

## Objective F: Open the Frontier to Space Weather Prediction

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

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

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

This results in a rich set of interacting physical processes, including intricate exchanges with the neutral gas in planetary atmospheres. Although physicists know the laws governing the interaction of electrically charged particles, the collective behavior of the plasma state leads to complex and often surprising physical phenomena.

[[[ Can you find a nice little picture from the rocket program showing a particle release at high amplitudes? - <http://www.1000plus.com/Imagic/8012041805ESTBariumReleaseExperiment.jpg> is much prettier than <http://www-istp.gsfc.nasa.gov/Education/wposion.html> but copyrighted.]]]

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

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

*Prediction provides the ultimate test for scientific understanding.*

The strategy for achieving this first science objective focuses on the knowledge gaps most vital to safe and productive exploration via the development of accurate forecasting of the space environment.

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

**[[ One-inch square image of TRACE reconnection ]]**

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

**[[ One-inch square image of quasar x-ray jet -**

**[http://images.google.com/imgres?imgurl=http://astrophys.de/news/2002/pks1127\\_xray.jpg&imgrefurl=http://astrophys.de/news/2002/020206\\_cfa\\_xrayquasarjet.html&h=150&w=150&sz=5&tbnid=KFgC6NJeKIUJ:&tbnh=90&tbnw=90&hl=en&start=4&prev=/images%3Fq%3Dastronomy%2Bxray%2Bjet%26hl%3Den%26lr%3D](http://images.google.com/imgres?imgurl=http://astrophys.de/news/2002/pks1127_xray.jpg&imgrefurl=http://astrophys.de/news/2002/020206_cfa_xrayquasarjet.html&h=150&w=150&sz=5&tbnid=KFgC6NJeKIUJ:&tbnh=90&tbnw=90&hl=en&start=4&prev=/images%3Fq%3Dastronomy%2Bxray%2Bjet%26hl%3Den%26lr%3D) ]]**

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

**[[ One-inch square image of comet with complex tail ]]**

*Plasma-Neutral Interactions:* The Sun-Solar System Connection requires understanding of the fundamental physics of plasma and neutral particle coupling. This coupling encompasses a variety of mechanisms and regions from turbulence and charge exchange in the solar wind to gravity waves and chemical/collisional interactions in planetary atmospheres. Space plasmas are often in a non-equilibrium state and they can be a highly nonlinear medium. Many of the techniques developed for understanding nonlinear systems resulted from basic plasma research – chaos theory is one example; another is the understanding of turbulence, which is so important to safer air travel. The goal is a comprehensive

understanding of how nonlinear processes influence plasma-neutral interactions from atmospheric to heliospheric scales. This work has specific applicability to the operation of satellites in the Martian atmosphere, the mitigation of the effects of global change, as well understanding how habitable planets retain their atmospheres.

[[ One-inch square image of polar aurorae from IMAGE]]

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

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

### **Research Focus Area F1: Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms.**

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

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

Most of our basic theoretical understanding of reconnection comes from an MHD perspective. Although this approach has provided important insight, it is inherently limited in that it cannot examine the very small scales on which ions and electrons decouple from the magnetic field or predict the particle energization process. Important questions that remain unanswered include: what initiates the

reconnection process? what are the kinetic processes that occur and what is their role? what is the range of scale sizes of the region over which reconnection occurs in different regimes? is reconnection quasi-steady or bursty? what mechanisms or boundary conditions control the spatial and temporal scales? and what is the 3D structure of the reconnection region and how does this structure affect particle acceleration?

Priority investigations are:

*Investigation F1.1. What are the fundamental physical processes of reconnection on the small-scales where particles decouple from the magnetic field?*

Relevant Mission: MMS; MTRAP

*Investigation F1.2. What is the magnetic field topology for reconnection at the Earth and at what size scales does magnetic reconnection occur on the Sun?*

Relevant Missions: MagCon, Solar-B; CLUSTER, DBC, DOPPLER, IMAGE, MMS, MTRAP, POLAR, RAM, SDO, SEPM, SHIELDS, SIRA, STEREO, THEMIS, TIMED, TRACE

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

## **Research Focus Area F2: Understand the plasma processes that accelerate and transport particles**

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

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

Energetic particles accelerated both at localized sites (solar flares, magnetotail reconnection sites, auroral double layers), and globally (coronal and interplanetary shocks, co-rotating interaction regions and global merged interaction regions in the solar wind, and the termination shock) need to be understood. An understanding of the acceleration of thermal plasmas is also vital to meeting NASA objectives. For example, both the interaction of the Sun with planets and the transport of solar energetic particles are mediated by the solar wind. Successful progress on the understanding of solar wind acceleration will significantly improve the predictive capability for determining the severity of solar

wind disturbances. The origin of the solar wind is not well understood and represents a large gap in our knowledge of fundamental processes.

