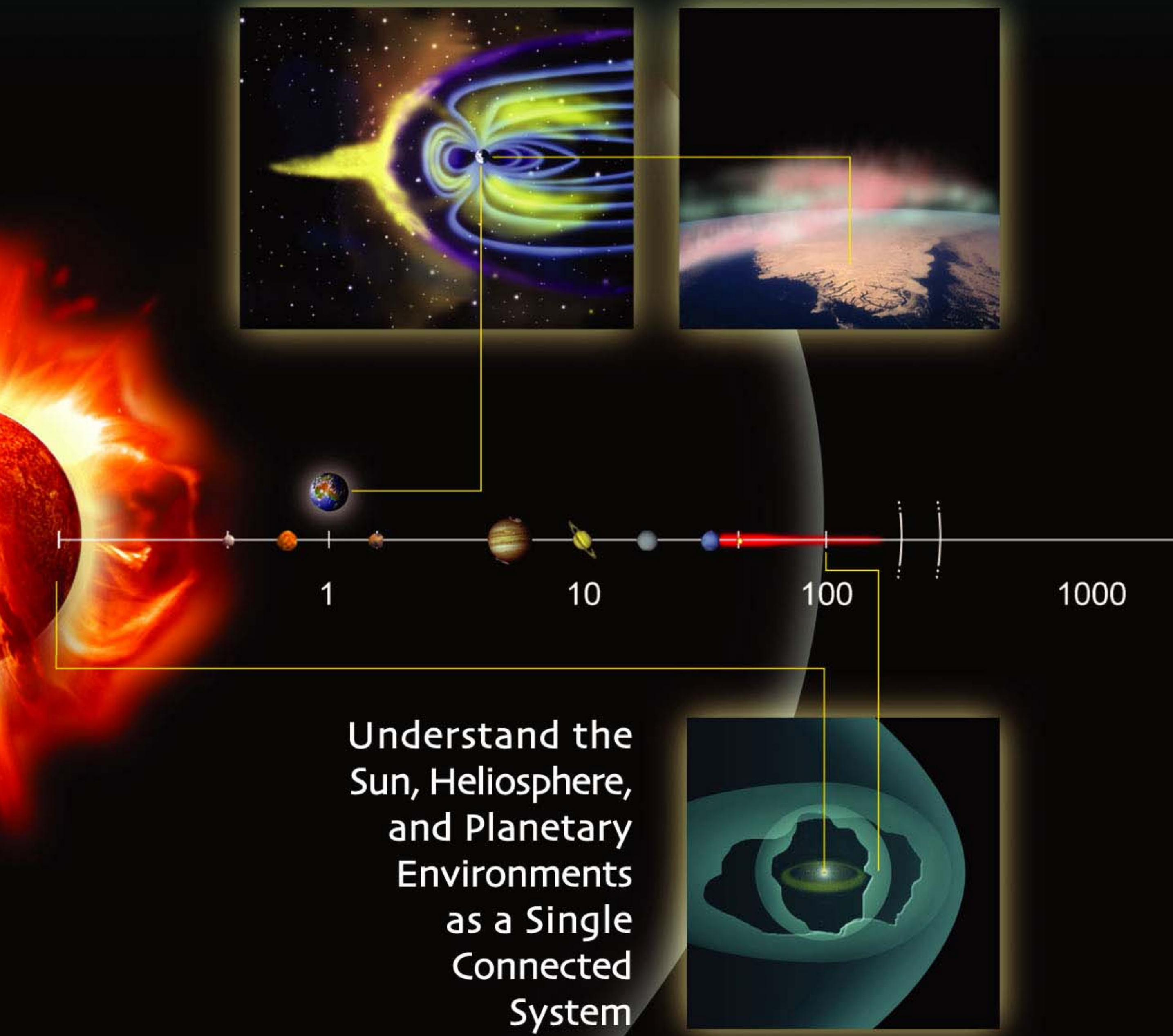
Sun-Earth Connection

ROADMAP 2003-2028



Understand the Sun, Heliosphere, and Planetary Environments as a Single Connected System

National Aeronautics and Space Administration

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The cover illustration highlights regimes of particular importance for understanding the Sun-Earth connection. The logarithmic distance scale shows the dynamic Sun, on the left, and its sphere of influence, the heliosphere, stretching out far beyond the planets. Formed by the solar wind, this magnetized cloud of plasma plows through the interstellar medium, generating a vast disturbance like the one shown in the lower inset. The Earth is embedded deep within this protective cocoon at 1 astronomical unit. Each planet handles the variable inflow of energy and matter carried out by the solar wind in a unique way. The box on the left shows Earth's magnetosphere responding to a buffeting storm of particles that came from material ejected days earlier from the Sun's corona. Geospace reacts to such impacts in many ways. One visible manifestation, the aurora, is caused by particles accelerated downward into the upper atmosphere at high latitude, as shown in the upper right inset. We need to understand how this system affects us here on our home planet.

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1.0 Introduction

Life on Earth prospers in a biosphere that is sustained by energy from the Sun. The Earth's upper atmosphere and magnetic field generally protect the biosphere against the more dangerous electromagnetic radiation and particles emanating from the Sun. In turn, the extended magnetic field of the Sun shields the Earth from very high-energy radiation that originates at supernovae and other cataclysmic events outside the solar system.

In the process of protecting the Earth, the upper atmosphere and magnetic field form a system that is connected in various ways to the Sun and *heliosphere*. The tremendous energy dissipation in the Earth's high-latitude auroral displays is dramatic evidence of this connection. Associated ionospheric disturbances can disrupt terrestrial communications, and associated electric currents can disrupt power grids. The connection between the heliosphere and the Earth's *magnetosphere* also results in the formation of time-variable radiation belts consisting of high-energy charged particles that encircle the Earth. These belts of dangerous, high-energy particles extend out to distances where communication and weather satellites operate.

The *heliosphere* is the region of space influenced by the Sun and its expanding solar wind. The outer boundary of the supersonic solar wind, called the *termination shock*, is probably located 1.5 x10^{10} km (~100 Astronomical Units, AU) from the Sun.

The *magnetosphere* is the region of space influenced by the Earth's magnetic field. Its boundary is the *magnetopause*, which is shaped like a windsock whose nose is located about 60,000 km upstream (i.e., in the sunward direction) from the Earth.

A *plasma* is a gas of positively and negatively charged particles. Most of the universe, including nearly every region of interest to the SEC Division, contains plasma. This includes the Sun, the solar corona, the solar wind, the interstellar medium, and the magnetospheres and ionospheres of Earth and other planets.

The Sun-Earth Connection

Within NASA's Office of Space Sciences, the Sun-Earth Connection (SEC) Division's primary goal is to understand these interconnections, that is to:

Understand the Sun, heliosphere, and planetary environments as a single connected system.

To accomplish this overarching goal, the SEC Division investigates the physics of the Sun, the heliosphere, the local interstellar medium, and all planetary environments within the heliosphere. Taken together, these studies encompass the scientific disciplines of solar physics, heliospheric physics, magnetospheric physics, and aeronomy (the study of planetary upper atmospheres). They address problems such as solar variability, the responses of the planets to such variability, and the interaction of the heliosphere with the galaxy.

Recent years have witnessed the growing importance of SEC investigations focused upon space weather, the diverse array of dynamic and interconnected phenomena that affect both life and society. Space weather effects disturb radio and radar propagation through the ionosphere, damage objects or astronauts outside the Earth's atmosphere, substantially modify the ozone layer, and may induce some climate shifts. Understanding space weather effects becomes more important as the government and private sectors rely increasingly on space- and ground-based assets subject to the influences of the space environment.

2.0 Sun-Earth Connection Goal and the Space Science Enterprise Strategic Objectives

The SEC is one of three divisions in the Office of Space Sciences (OSS). The SEC Division's overarching goal is linked to the OSS Space Science Enterprise Strategic Plan through Strategic Science Objectives. These objectives define the multi-decadal studies needed to thoroughly understand the environment as a system and this system's impact on life and society. The three primary science objectives are to:

1) Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

Determining how energy and matter are transferred from and through each link in the system and how the system responds to this transfer.

2) Explore the fundamental physical processes of space plasma systems.

Understanding how *plasma* processes within and outside the heliosphere create links in the Sun-heliosphere-planet system.

3) Define the origins and societal impacts of variability in the Sun-Earth connection.

Determining the effects of short-time scale variability on space weather and the Earth's atmosphere and the effects of long-term variations that lead to "space climate" and climate change on Earth.

In addition to these three primary science objectives, the SEC Division contributes to five additional science objectives. These objectives, from the 2000 OSS Strategic Plan, are primary objectives for astrophysics and planetary physics. They concern the structure and evolution of the universe, the formation of the solar system, and the search for the origin of life in the solar system. Specifically, they are to:

- **Understand the structure of the universe, from its earliest beginnings to its ultimate fate.**
- **Learn how galaxies, stars, and planets form, interact, and evolve.**
- **Understand the formation and evolution of the solar system and Earth within it.**
- **Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our solar system.**
- **Chart our destiny in the solar system.**

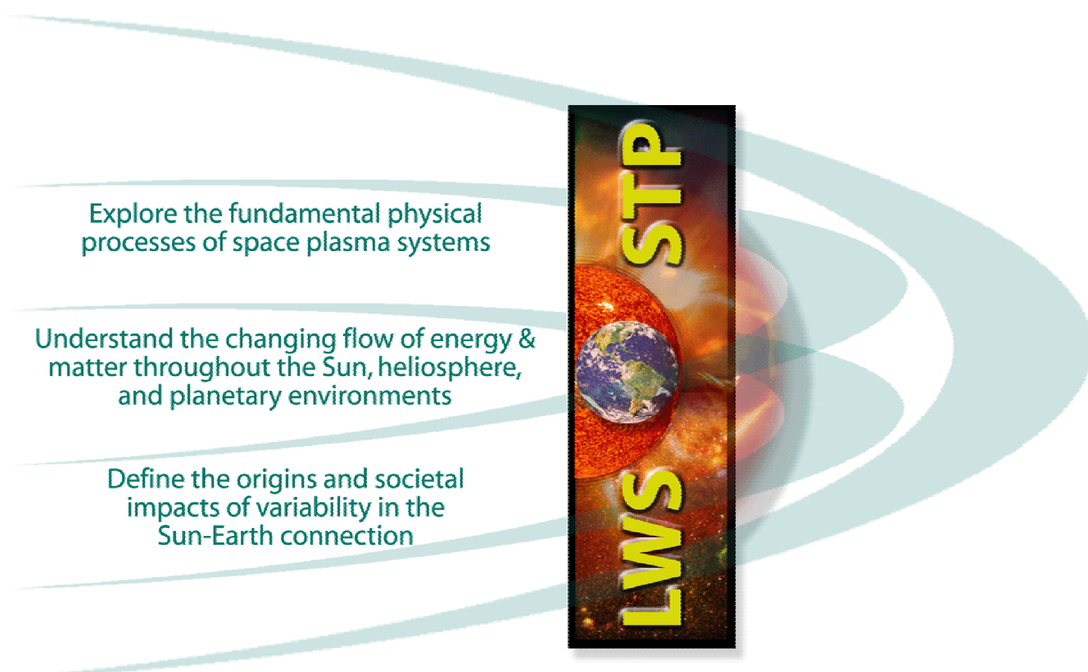


Figure 1.1 The three primary science objectives of the SEC Division and their relationship to the Solar Terrestrial Probe (STP) and Living With a Star (LWS) missions.

