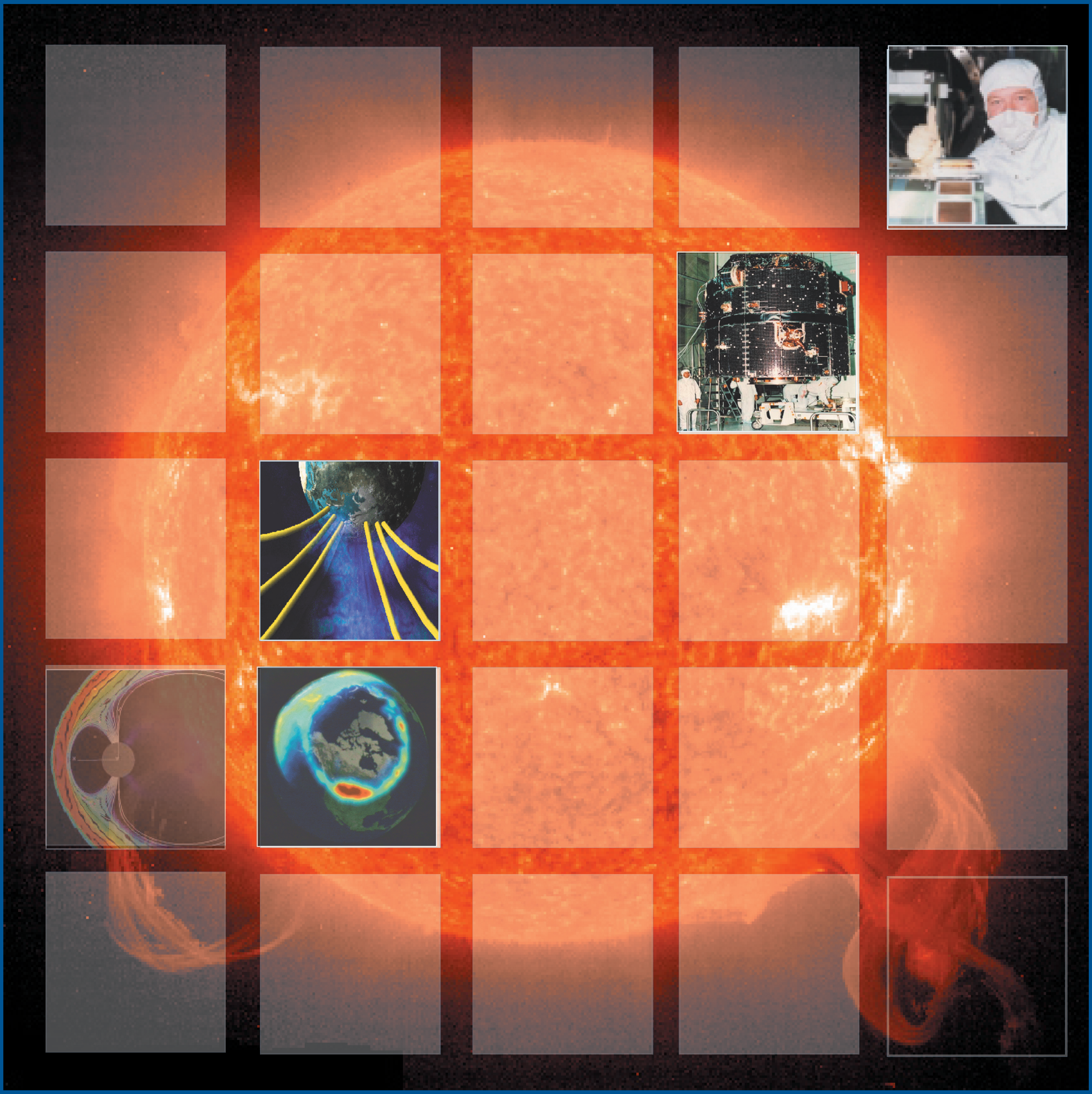
At 15:00 UT, yearly limit for skin exposure exceeded

At 16:00 UT, career limit for eyes and yearly limit for blood-forming organs exceeded

At 17:00 UT the career limit for skin exceeded

At 21:00 UT the shock arrived at earth

The shock transit time for the Aug 4 1972 remains the shortest ever recorded. Even though there was no CME observation, models estimate that the speed of the progenitor CME to be 2857 km/s when it was near the Sun.



Section 5: Recommended Investigations

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