Priority investigations are:

*Investigation F2.1. How are charged particles accelerated to high energies?*

Relevant Missions: SEPM, IHS, AAMP, SIRA; ACE, Heliosstorm, L1 Observations, RHESSI, SPI, STEREO, SWB, Telemachus, TRACE, Wind

*Investigation F2.2. How are energized particles transported?*

Relevant Missions: IH Sentinels, ITSP, RBSP, SIRA, SWB; AAMP, HIGO, IBEX, ISP, SEPM, SOHO, SPI, STEREO, Telemachus, WIND

*Investigation F2.3. How is the solar wind accelerated and how does it evolve?*

Relevant Missions: Solar Probe, Doppler, IH Sentinels, Solar Orbiter, SWB; Heliosstorm, L1 Observations, Pluto-Kuiper, SEPM, SHIELDS, SOHO, SPI, STEREO

*Investigation F2.4. How are planetary thermal plasmas accelerated and transported?*

Relevant Missions: MagCon, DBC, IMC; AAMP, ADAM, CLUSTER, GEC, IMAGE, ITMC, ITMWaves, MARS, POLAR, THEMIS, TIMED

Figure Caption: **[[ Current figure in current location is fine. I suggest putting the right-hand picture of moss in the center\*\* - this rearrangement is reflected in the caption below.]]**

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

### **Research Focus Area F3: Understand the role of plasma and neutral interactions in the nonlinear coupling of regions throughout the solar system**

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

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

The atmosphere is periodically pumped and heated, giving rise to a spectrum of small-scale gravity

waves and longer-period oscillations. These waves can propagate into the mesosphere and thermosphere depositing momentum into the atmosphere. The atmospheric mean circulation is thereby modified, resulting in vertical winds, changes in the temperature structure, and the redistribution of radiation absorbers. The mean wind and temperature structures in turn influence the propagation of the waves and the manner in which they couple the lower and upper atmosphere. Similar processes and scenarios are also key to understanding the upper atmosphere weather and climate on Mars and Venus.

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

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

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

Priority investigations are:

*Investigation F3.1 What governs the coupling of neutral and ionized species at various spatial and temporal scales?*

Relevant Missions: ITSP, GEC, ADAM, ITMWaves, ITMC, MTRAP; VAP, MARS, Solar B, Doppler

*Investigation F3.2 How do energetic particles chemically modify planetary environments?*

Relevant missions: SECEP, ADAM, ITMWaves, TIMED, MARS, Io-E

*Investigation F3.3 How do the magnetosphere and the ionosphere-thermosphere (IT) systems interact with each other?*

Relevant Missions: GEC, AAMP, ITSP, RBSP

*Investigation F3.4. How do the heliosphere and the interstellar medium interact?*

Relevant Missions: ISP, HIGO, IBEX, Voyagers 1&2, Pluto-Kuiper

*Investigation F3.5. How do the neutral environment in planetary and cometary systems affect the global morphology through charge exchange and mass loading processes?*

Relevant Missions: VAP, STEREO, SCOPE

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

## **Research Focus Area F4: Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments.**

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

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

There are four investigations that address these issues.

*Investigation F4.1. How do subsurface flows drive the solar dynamos and produce the solar cycle? How do solar and stellar dynamos evolve on both short and long time scales?*

Relevant Missions: SDO, Solar Orbiter, Stellar Imager; RAM, Solar-B, SOHO, SPI, Telemachus

*Investigation F4.2. How are open flux regions produced on the Sun, and how do variations in open flux topology and magnitude affect heliospheric structure?*

Relevant Missions: STEREO, Solar Orbiter, Farside, SHIELDS, Solar Polar Imager, Telemachus; ACE, IH Sentinels, SOHO, SWB, TRACE, Ulysses

Investigation F4.3. How do planetary dynamos function and why do they vary so widely across the solar system?

Relevant Missions: Cassini, Juno/JPO, Messenger, ACE, ADAM, SECEP, WIND

Relevant Missions: GEC, ITSP, ITMC

Figure Caption: About one-third of the way down toward the center of the Sun (white line), the rotational flows change

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

[Image credit: ??? - The image is **derived** from an NSO press release in 2000 and Rachel Howe was the first author.]

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

Table Caption:

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