To accomplish the primary science objectives, the SEC Division has developed a cohesive, multi-disciplinary plan that focuses on specific research areas through the combination of space missions. Most of these missions are in the Solar Terrestrial Probe (STP) or Living With a Star (LWS) mission lines within the SEC, with primary objectives and mission lines delineated in Figure 1.1 and Table 1.1. The new missions focus on processes that connect the elements of the Sun-heliosphere-planet system. To understand these processes, the measurement approaches are evolving from single-point or widely spaced multi-point missions that have previously employed a single measurement technique, to coupled, multi-point missions that employ a variety of measurement techniques.

- New solar/heliospheric missions will employ combinations of imaging and *in situ* measurements that will directly link the particles to transient features imaged on the Sun, (e.g., by identifying the particles accelerated by a solar flare). These new missions will view the Sun as it has never been seen before, including new vantage points such as high-latitude and polar regions, where the origin of the magnetic activity that starts a new solar cycle remains a mystery.
- New heliospheric missions will visit unexplored regions of space including the region within a few solar radii of the Sun, where the solar wind originates. Other new missions will explore, first indirectly, and later directly, the properties of the local interstellar medium.
- Magnetospheric missions will use combinations of imaging and multi-point *in situ* measurements to explore the very center of reconnection regions. In these regions, the electrons in the plasma decouple from the magnetic field, allowing the field to "reconnect" and mass, energy, and momentum to flow across plasma boundaries.
- Ionospheric missions will sample the ionosphere near 100 km altitude, where the bulk of the energy from the magnetosphere is collisionally dissipated. This region has previously been accessed only by brief visits from sounding rockets.
- Combined results from missions that explore individual links in the Sun-heliosphere-Earth chain will result in true systems-level understanding. For example, the near-term Solar B, STEREO, SDO, MMS, Radiation Belt Storm Probes and IT Storm Probes missions (see Table 1.1) represent a combination that provides unprecedented detailed measurements extending from inside the Sun down to the ionosphere. SDO will provide measurements of the solar interior and development of solar disturbances, Solar B and STEREO will determine the evolution of these disturbances in the heliosphere, MMS will determine the coupling between the solar disturbances and the Earth's magnetosphere and the Geospace Storm Probes will determine consequences for the radiation belts and ionosphere. The result will be a system-wide understanding of the physics behind solar disturbances and their geo-effectiveness.

A strong theory and modeling program is essential to the success of the focused research that these new missions will provide. The systems under study are complex, requiring well-tailored development of representative models. The space weather element of Living With a Star program places additional requirements that include development of models with predictive capability. Such predictive models must be deeply rooted in the underlying theoretical physics derived from the observations provided by multiple spacecraft.

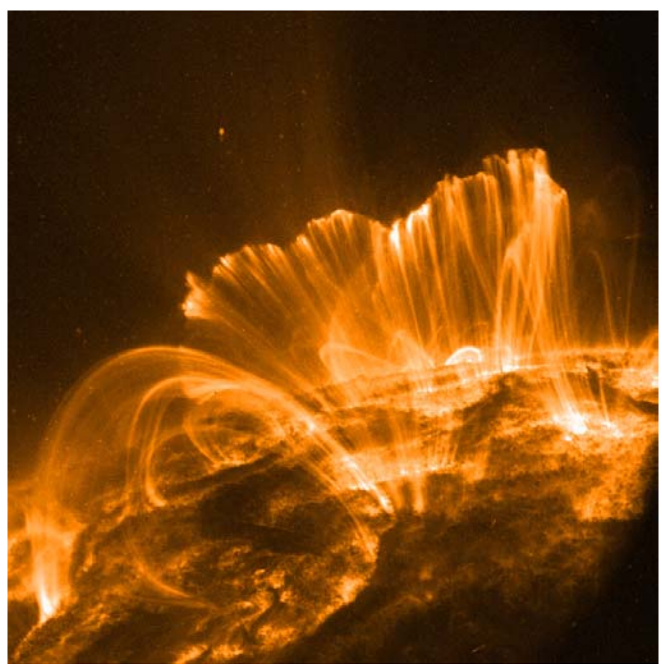


Figure 1.2 Transition Region And Coronal Explorer (TRACE) image of the solar corona illustrate the dynamic Sun.

Technology will play an important role in maximizing the science return from these SEC missions. Improving the technology for spacecraft manufacture and operations will be critical for reducing the cost of multi-spacecraft missions. High spatial and temporal resolution, multi-spectral imaging and the optimal use of data obtained from multi-spacecraft missions will require new techniques for data assimilation and analysis. Remote sensing instrumentation that produces high-resolution multi-spectral images will benefit from additional detector development. Finally, advanced propulsion systems such as solar sails will be needed for access to orbits, including “non-Keplerian orbits,” that would otherwise require significant increases in launch vehicle capability, spacecraft propulsion requirements, and cost.

The new SEC missions will expand the frontiers of human knowledge and ignite curiosity in students and non-specialists. Newer, higher resolution images of the Sun, many times the resolution of images currently available from the TRACE mission (see Figure 1.2), will continue to fascinate the general public. While these new images will result in a revised and improved understanding of the solar corona and a new view of the Sun’s atmosphere in three dimensions, they will also be recognized for their inherent beauty. Heliospheric spacecraft will voyage to unexplored regions of the solar system and will become the first man-made objects to leave the heliosphere and venture into interstellar space. Close-up images of the Jovian aurora, the most powerful in the solar system, will bring a new public appreciation to the Earth’s auroral displays (see Figure 1.3). Finally, new measurements of the Earth’s upper atmosphere will demonstrate the fragility of this region and will establish the role of solar forcing in its modification.

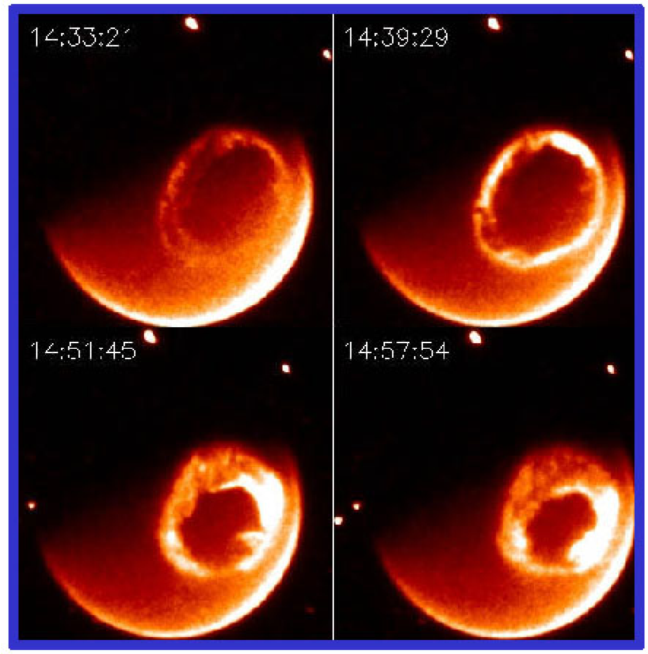


Figure 1.3 Imager for Magnetopause-to-Aurora: Global Exploration (IMAGE) images of the Earth’s auroral oval during a powerful geomagnetic storm.

Table 1.1 The SEC goal and strategic science objectives and their links to SEC near- and intermediate-term missions. The missions under a particular objective are listed in chronological order.

Goal	**Understand the Sun, heliosphere, and planetary environments as a single connected system.**		
Strategic Science Objectives	1) Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments	2) Explore the fundamental physical processes of space plasma systems.	3) Define the origins and societal impacts of variability in the Sun-Earth connection
Near-Term Missions (2003-2008)	- Solar B - Solar-Terrestrial Relations Observatory (STEREO) - Geospace Electrodynamics Connections (GEC) - Solar Probe	- Magnetospheric Multiscale (MMS) - Bepi-Colombo	- Solar Dynamics Observatory (SDO) <u>Geospace Storm Probes:</u> - Ionosphere Thermosphere Storm Probes - Radiation Belt Storm Probes
Intermediate Term Missions (2009-2014)	- Magnetospheric Constellation (MagCon) - Telemachus - Ionosphere Thermosphere Mesosphere Waves Coupler - Heliospheric Imager and Galactic Observer (HIGO)	- Jupiter Polar Orbiter (JPO) - Reconnection and Microscale (RAM)	- Inner Heliosphere Sentinels (IHS) - Solar Orbiter - Inner Magnetospheric Constellation (IMC) - Tropical ITM Coupler - Magnetic Transition Region Probe (MTRAP)

2.0 SEC Science Objectives and RFAs Introduction

All of the SEC Division strategic planning and implementation, including the missions, technology, theory and modeling, and education and public outreach, is based on the science objectives in Table 2.1 and 2.2. To accomplish these broadly defined science objectives will require a number of missions spread over several decades and a long-term theory and modeling effort.

In order to articulate near- and intermediate-term missions within the SEC, the science objectives in Tables 2.1 and 2.2 are further divided into Research Focus Areas (RFAs). These Research Focus Areas are further divided into Investigations, which describe specific SEC science goals that map directly into individual missions, theory and modeling, and education and public outreach efforts. Within the next decade, these individual missions are expected to make significant progress on the SEC Investigations.

This section details the SEC RFAs and Investigations. In Section 3, the near- and intermediate-term missions are mapped into the Research Focus Areas and Investigations. Section 4 highlights the technology development needed to complete the missions, Section 5 discusses the near- and intermediate-term theory and modeling, and Section 6 discusses the education and public outreach associated with the missions. Finally, Section 7 introduces the external and internal factors that affect the SEC science program.

Table 2.1 Primary Sun-Earth Connection Science Objectives and Research Focus Areas.

Sun-Earth Connection Science Objectives	Sun-Earth Connection Research Focus Areas	Sun-Earth Connection Investigations
Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.	- Understand the structure and dynamics of the Sun and solar wind and the origins of magnetic variability.	(a) Understand the transport of mass, energy, and magnetic fields within the Sun and into the solar atmosphere. (b) Determine through direct and indirect measurements the origins of the solar wind, its magnetic field, and energetic particles.
	- Determine the evolution of the heliosphere and its interaction with the galaxy.	(c) Determine the evolution of the heliosphere on its largest scales. (d) Determine the interaction between the Sun and the galaxy.
	- Understand the response of magnetospheres and atmospheres to external and internal drivers.	(e) Differentiate among the dynamic magnetospheric responses to steady and non-steady drivers. (f) Explore the chain of action/reaction processes that regulate solar energy transfer into and through the coupled magnetosphere-ionosphere-atmosphere system.
Explore the fundamental physical processes of space plasma systems.	- Discover how magnetic fields are created and evolve and how charged particles are accelerated.	(a) Discover the mechanisms for creation, annihilation, and reconnection of magnetic fields. (b) Determine how charged particles are accelerated to enormous energies.
	- Understand coupling across multiple scale lengths and its generality in plasma systems.	(c) Understand how small scale processes couple to large-scale dynamics. (d) Test the generality of processes in diverse plasma environments.
Define the origins and societal impacts of variability in the Sun-Earth connection.	- Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere and affect the Earth	(a) Develop the capability to predict solar activity and its consequences in space. (b) Develop an understanding of the evolution of solar disturbances, how they propagate through the heliosphere, and affect the Earth.
	- Specify and enable prediction of changes to the Earth's radiation environment, ionosphere, and upper atmosphere.	(c) Develop the capability to specify and predict changes to the radiation environment. (d) Develop an understanding of the upper atmosphere and ionosphere response to solar forcing and coupling from the lower atmosphere.
	- Understand the role of solar variability in driving space climate and global change in the Earth's atmosphere.	(e) Understand the connection between solar variability, the Earth's upper atmosphere, and global change. (f) Develop the capability to predict the long-term climate of space.

Table 2.2 Additional Sun-Earth Connection Science Objectives and Research Focus Areas.

Science Objectives	Research Focus Areas
Understand the structure of the universe, from its earliest beginnings to its ultimate fate.	(a) Develop helioseismological constraints on the structure of the Sun as a star.
Learn how galaxies, stars, and planets form, interact, and evolve.	(a) Determine the roles magnetic dynamos and angular momentum transport play in how stars and planetary systems form and evolve. (b) Delineate the current state of the local interstellar medium and its implications for galactic evolution (c) Determine the interaction between the interstellar medium and the astrospheres of the Sun and other Stars
Understand the formation and evolution of the solar system and Earth within it.	(a) Explore the role of planetary magnetic shielding in establishing diverse atmospheres of Earth, Venus, and Mars
Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our solar system.	(a) Explain the role of varying solar activity as life evolves (b) Search for molecules and the building blocks of life from comets, Kuiper Belt objects, and dust in the heliosphere and the interstellar medium. (c) Understand the effects of energetic particles on the evolution and the persistence of life.
Chart our destiny in the solar system.	(a) Explain the role of varying solar activity in the future of terrestrial climate and habitability.

2.1 Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

The flow of energy and matter within and outward from the Sun, past the planets and into their atmospheres, and finally out past the heliopause and into the interstellar medium encompasses all the major scientific disciplines of the SEC Division. Recent spacecraft missions have focused on individual aspects of this coupled system, identifying processes that may contribute to this flow. In addition, widely separated spacecraft have been able to track the flow of energy and matter through large parts of the coupled system, from its origin in the solar atmosphere through to the Earth's upper atmosphere.

These pioneering investigations have identified and isolated specific areas within the coupled Sun-heliosphere-planet system that require new observational methods to progress from observation to understanding. New missions to unexplored regions of the Sun-heliosphere-planet system coupled with data analysis, modeling, and theory will provide new insights to the processes that allow energy and matter to flow across individual components in the system. New understanding will be developed starting with the processes deep within the Sun, progressing through the solar atmosphere and inner heliosphere, including the magnetospheres, ionospheres, and atmospheres of planets within the solar system, to the outer heliosphere and beyond the limits of the solar system.

(a) Understand the transport of mass, energy, and magnetic fields within the Sun and solar atmosphere.

As illustrated in Figure 2.1, helioseismology has revealed a complex pattern of surface flows within the Sun. Synoptic maps of these Solar Subsurface Weather flow patterns produced from localized helioseismology suggest that solar magnetism strongly modulates the flow speeds and directions of the large-scale horizontal flows just below the surface of the solar convection zone from one day to the next. Turbulent convection, rotation, and large-scale flows interact globally to generate the solar magnetic field and produce the quasi-periodic activity cycle. In conjunction with MHD simulations, multi-instrument observations of these flow patterns place strong constraints on models for the solar dynamo, structure, and 22-year solar cycle. To resolve the most significant discrepancies between observations and MHD model results that occur at high-latitudes, a polar monitor will be essential.

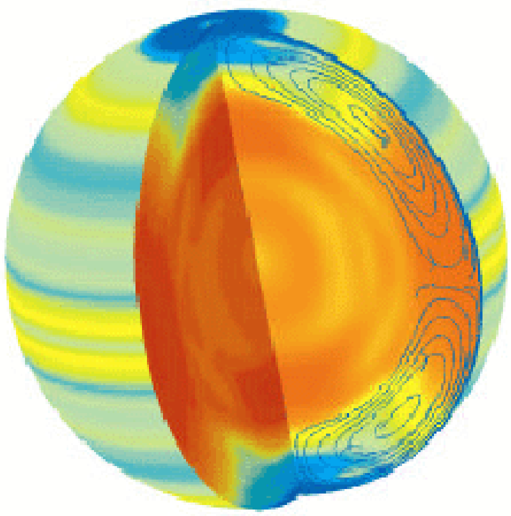


Figure 2.1 Solar rotation and polar flows inside the Sun determined using helioseismology. The colored bands on the surface of the sphere show differences from the average rotation speed of regions on the Sun. Red-yellow is faster than average and blue is slower than average. The light orange bands are zones that are moving faster than their surroundings, extending down approximately 20,000 km into the Sun. Sunspots tend to form at the edge of these bands. The cutaway reveals rotation speed inside the Sun. The large dark orange band is a fast flow beneath the solar equator. Of particular interest are the poorly resolved plasma streams near the poles, which can be seen as a light blue areas embedded in slower moving dark blue regions.

In the absence of fundamental measurements describing the characteristics of the chromosphere and corona, our understanding of the heating that occurs there remains limited. As in all stars with a shell that overlays a strong convection zone, the evolving magnetic field in the atmosphere of the Sun causes heat to be deposited and temperatures to increase to values that are a thousand times higher than that of the solar surface. According to the classical picture, heating occurs within flux tubes reaching from the photosphere into the corona, where coronal energy is conducted downward to form a thin transition region. New measurements indicate that this picture is incomplete. The fact that the chromosphere extends over several thousand kilometers implies that it cannot be hydrostatically stratified, but must be intrinsically dynamic. Moreover, comparison of space and ground-based observations suggests that on small spatial and time scales of 1 arcsec and 15 s, coronal and lower chromospheric heating are not spatially correlated. Either the magnetic topology differs from that expected, or heating within the two domains occurs along different field lines. The classical interface between these two domains, the thin transition region, presents a similar puzzle: it is too extended (as large as 2000km deep). Rather than being a thin layer, it often shows loop-like structures that appear to have no chromospheric counterpart near their footpoints. This leads to the large differences in appearance of images from different layers shown in Figure 2.2.

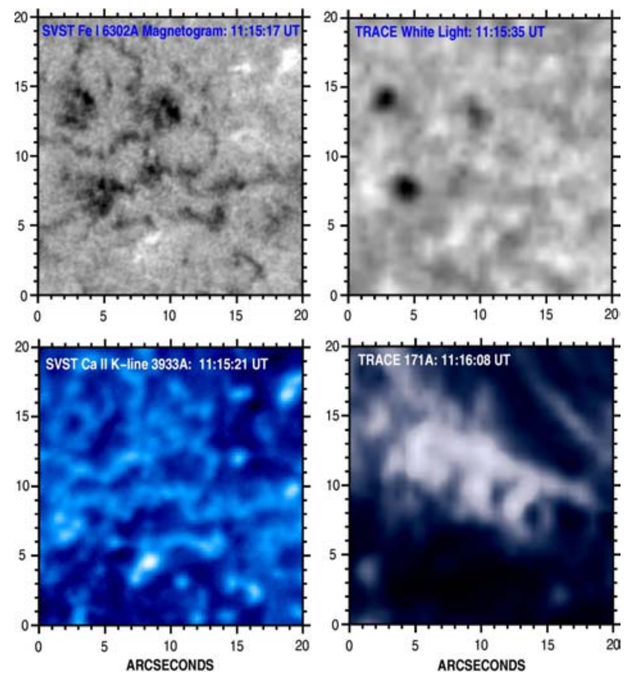


Figure 2.2 Simultaneous views at different altitudes in the solar atmosphere from the chromosphere to the corona of the same solar feature. The lack of correlation between the images shows that, with current time and spatial resolution, chromospheric features do not correspond directly to features in the lower corona.

High spatial and temporal resolution observations of the plasma and magnetic field will be needed to measure the heating processes that occur in the photosphere and atmosphere. The temperature change from a few thousand to a few million degrees across this domain will require multi-spectral observations from the optical to the extreme ultraviolet.

(b) Determine through direct and indirect measurements the origins of the solar wind, its magnetic field, and energetic particles.

Since the discovery of the solar wind, its true sources and the means by which energy is so rapidly dissipated to heat and accelerate it, have remained elusive. With the remote and *in situ* measurements of solar wind composition from a variety of spacecraft and the determination of large-scale 3-D solar wind structure from the Ulysses spacecraft came the realization that there is not one source, but multiple sources of solar wind plasma. The solar wind is currently classified in terms of fast and slow states that reflect the final speeds of the streams. However, this classification masks a deeper question: is there an inherent bimodality to the solar wind, or is it in truth a continuum of states? *In situ* solar wind measurements made in regions > 0.3 AU from the Sun (>64 Solar Radii) place strong constraints on the means of acceleration of solar wind, the sources of solar wind, and the sources of transient events. Remote UV spectral observations have placed constraints on energy flow and dissipation in the corona near the Sun, wave motion at the base of the corona, and reconnection. Additionally, there exists a critical region below ~20 solar radii where the solar wind is sub-Alfvénic and a region inside ~10 solar radii where the magnetic field often dominates the dynamics. Because of large wave pressures, energetic particles, and non-Gaussian distributions of electrons and ions in this region, the evolution of transient events and shocks is very different than in the region beyond ~0.3 AU.

The region inside ~20 solar radii is also a region where energetic particles are often accelerated. These particle populations are observed at the Sun indirectly by looking at their electromagnetic signatures, or by observing them *in situ* after they escape the Sun's atmosphere and are injected (via open field lines) into the heliospheric magnetic field. The current paradigm is that the electrons are accelerated by shocks in the high corona (>2 solar radii), driven by outgoing CMEs. Since acceleration in most theories is primarily a velocity-dependent process, it is reasonable to expect that very fast ions are also accelerated in the high corona by the same mechanism.

In summary, this region close to the Sun is permeated with plasma in a physical regime that has never been explored, but plays a critical role in controlling the structure, evolution, and variability of the solar wind and particles accelerated in it. Full understanding of this region inside ~20 solar radii requires comprehensive *in situ* and remote sensing measurements of the plasma, fields and energetic particles. Since the corona is essentially 3-D, these near-solar measurements are needed at all latitudes and over as wide a range of solar radii as feasible.

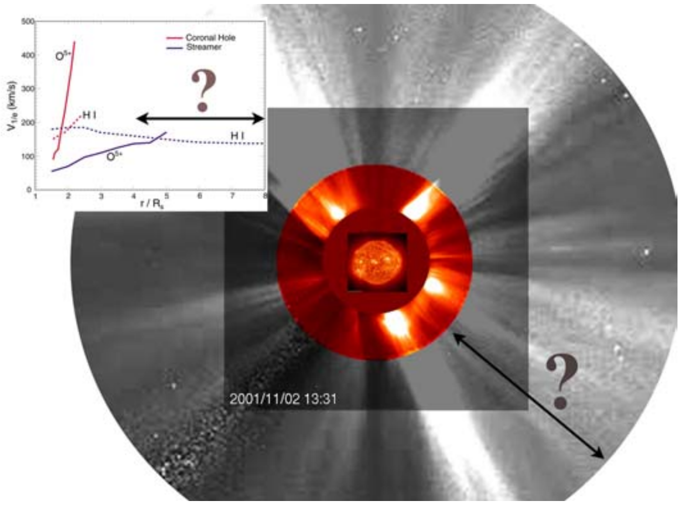


Figure 2.3 In the region inside 20 solar radii, the solar wind is sub-Alfvénic. Because of large pressures and differences in the particle populations, the evolution of solar disturbances is different from that further out. This region remains the last unexplored region of the inner heliosphere that is accessible with today's technology.

(c) Determine the evolution of the heliosphere on its largest scales.

Interplanetary missions in the past three decades have demonstrated that the global configuration of the heliosphere, from the Sun to almost 100AU, is drastically different at the minimum of solar activity compared to the maximum. The large-scale evolution of the solar magnetic field is manifested in the reversals of the Sun's magnetic polarity during each 22-year solar cycle. At solar minimum, fast solar wind from the polar coronal holes maps out into >2/3 of the total volume of the heliosphere. It interacts with the slow solar wind from equatorial latitudes, forming corotating interaction regions (CIRs) of compressed plasma, magnetic field and accelerated energetic particles. On the other hand, at solar maximum the slow solar wind emerges from almost all latitudes. Energetic particle events appear out to 5AU with comparably high intensities from the equator up to polar latitudes >60°. In the distant heliosphere (50-80 AU), during solar minimum there are 26-day recurrent compression regions in the plasma and magnetic field accompanied by increases in energetic particle intensities. These are the remnants of CIRs formed in the inner solar system. In dramatic contrast, during maximum each of the greatest active regions on the Sun produces a series of large solar flares and CMEs that appear a year or more later in the outer heliosphere as huge global merged interaction regions (GMIRs) of plasma, magnetic field, and energetic particles that take months to pass over an individual spacecraft. These great events can even produce episodes of 2-5 kHz radio emissions from the immense region beyond the termination shock.

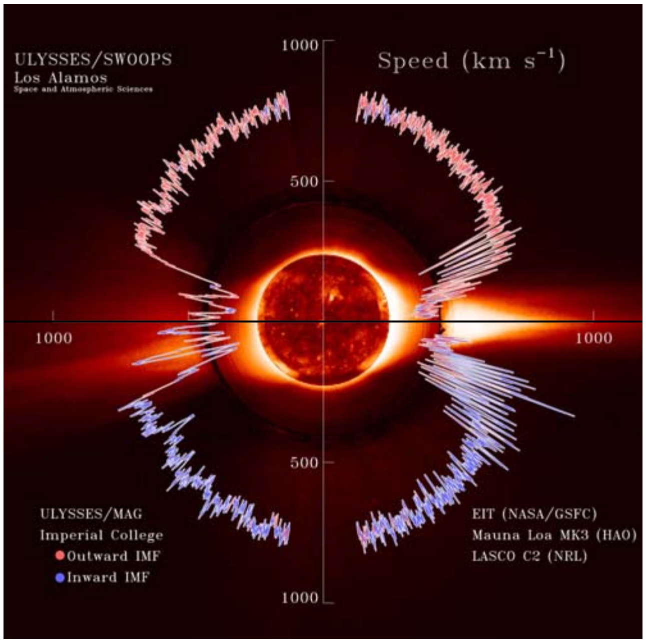


Figure 2.4 The variation in the solar wind speed with latitude observed by the Ulysses spacecraft demonstrates the large-scale structure of the heliosphere. A spatial or temporal interpretation of north-south asymmetries in the heliosphere depends on observations of the high latitude heliosphere over a significant time period.

The critical questions remaining are how the entire heliosphere evolves between the two extreme states and how the solar wind structure/dynamics and energetic particles co-evolve. The basic fact that the solar wind is supersonic (at least for the ions which carry the bulk of the mass and momentum) indicates that physical information describing the plasma propagates outward. Consequently, even though the interactions that form the structure of the outer heliosphere may be quite complex, a great deal of information can be inferred from *in situ* and remote sensing observations of the inner heliosphere (<5AU). Techniques are well established for imaging the solar atmosphere and corona across the electromagnetic spectrum (from the visible through hard x-rays). Outgoing shocks and CMEs can be tracked using "passive sounding" of interplanetary radio bursts. It is now time to extend these efforts to study the phenomena that occur at higher latitudes.

(d) Determine the interaction between the Sun and the galaxy.

Exploration of the interaction of the Sun with the local interstellar medium (LISM) is a voyage into the unknown and holds the promise for a wealth of scientific discovery. This immense structure is truly the outer frontier of the heliosphere in both the sense of matter and of knowledge. The study of the complex boundary itself is a uniquely valuable entry into the basic physics of "astrospheres" (the plasma and magnetic field envelopes of stars having a convective zone like our Sun). The heliospheric termination shock at ~100 AU is where the supersonic solar wind makes its transition to subsonic flow. The immense inner heliosheath region extends another ~100 AU beyond the termination shock. The interstellar plasma then has to deflect its 25 km/s flow around the inner heliosheath (due to the motion of the Sun through the LISM), thus forming the outer heliosheath that is yet another ~100 AU thick in the "upwind" direction. The intervening separatrix between the subsonic solar wind and the interstellar plasma is called the heliopause. Yet further away may be a heliospheric bow shock. Most neutral interstellar matter (thought to be ~10% ionized) flows almost undisturbed throughout this "interface" region. The bulk of the non-ionized gas streams into the inner heliosphere (<3 AU), before photo-ionization by solar extreme-ultraviolet emission or charge exchanged with the solar wind. These ionized atoms and molecules are entrained in the solar wind flow and become "interstellar pickup ions." Definitive numbers for the density, temperature, and bulk flow vector velocity of interstellar hydrogen and helium atoms can be obtained from measurements of the interstellar atoms and interstellar pickup ions in the heliosphere inside 3 AU.

Much about the Sun-galaxy interaction remains unknown. In particular, the properties of the LISM are currently based on estimates and assumptions. Astronomers have learned much about the average properties of the interstellar medium between the Sun and the nearest stars, but because these stars are many light years away, the average properties may differ vastly from those in the LISM. The use of average properties results in large uncertainties in the form and even existence of boundaries such as the heliospheric bow shock. Furthermore, critical factors such as the chemical and isotopic composition, plasma density and temperature, and ionization state, cannot be determined from average properties of the medium.

An entirely new level of information on the interface between the heliosphere and the LISM is required. An extension of the resolution of interstellar pickup ion measurements inside 5 AU to include isotopic ratios of critical astrophysical significance ($^{2}H/^{1}H$, $^{3}He/^{4}He$, $^{22}Ne/^{20}Ne$, etc.) is needed to make the first real determination of the chemical and isotopic composition of the LISM. These observations may also reveal ionized interstellar molecules. Neutral oxygen is particularly interesting because it provides a diagnostic of the heliospheric interface. Imaging of the outer boundaries ~100 AU away can also be done from orbits near 1 AU. Remote-sensing techniques such as energetic neutral atom (ENA) imaging of energetic protons and EUV (83.4 nm) imaging of oxygen ions near the termination shock and in the heliosheath should provide additional diagnostics of the interfaces with the galaxy. These images may contain information on the magnitude and direction of the local interstellar magnetic field. Surprisingly, the magnitude (and especially the direction) of the local interstellar magnetic field are among the least well known quantities determining the configuration of the Sun's astrosphere. Ultimately, *in situ* measurements at the heliospheric interface with the galaxy will be needed to truly understand the interaction.

(e) Differentiate among the dynamic magnetospheric responses to steady and non-steady drivers.

The magnetosphere responds dynamically to varying solar wind input. The response remains weak and limited to high-latitudes during northward interplanetary magnetic fields (IMF) when the coupling is least efficient, ranges through repeated cycles of substorm activity during intervals of prolonged southward IMF, and increases to giant storms when large-scale, geo-effective interplanetary disturbances, such as CMEs and high-speed streams strike the magnetosphere. Until recently, research centered on "directly-driven" responses to changing solar wind conditions. However, the complex response of the Earth's magnetosphere to relatively steady solar wind conditions is now receiving increasing attention. Even in the absence of solar wind variability, the Earth's magnetosphere exhibits dynamic "loading-unloading" responses that can be triggered by internal processes.

An inability to resolve spatial and temporal variations on a systems level compromises current efforts to differentiate between and understand the responses to time varying and constant solar wind conditions. Understanding the responses will require dedicated solar wind monitors and *in situ* measurements within the magnetotail and other magnetospheric regions at resolutions similar to those provided by current global MHD and kinetic simulations. Indeed, it is the predictions from these simulations that motivate the measurements. The multi-scale measurements at both fine and coarse scales will trace causality, establish linkages, and resolve how mass and energy flows from sources to sinks. Figure 2.5 shows some of the possible structures in the Earth's magnetotail that can be imaged. Magnetospheric imaging techniques, such as stereoscopic energetic neutral atom (ENA) imaging and radio tomography, will provide critical multi-scale measurements of plasma densities without the need to employ large numbers of spacecraft.

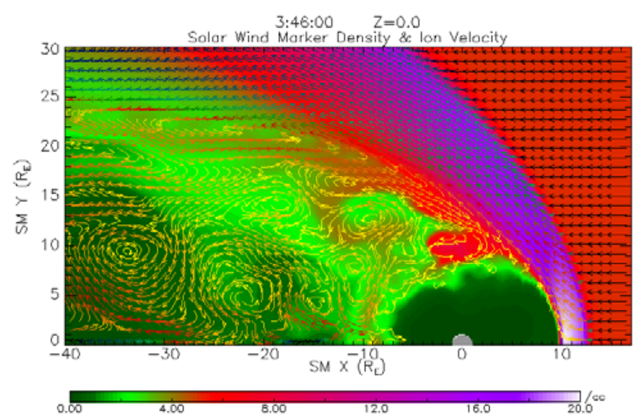


Figure 2.5 Some possible structures in the Earth's magnetotail. Density is color coded and arrows show flows.

In all cases, much of the energy released by magnetospheric activity is dissipated in the ionosphere and thermosphere. The coupling of this energy from high to low altitude is a subject of intense interest, since many of its most dramatic and practically important manifestations involve the low altitude end of the chain. Thus, global imaging of the ionosphere is a critical element in the tracing of energy released by magnetospheric activity.

Finally, differentiating among the dynamic magnetospheric responses to steady and non-steady solar drivers will require extensive monitoring of the solar wind while the multi-scale magnetospheric measurements are being made.

f) Explore the chain of action/reaction processes that regulate solar energy transfer into and through the coupled magnetosphere-ionosphere-atmosphere system.

The electrodynamic interactions between the ionospheric plasma and the thermospheric neutral gas process, redistribute, and dissipate the energy received from the magnetosphere. They also modify the energy exchange process itself through changes in electric conductivity and injection of ionospheric ions into the magnetosphere. While feedback to the magnetosphere is known to exist, its importance is not always clear. For example, it is not known what role the ionosphere may play in facilitating or quenching the development of a magnetic substorm, but the ionospheric plasma plays a critical role in intensifying the ring current during major magnetic storms.

The lower part of the Magnetosphere-Ionosphere-Atmosphere (MIA) system lies at the end of an extended chain of processes. These processes involve the conversion of solar energy that has passed through the MIA system into an upward flow of energy. This conversion is due primarily to wave motions and wave breaking of various types (latitude-seasonal variations, tides, planetary waves, gravity waves, etc.), which occur in the upper mesosphere and lower thermosphere. It is expected that changes in the structure of the neutral atmosphere will affect electrical conductivity in the ionosphere and dynamo action and thus be connected to the ionosphere and magnetosphere. Transport and chemistry of water vapor is another physical process that is dramatically affected by forcing from below. Through a poorly understood dusty plasma interaction, this water vapor is involved in the formation of noctilucent clouds over the summer polar cap. The presence of these clouds has important implications for global climate change, since they modify the Earth's albedo. Finally, tropospheric thunderstorm activity may influence the electrical and chemical properties of the middle and upper atmosphere through upward directed lightning discharges and upward conduction currents. Little is known about the upward flows of mass, energy and momentum but these final links in the coupling likely contain the processes ultimately responsible for modulating weather and climate.

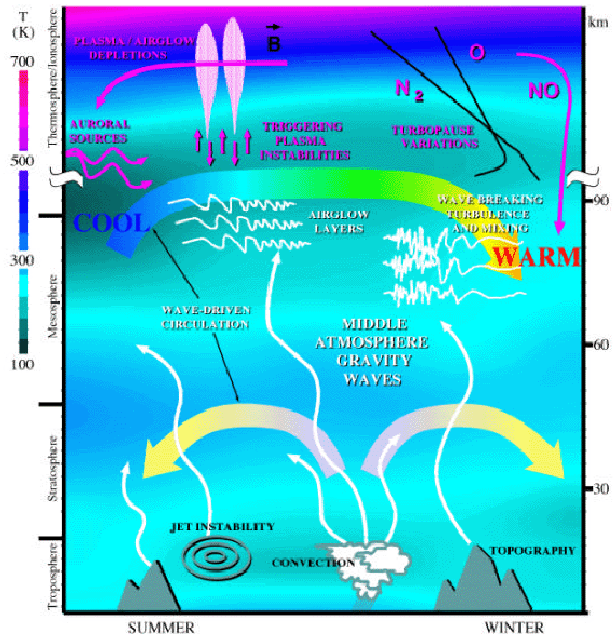


Figure 2.6 Latitude, height cross-section illustrating small-scale wave effects in the ionosphere and atmosphere. Small-scale waves are the fuel driving the summer to winter transport and dynamic coupling between the lower and upper atmosphere. Solar variability influences composition and transport rates. Quantifying the transport between the upper and lower atmosphere requires a better understanding of the relative forcing from above and below the regions.

The steady-state view of the linkage between processes that begin on the Sun and proceed outward/downward through the magnetosphere – ionosphere - atmosphere (MIA) system is slowly being replaced with a dynamical, collective view. There is a two-step path to this better understanding of the system. The first step is a detailed understanding of the dynamical behavior of the individual geospace elements is needed, in particular the ionosphere and atmosphere elements. The second step is an understanding of the interplay between components and feedback processes that dictate the collective global system response. The first step requires detailed observations (either *in situ* or imaging) targeted to a specific region in the

MIA system, and the second step requires combinations of observational techniques and vantage points that target the entire system.

2.2 Explore the fundamental physical processes of space plasma systems.

Most of the universe contains *plasma*, a gas of approximately equal concentrations of positive and negative charged particles. This state of matter behaves in fascinating and complex ways, quite unlike the behavior of neutral gas. Whereas the plasmas in the vastness of the universe are not directly accessible to humans, there are numerous and diverse cosmic "plasma laboratories" within the solar system that are accessible to space missions. Comparison of the near-Earth plasma laboratories with others in the solar system has underscored the amazing diversity among these systems. For example, the magnetic poles of Uranus lie close to the ecliptic plane, presenting a completely different magnetospheric configuration from that at Earth. Mercury's magnetosphere is small and its atmosphere is tenuous, while Jupiter and Saturn's magnetospheres are huge and the presence of a dense atmosphere, moons, rapid planetary rotation, and electrically charged dust and ice play significant, even dominant roles in magnetospheric dynamics.

Although there is a diversity of plasma systems, there is also a commonality of basic physical processes within these systems. Thus, nearby plasma laboratories provide an opportunity to explore the fundamental properties of plasmas that are directly applicable to many other regions of the universe. Three properties of plasmas that are especially important to understanding Sun-heliosphere-Earth connections also, not by coincidence, play a role in many important astrophysical phenomena. These plasma properties are the creation, support, and annihilation of electric and magnetic fields, the acceleration of charged particles to ultra-high energies, and the coupling across physical scales. All of these fundamental properties are related ultimately to the capability of a plasma to maintain electric and magnetic fields. The desire to discover the physics behind these fundamental properties of plasmas leads to three distinct research focus areas.

a) Discover the mechanisms for creation, annihilation, and reconnection of magnetic fields.

Motions in a plasma can generate, modify, and dissipate magnetic fields. Such dynamo action is one of the basic physical processes that determine the nature of the observable universe. This happens in stars, galaxies, the interior of planets, and protostellar clouds of tenuous gas. Most important for the Sun-Earth system are the generation of magnetic fields in the Sun and planets.

Simple models can reproduce cyclic solar magnetic fields in idealized simulations, but they have limited predictive value. Current theories suggest that the solar magnetic field is generated in the "tachocline," a region of strong radial shear between the convection zone of the Sun and the radiative interior, as illustrated in Figure 2.7. However, current models do not reproduce the large-scale structure of the convection zone or the tachocline, much less the detailed generation of magnetic flux and its eruption through the photosphere. The next generation of models requires further developments in computational methods and more complete knowledge of sub-photospheric conditions. Helioseismology holds great promise for detecting strong concentrations of magnetic flux in the convection zone and for measuring the large-scale motions within the convection zone.

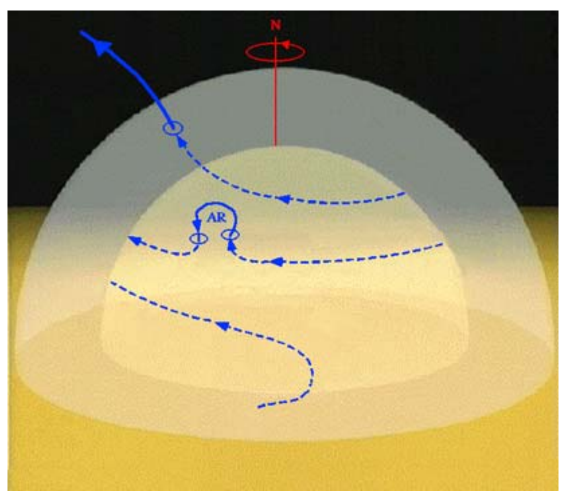


Figure 2.7 The tachocline field line shown in the figure is confined near the bottom of the solar convection zone and has been wrapped up by differential rotation. The deep intense flux tubes may develop instabilities that rise, emerging as active regions in the photosphere. Near the surface, small-scale fields may be generated by intense motions.

Dynamos in some planetary cores, including Earth's, also create magnetic field systems that have an important influence on solar wind interactions. The planetary community investigates these dynamos. However, similarities in the techniques used to study these fields provide cross-fertilization of ideas about the solar and planetary dynamos.

Magnetic field reconfiguration can result in the direct conversion of magnetic energy into plasma kinetic energy (i.e., particle acceleration, heating, and bulk flow) through a process known as magnetic reconnection or magnetic merging. This process is believed to accelerate particles in solar flares, at the Earth's magnetopause, and in the Earth's magnetotail. It is also probably fundamental to the mechanisms by which plasma is energized in the corona and solar wind and is a means for energy transfer in a variety of astrophysical systems. Despite the importance of this process, there is still no fundamental answer to the question: "how do magnetic fields undergo reconnection?" Clues to the answer to this question are found in understanding the stability of the reconnection process and which types of magnetic field configurations are conducive to the process.

Understanding the topology and stability of the magnetic field configuration is crucial for understanding reconnection. In the photosphere, for example, the process has been inferred from the merging and disappearance of myriads of small magnetic flux elements with opposite polarities. These small elements vary little with the 22-year solar cycle and likely result from a distributed near-surface dynamo sustained by small-scale convective motions. This small-scale dynamic field may be in part responsible for driving the solar wind. By imaging the Sun in higher spatial, temporal, and spectral resolution, the topology, physical conditions, and perhaps inferences of micro-instabilities in the reconnection regions will be determined. These improved observations will also advance the understanding of the regions of particle acceleration in solar flares, the photosphere in general, and processes operating in the solar corona.

Single-point and even multi-point measurements of reconnection occurring near Earth lack the global information on reconnection topology available with solar imaging. However, the ability to sample the reconnection region *in situ* provides the opportunity to directly determine micro-instabilities responsible for magnetic reconnection. These micro-instabilities act in the relatively small volume in space called the diffusion region, where electrons decouple from the magnetic field. The electron diffusion region has not been investigated because past *in situ* missions have lacked the proper instrumentation and the multi-point perspective to determine its properties. Furthermore, theory and particle simulations had not progressed to the point where predictions could be made about the nature of this region. Armed with specific predictions from theory, new, more detailed observations will be made to reveal the nature of this critical region in the magnetosphere.

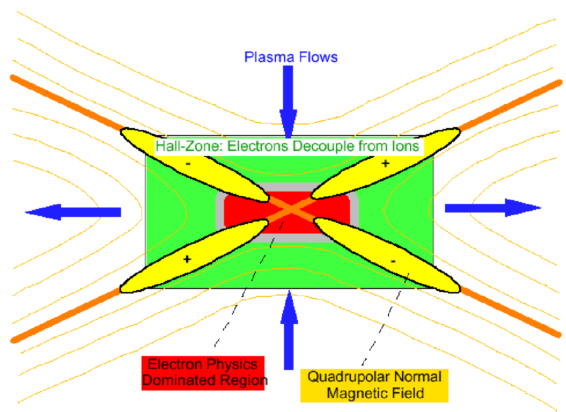


Figure 2.8 The structure and topology of magnetic fields that undergo magnetic reconnection. Magnetic reconnection is dominated by the physics in the very small (~100 km thick) region called the electron diffusion region. High-resolution, *in situ* measurements from a multi-spacecraft mission will reveal the nature of this energy transfer process.

b) Determine how charged particles are accelerated to enormous energies

Charged particles are accelerated in the solar atmosphere, interplanetary space, planetary magnetospheres, the interstellar medium and more-distant astrophysical objects. They exhibit energies ranging from just above the modest thermal energies of the ambient plasma to cosmic rays that enter the heliosphere with enormous energies exceeding 10^{20} eV. It is quite remarkable that energetic particle populations in diverse regions within the heliosphere display the same kind of distribution of number versus energy---a "power law" energy spectrum.

This remarkable property raises the question of how to accelerate a small fraction of the charged particles from the ambient plasma while creating a power law energy distribution that is not very sensitive to the parameters of the particular acceleration process or region of acceleration. Candidates include impulsive particle acceleration by inductive electric fields, resonant acceleration associated with the myriad periodic particle and field modes of a magnetized plasma, and Fermi acceleration during multiple reflection between two magnetic structures approaching each other. One important acceleration site is at collisionless shocks. They are generated throughout the heliosphere, from the solar corona to the termination shock at about 100 AU that marks the outermost limits of the solar wind. Coronal mass ejections are particularly effective drivers of transient shocks in the heliosphere, while the pervasive overtaking of low-latitude slow-speed solar wind by high-speed solar wind from coronal holes produces "corotating" forward/reverse shock pairs. *In situ* observations at all shocks reveal populations of energetic particles. Conversely, understanding the propagation of energetic particles from remote regions along magnetic fields allows inference of the acceleration processes within the region. An example of great interest currently is the population of "anomalous" cosmic rays (ACRs with energies ~100 MeV). Current theories ascribe these to "pickup ions" accelerated at the heliospheric termination shock, i.e., galactic gas atoms that are ionized while drifting though the heliosphere and then swept out to the boundary by the solar wind. This process is diagramed in Figure 2.9. Right now, the strongest observation-based information on the nature of the termination shock comes from inferences drawn from the comparison of acceleration and propagation theory with ACR observations. However energetic particles are also widely found where there are no shocks, e.g., in the trapped radiation of planetary magnetospheres, so other non-shock-associated acceleration mechanisms are required. There is considerable debate about how and even where particles are accelerated in solar flares, even though there are remote sensing of the acceleration process through the tell-tale radio, x-ray and gamma-ray emissions.

Both *in situ* and remote sensing measurements from spacecraft are necessary to determine the modes of acceleration and the transport of energetic particles. In planetary magnetospheres, the solar corona, and throughout the heliosphere, it is essential to go to unexplored regions and novel vantage points to gain this information. Coverage of the energetic particle and electromagnetic spectrum should be as wide as possible. Examples of important vantage points are the polar-regions of the Sun (at distances much closer than the 2.4 AU passes of Ulysses) and of a giant planet like Jupiter, out to the heliospheric boundary, and within the Earth's magnetosphere at high and low altitudes.

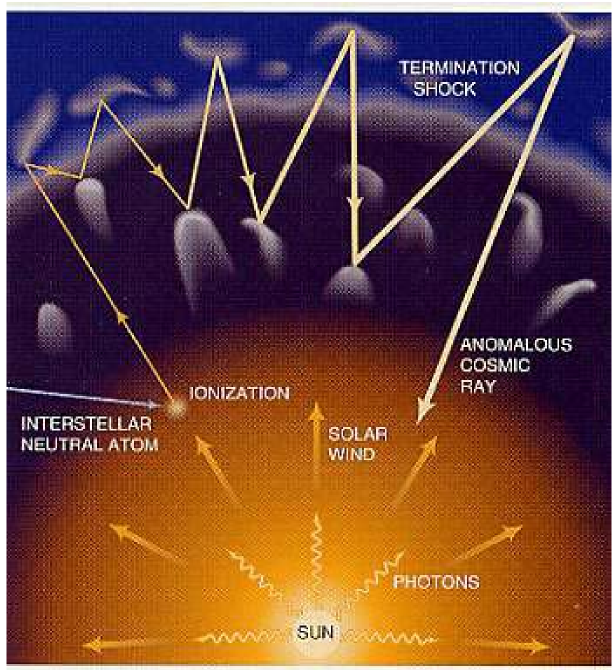


Figure 2.9 Anomalous cosmic rays are one of many examples of energetic particle production and transport. These energetic particles may be accelerated by ambient wave turbulence and by acceleration at the termination shock. By studying these and other energetic particle populations in other regions, the primary acceleration mechanism(s) will be revealed.

c) Understand how small-scale processes couple to large-scale dynamics.

Magnetic reconnection (discussed above in 2.2a) is an important example of small-scale processes that couple to large scales. The small-scale reconnection of magnetic fields in the solar corona can destabilize the magnetic field in an entire hemisphere, resulting in a CME. Similar small-scale to large-scale coupling attributed to the reconnection process occurs in the Earth's magnetotail. Progress on the understanding of annihilation of magnetic fields requires an understanding of relevant small-scale processes.

Another prime example of how small-scale processes affect global dynamics is the formation of narrow auroral arcs in the Earth's auroral zone (at latitudes above ~65°). Observations show that particles are accelerated by moving through localized parallel electric fields in these filamented structures. These narrow regions may be fast flow channels that extend deep into the Earth's magnetotail. The difficulty with current observations is that the highest time resolution measurements have been made from single spacecraft and have not resolved spatial and temporal processes. Furthermore, the detailed, *in situ* measurements have not been accompanied by similar resolution (~km scale length) imaging of the aurora. Significant progress in unraveling the contributions of these structures to large-scale dynamics and the time dependence of these structures requires high time resolution, multi-point *in situ* and imaging measurements in the auroral zone.

Turbulence is another very important multi-scale process. Turbulent processes transport particles and fields effectively, but are not well understood. Numerical simulations and laboratory experiments demonstrate that, in the presence of rotation or magnetic fields, turbulent motions create both small-scale and large-scale dissipative structures via "inverse cascades". Examples of this dissipative process are found in the small-scale magnetic interactions in the chromosphere and transition regions of the solar atmosphere and their possible coupling to the corona and solar wind. Further, the solar wind itself has been observed to evolve toward a fully MHD turbulent state as it propagates toward the magnetosphere. In the magnetosphere, thin boundary layers such as the magnetopause may be unstable to turbulent plasma processes (see Figure 2.10). Non-linear growth and saturation of these processes may lead to enhanced particle transport and heating. Finally, turbulence probably plays an important role in the Earth's magnetotail. Recent observations of current disruptions and bursty bulk flows and their correlation with large magnetic field fluctuations appear to have the stochastic (i.e., turbulent) properties.

Fundamental questions concerning turbulence remain unanswered. They include the role of fluid turbulence in transport across plasma boundary layers, the control of the onset of turbulence in thin current sheets, and the processes that drive micro-turbulence and its coupling to large-scale disturbances. Finally, it is not known how turbulence affects the mapping of magnetic fields and the predictability of plasma systems.

By its very nature, turbulence is a multi-scale process and therefore requires multi-point measurements. Multi-point *in situ* observations on a variety of spatial scales within the solar wind and magnetosphere can provide the information needed to characterize turbulence in these regions. Some questions, such as small-scale turbulence in the solar wind or local, turbulent transport across thin boundaries, may be answered using a small number of multi-point measurements, while others, such as small-scale to large-scale coupling in the solar wind or magnetosphere, will require a larger number of multipoint measurements with a variety of separation scales. While solar observations of turbulence cannot be made *in situ*, the multi-scale nature of solar turbulence can be investigated using multi-spectral imaging.

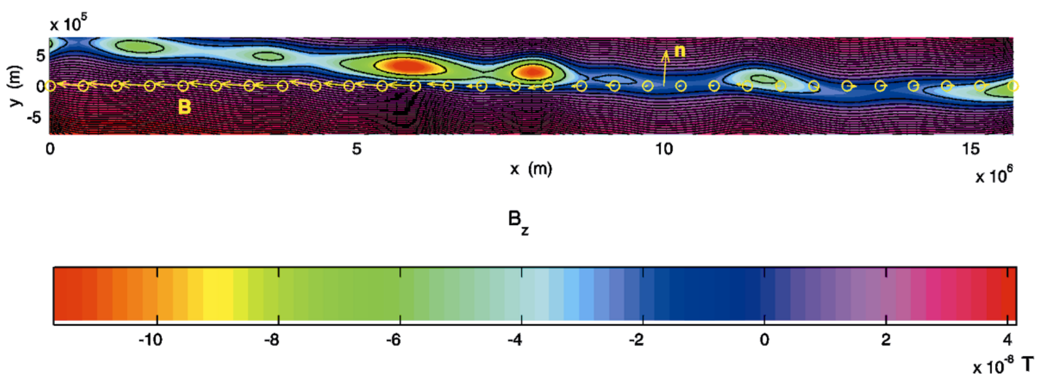


Figure 2.10 Turbulent magnetic field structures, or "islands" inferred from a single spacecraft trajectory through the Earth's magnetopause. The contours and colors represent the strength of the magnetic field. These island structures may grow to saturation and lead to enhanced particle transport.

d) Test the generality of processes in diverse plasma environments.

While the diversity of plasma systems often leads to new and different plasma discoveries, it also affords an opportunity to test the generality of processes that are thought to be fundamental. Tests can be performed using observations in the heliosphere, and the magnetospheres and ionospheres of the Earth and other planets.

The ubiquity of energetic particles or cosmic rays in the rarefied space plasmas provides an opportunity to test a fundamental plasma process in diverse plasma environments. The importance of energetic particles in plasma environments ranges from minimal to significant. The properties of a plasma where energetic particles play a significant role are poorly understood. Detailed energetic particle measurements proceeding from the inner heliosphere and near strong and weak shock waves, to remote observations of regions such as the solar wind termination and interstellar shocks provide a range of measurements that allow determination of the progressive importance of energetic particles in plasmas.

The magnetospheric substorm appears to be a fundamental dynamical mode of Earth's magnetosphere. If this is the case, then this process of magnetic flux conversion probably occurs in other planetary magnetospheres. Scant evidence of substorm-like phenomena exist from observations in the magnetospheres of Mercury and Jupiter. While the substorm (or something very much like it) appears likely to be a feature of planetary magnetospheres in general, it is not understood how this systematic behavior operates so similarly in such vastly different planetary conditions and environments. *In situ* measurements at other planets similar to those available at Earth are needed to answer this question.

An important test of cross-scale coupling and its effects in diverse plasma environments is the electric forcing between different plasmas connected by a magnetic field. At Earth, this process occurs in several regions including the auroral zone. An ideal environment for testing the theories about magnetic field forcing and M-I coupling is Jupiter. Jupiter has the most powerful aurora in the solar system. It is driven by the breakdown of magnetospheric rotation associated with the shedding of angular momentum from the central body to the surrounding nebula by means of magnetic fields and field-aligned currents. It is not known why these field-aligned currents are so highly structured in space and time, whether this structuring is a fundamental aspect of momentum transfer, how the field-aligned impedance is established, and what effect this impedance has on the forcing that occurs between the magnetosphere and ionosphere. Answers to these questions require a detailed comparison of the auroral generation mechanisms at Earth and Jupiter obtained from a combination of imaging and *in situ* measurements at both planets.

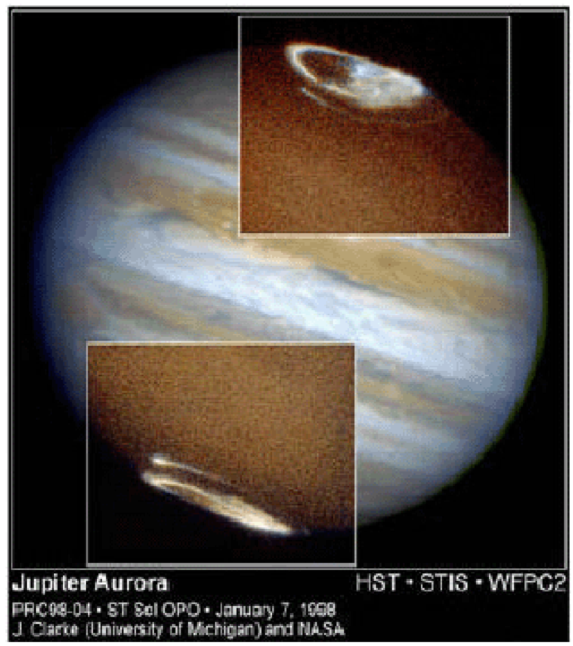


Figure 2.11 The Jovian aurora is the most powerful in the solar system. The aurora results from the shedding of very small amounts of the planet's angular momentum. Study of the fundamental process of auroral formation will be possible when combined imaging and *in situ* measurements of the Jupiter aurora become available.

Finally, the phenomena associated with dusty plasmas are important in a variety of plasma environments such as in the Earth's upper mesosphere, comets, planetary rings, and in interstellar space. The dust provides a sink for plasma and, when charged, affects instabilities in the plasma. One place where the effects of dust in a plasma can be studied is in the mesosphere. Here, the physics of dusty plasmas involves plasma instabilities and polar mesospheric clouds, with dust provided by oblation of meteoroids. The nature of the chemical, dynamical, and plasma processes leading to a variety of phenomena in this region are not well established. Answers require *in situ* measurements of the plasma and neutral gas (including composition) in the region.

2.3 Define the origins and societal impacts of solar variability in the Sun-Earth connection.

Human exploration of space and increasing reliance on space technology drive the need to determine the origins and societal impacts of solar variability. Societal impacts of interest include radiation doses on spacecraft, astronauts, and passengers and crew in high-altitude aircraft; solar induced effects on navigation systems, communication signal paths, and ground electrical currents; and changes in atmospheric structure, chemistry, and climate.

The understanding of the Sun-Earth system has progressed to the point where solar phenomena can often be observationally linked to changes in the heliosphere and in the Earth's magnetosphere, ionosphere, and atmosphere. It is now necessary to develop a more complete understanding of the processes in the Sun-Earth system that lead to specific societal impacts. This system-wide understanding will start with the underlying causes of solar variability, progress through the heliospheric changes to this solar variability, and end with the coupling of this variability to the Earth's magnetosphere, ionosphere, and atmosphere. The next step will be to forecast solar variability and the corresponding magnetospheric and ionospheric responses in the same manner as current weather and long-term climate forecasts.

(a) Develop the capability to predict solar activity and its consequences in space.

Solar activity, as reflected in the sunspot cycle, flares, coronal mass ejections, and changing solar emissions over the solar cycle, is the starting point for defining societal impacts. Phenomena that affect the Earth originate beneath the solar surface, but are often triggered in the solar atmosphere. Advances in helioseismology and simultaneous imaging of the 3-D evolving solar atmosphere make it possible to develop a firm understanding of the solar activity that most influences geospace.

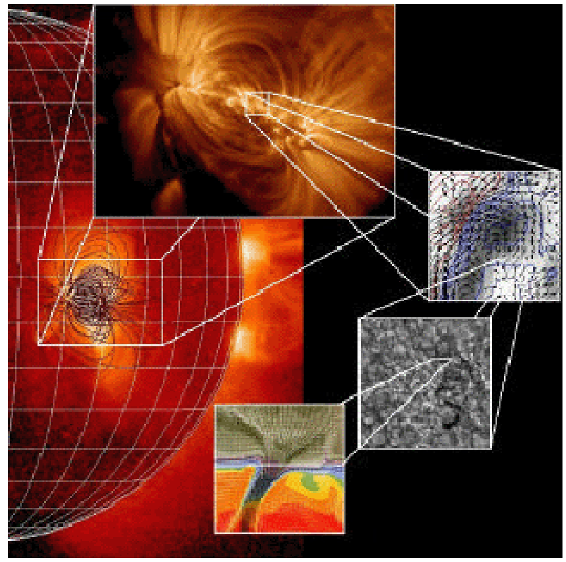
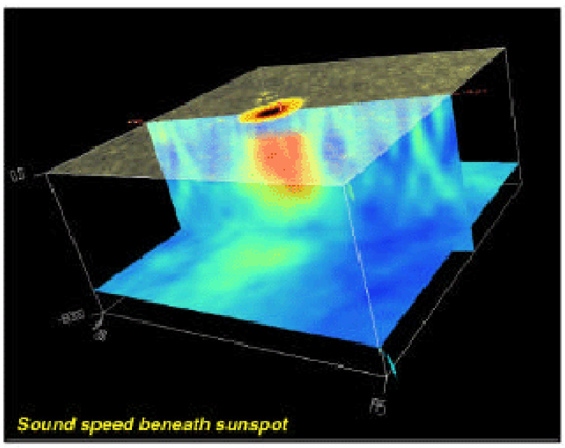


Figure 2.12 A series of images showing an active region, overlying loops, a vector magnetogram of an active region, granulation, and finally a high-resolution model of the magnetic transition region overlying a granule. Evolution on various scales leads to reconnection. Reconnection leads to heating seen in the magnetic loops and also leads to flares.

The birth and evolution of sunspots, active regions, and complexes of activity can be studied using helioseismology. Figure 2.12 reveals a snapshot of the evolving subsurface structure associated with the magnetic field beneath a sunspot. Observations have shown that once an active region emerges, there is a high probability that additional flux eruptions will occur nearby. Current thinking suggests that the flux emerging in active regions originates in the tachocline, but that the photospheric distribution of flux requires no long-term connection to flux below the surface. The critical element in this process is the timing of the weakening, or complete disconnection, of the link between the active region flux and the deeper ropes. This timing needs to be studied by developing uninterrupted sound-speed and flow maps under the visible surface of the Sun combined with surface magnetograms. High-resolution helioseismology will determine if active regions disconnect rapidly from sub-surface flux and will establish the feasibility of using helioseismology to predict active region emergence and the formation of long-lived complexes of solar activity.

Magnetic field reconfigurations release stored solar energy into the heliosphere as radiation, plasma flows, and energetic particles that sometimes impact Earth. Establishing the details of processes like the reconfiguration of magnetic flux in supergranules or the eruption of sigmoid magnetic field configurations within the corona into CMEs will help identify the sources of the solar wind, predict the occurrence of transient events such coronal mass ejections, flares, and solar energetic particle events, and determine how they propagate through the heliosphere. To address these questions, accurate high-resolution measurements of the vector magnetic field at the Sun over the wide range of spatial scales illustrated in Figure 2.13 will be needed in conjunction with other remote observations and *in situ* plasma, fields, energetic particle, and composition observations of the solar wind.



Sunspot data from MDI High Resolution, 18 June 1998

Figure 2.13 The magnetic structure below a sunspot is revealed in this plot of sound speed derived using helioseismology. Three planes are presented. The top shows and image of the sunspot with a dark central umbra. The second is a vertical cut (to a depth of 24,000 km) showing areas of faster sound speed as red and slower as blue. The third (bottom) is a horizontal cut showing the horizontal variation of sound speed over a 150,000 square km.

(b) Develop an understanding of the evolution of solar disturbances, how they propagate through the heliosphere, and affect the Earth.

Following their creation at the Sun, heliospheric structures, such as CMEs and co-rotating interacting regions (CIRs) evolve and are modified as they travel outward through the heliosphere. Propagating heliospheric structures can generate strong shock waves that strike the magnetosphere and accelerate energetic particles that enter the Earth's radiation environment. As they move beyond 1 AU some of these disturbances merge to create massive global merged interaction regions (GMIRs) that shield the Earth by modulating galactic and anomalous cosmic rays.

Given the sparseness of heliospheric spacecraft, most *in situ* observations of heliospheric disturbances have been 1-D. However "passive sounding" of CMEs from a distance, using naturally occurring radio emission generated by co-traveling populations of suprathermal electrons (~1-10 keV), has been used to trace the motion of the CMEs out into the heliosphere. Observations of the propagation and development of shocks near 1 AU have been shown to agree reasonably well with simple shock theory, but substantial research is needed to understand how the large-scale magnetic field, plasma flows, and turbulence properties vary throughout the three-dimensional heliosphere.

To unravel the evolution of inherently three-dimensional structures, multiple spacecraft observations will be necessary. Multi-point observations inside Earth's orbit, in conjunction with global imaging of the corona, and remote sensing of the inner heliosphere will help the understanding of the 3-D changes in CMEs as they propagate toward Earth and will help relate these changes back to their solar origin.

(c) Develop the capability to specify and predict changes to the radiation environment.

The understanding of magnetospheric dynamics underwent a revolution following March 1991 CRRES satellite observations. These observations indicating that an entirely new belt of >25 MeV electrons was produced in the magnetosphere in a matter of minutes. Additional observations have now shown that the radiation belts are highly structured and highly dynamic, exhibiting variability on time scales of minutes, days, season, and solar cycle (see Figure 2.14). At the same time, their impact on a technology-based society was increasing with every new satellite system placed into Earth orbit.

Although it is known that solar particle events provide a source population for the radiation belt enhancements and that these enhancements occur in association with high-speed solar wind streams and shock compressions of the magnetosphere, much work is still required to clearly define the physical processes that link these phenomena. Because radiation belt enhancements can occur on time scales shorter than spacecraft orbital periods (typically > 12 h), multiple spacecraft measurements are needed to define the dynamics of the belts.

Radiation belt losses occur through a combination of collisions with cold plasma, interaction with plasma waves, (both generated by magnetospheric processes and by tropospheric lightning), by scattering in magnetospheric current sheets and by drifts out of the dayside magnetopause during compressions (called magnetopause shadowing) and by adiabatic energy changes in response to large-scale magnetic field disturbances. The coupling to the ring current (whose strength and dynamics are influenced by outflows and electrodynamic coupling with the ionosphere-atmosphere system) and to propagating plasma waves from tropospheric lightning means that a complete understanding of the radiation belt structure and dynamics requires treating the ionosphere-thermosphere, radiation belts, inner magnetosphere, and the heliospheric input as an integrated system. This in turn requires simultaneous multipoint measurements of radiation belt and ring current particles as well as the electric and magnetic fields in the various regions. Time dependent radial profiles of relevant quantities must be obtained in order to differentiate among various physical mechanisms such as radial diffusion vs. localized acceleration. All of these measurements must be placed into context with input from the Sun (both photon and particle input) and the response of the ionosphere/atmosphere.

The true test of physical understanding lies in the development of new computational and empirical models of the radiation belts. These next generation models must be based on improved physics and assimilate observations in order to enable a future space weather capability, these models will need to be time-dependent and data-driven. They must also apply over sufficiently long time scales to enable reliable and cost-effective spacecraft design.

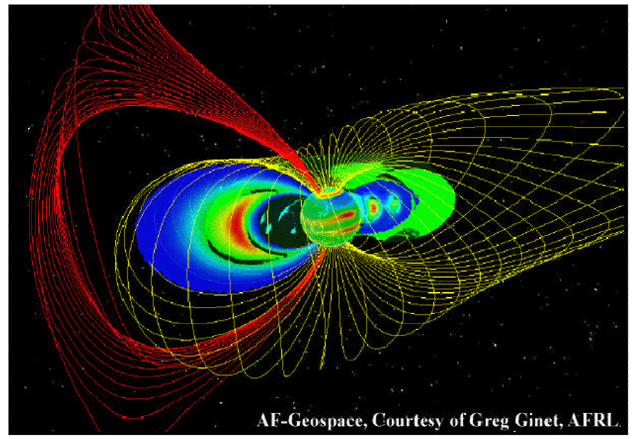


Figure 2.14 The energetic electron radiation environment around the Earth is generally structured into an inner and outer belt clearly seen in cross-section on the left-hand side of the figure. During high-speed streams and/or solar wind disturbances the belts can intensify and move closer to Earth, and the slot region separating the belts can temporarily fill. Occasionally transient, shorter-lived belts (depicted by the small enhancement between the inner and outer belts on the right-hand side) are generated during impulsive events like solar wind shocks or solar particle events. The auroral oval appears at high latitudes on the Earth and maps along field lines to larger radial distances than the radiation belts. Also depicted in two-bands on either side of the equator are equatorial arcs.

(d) Develop an understanding of the upper atmosphere and ionosphere response to solar forcing and coupling from the lower atmosphere.

The highly variable space weather phenomena that occur within the ionosphere and atmosphere represent the most significant threats to human endeavor. This variability is driven by changing solar x-ray, far ultraviolet and extreme ultraviolet (FUV and EUV) radiation as well as by electrodynamic coupling, heat and particle fluxes from the magnetosphere. Gravity waves and tides that propagate into the upper atmosphere can also appreciably modify the basic state and structure of the ionosphere-atmosphere system on a variety of scales. This influence from below is the least understood of all the effects on the ionosphere. Ionospheric structures that develop in response to these inputs span a range of scales from centimeters to 1000 kilometers.

Over the next decade, a revolutionary new view is expected of the dynamical behavior of the magnetosphere-ionosphere-atmosphere (MIA) system as it responds to energy inputs from the Sun and lower atmosphere. This understanding of the "systems" response will follow directly from new multi-point and remote-sensing observational approaches that create snapshots of large regions of the system. The new view will be instrumental in enabling detailed understanding of space weather disturbances in the ionosphere-upper atmosphere system that interrupt communications and cause errors in surveying and navigation systems, introduce background variability within various space-based surveillance systems, generate ground induced currents that interrupt power grids and erode pipelines, and impact satellite lifetimes and satellite tracking capabilities by increasing drag on low Earth orbiting spacecraft.

Of these effects, a highly-focused investigation into the generation of ionospheric irregularities that degrade communications and navigation systems is considered to be a top priority, both because of the severity of the societal consequences and the high probability that major scientific advances in physical understanding and predictive capabilities will result from this effort. At high-latitudes, investigations of irregularities continue through polar-orbiting missions and, at low latitudes, global characterization begins through new observations from space. At mid latitudes, irregularities have a dramatic impact on navigation systems. Global characterization of the ionospheric density and structure by GPS receivers and simultaneous imaging of the inner magnetospheric plasma populations have recently established the association of these irregularities with stormtime changes in the inner magnetosphere. As plasma density fronts move through the mid-latitude ionosphere during these times, steep plasma density gradients play havoc with technologies like the global positioning system (GPS), and ionospheric irregularities disrupt communication systems. As much as 120 m errors in single-frequency GPS positions have been observed in association with this dramatic redistribution of ionospheric plasma.

High levels of geomagnetic activity are known to produce large time-dependent disturbances in the ionosphere and thermosphere that extend to mid-latitudes from both equatorward and poleward sources. Enhancements linked to the poleward transport of equatorial plasma occur during the growth phases of geomagnetic storms. These intrusions of high-density plasma (shown in Figure 2.15) are associated with distorted stormtime electric field patterns resulting from coupling between the partial ring current and ionosphere. During the recovery phase, depletions in the ionospheric plasma appear at mid latitudes. Strong and persistent heating in the auroral oval results in upwelling of the neutral atmosphere in this region with increased density at high altitude, then advection to lower latitudes and downwelling. Associated composition changes in the neutral atmosphere combined with enhanced flows result in ionospheric density depletions that can persist for more than a day. Modeling these mid latitude phenomena is extremely difficult.

The role of upward propagating gravity waves and tides in triggering and generating equatorial irregularities is as important as the more familiar "downward" propagating effects. Large-scale bubbles with dimensions of several thousand km along the magnetic field direction and east-west dimensions of several hundred kilometers appear in the equatorial ionosphere at local sunset. Smaller scale irregularity structures (tens of km to tens of meters) develop through a hierarchy of instability mechanisms. The trigger mechanisms that cause the extreme day-to-day variability have yet to be isolated and may involve gravity waves in the neutral atmosphere, disturbed stormtime electric fields and/or neutral wind patterns. The mechanisms producing day-to-day variability and the longitudinal extent of equatorial irregularities on any given evening remain outstanding problems.

Identifying the mechanisms driving instabilities in MIA coupling will not only require *in situ* measurements of the irregularity spectra, wave characteristics, electric fields, neutral winds, and plasma density gradients in the ionosphere and thermosphere, but also imaging and wave climatology. Airglow imaging of mid-latitude regions will provide the dayside O/N_2 ratios and nightside line-of-sight electron densities needed for the global context. ENA imaging of the ring current structure and dynamics from a high altitude polar platform will provide further details concerning coupling with the mid-latitude ionosphere. Simultaneous FUV images will define is the global magnetospheric dynamics and indicate high-latitude composition disturbances spreading to mid latitudes.

Finally, because the role of upper atmospheric waves in triggering instabilities is unknown but thought to be significant, a global climatology of their occurrence patterns will prove essential. The successful development of global circulation models that specify the state and evolution of physical quantities over large regions will prove the ultimate test of our understanding.

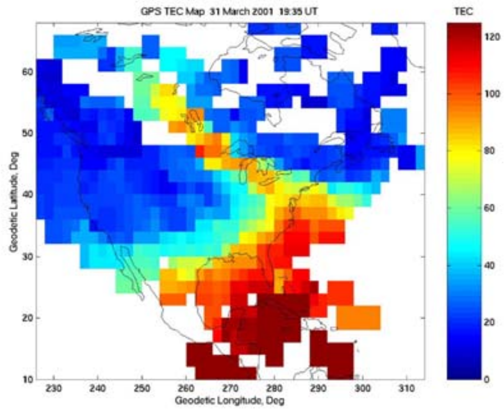


Figure 2.15 GPS map of total electron content in the ionosphere over the United States showing the intrusion of high density low-latitude plasma into midlatitudes as it moves along distorted magnetic stormtime convection patterns toward the polar regions. Steep plasma density gradients cause large position errors in single-frequency GPS navigation systems. The complexity of coupling and feedbacks between geospace regions involved in producing this phenomena makes a true predictive capability difficult to achieve.

(e) Understand the connection between solar variability, the Earth's upper atmosphere, and global change.

The upper atmosphere (altitudes above ~90 km) is important for climate change studies both as an active participant in modulating climate and as a sensitive (and thus early) indicator of possible changes already underway. These changes may not necessarily be induced from anthropogenic sources. For example, a connection between the global mean temperature and the solar activity cycle has been suggested on the basis of statistical evidence. However, observed changes in the solar constant over a solar cycle are too small to be the source of this relationship. Other processes that may provide the basis for such a correlation include: changes in the spectral irradiance which drive the chemistry and dynamics of the middle atmosphere (and have been shown by modeling studies to influence the dynamics of the troposphere), the solar cycle modulation of cloud nucleation through cosmic ray intensity, the impact of energetic particle precipitation on ozone chemistry, and solar cycle variations in the global electric circuit. Figure 2.16 illustrates the dramatic natural variability in the production and transport of Nitric Oxide (NO) at 110 km in quiet times and in response to particle precipitation during a magnetic storm and a solar particle event. NO acts as a thermostat, increasing atmospheric cooling and disrupting mesospheric ozone as it diffuses to low altitudes in the polar regions.

The strong impact of radiative forcing on the atmospheric structure in the upper atmosphere is the basis for its value as an excellent indicator of atmospheric change. Enhancements in anthropogenic trace gases such as carbon dioxide or methane (which increase the radiative forcing) will produce an unambiguous signature – not confused by the complexity of cloud feedbacks and competing effects (due to aerosols) that occur in the troposphere. Possible signs of global climate change include noctilucent clouds formation. These clouds are a high-altitude polar region phenomena and are occurring more frequently with sightings now at lower latitudes. Since these clouds require temperatures below 140^{o} K to form, the equatorward advance of cloud sightings are part of a growing body of information that indicates the upper atmosphere has cooled over the past 20-50 years. This cooling is thought to be the result of a warming trend at lower altitudes, possibly due to anthropogenic influences. The residual circulation (meridional) cell coupling the troposphere to the lower thermosphere upwells in the summer, convects from the summer to the winter pole in the mesosphere, and downwells to the lower atmosphere in the polar night. The fuel for this cell is predominantly small-scale waves coupling from the lower atmosphere into the mesosphere. Variation in the fuel (waves) will affect the rate at which the cell exchanges composition between the regions as well as the cooling rate in the summer mesosphere.

The distinct contrast between Sun-induced and anthropogenic changes in the upper atmosphere and the implications for changes in these regions underscore the importance for separating the possible forcings. Furthermore, the distinct changes in the upper atmosphere that have occurred over the past 20-30 years indicate the need to define the current state of the upper atmosphere structure and dynamics for comparison with measurements made in the near and distant future.

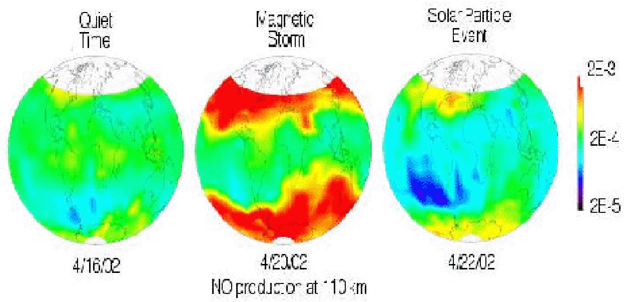


Figure 2.16 Global composite of NO production at 110 km altitude, comparing quiet time to magnetic storm and solar particle event times. The NO is produced by collisions of high-energy charged particles with the neutral atmosphere. There is a significant high latitude source region and diffusion from higher to lower latitudes during disturbed times. NO acts as a thermostat, increasing the cooling of the neutral atmosphere following a magnetic storm. Major questions remain as to how deep magnetic storm effects penetrate into the upper atmosphere. NO diffuses to low altitudes in the polar regions and impacts ozone chemistry in the mesosphere. Only when natural variability is understood can the impact of anthropogenic sources be identified.

(f) Develop the capability to predict the long-term climate of space.

Life on Earth depends on the long-term climate in space as well as the long-term stability of the Earth's atmosphere. The climate of space is the ensemble of transient heliospheric disturbances, modulation of the solar output due to the rotation of the Sun, variations in solar activity associated with the 22-year solar cycle, other, longer and less well understood cycles in solar activity, and very long-term variations in the interstellar medium. A multitude of physical processes couple this space climate to the Earth's climate. This is in addition to those processes within the Earth's atmosphere that contribute to climate variability. Understanding space climate and separating its contribution from internal contributions to the Earth's climate are key elements to determining the destiny of life in the solar system.

To forecast space climate will require an understanding of the behavior of many aspects of the Sun through time, i.e., much broader than simply the Sun's radiation output. Obviously, such understanding will not come directly from study of the Sun over relatively short periods (several solar cycles). However, there is another important way to study the evolution of the Sun and its effect on space climate. Studying other stars like the Sun will provide a context for understanding where the Sun lies in the ensemble of all possible states it might take during its lifetime on the main sequence of evolution. This study holds the best promise for determining the possibility of the Sun becoming radically different from its current state.

A second input to the long-term prediction of space climate is the role of the interstellar medium. Some historic climate variations appear to show twice the frequency of the rotation of the galaxy, which would plausibly be coupled to climate through the interstellar medium. Understanding the implications of the interstellar medium on space climate requires first an understanding of the current properties of the Local Interstellar Medium (i.e., its density, temperature, magnetic field, cosmic ray distribution, dust properties, composition, and ionization state). The next step in understanding the role of the interstellar medium on space climate is to conduct remote sensing observations to compare the properties of the medium directly upstream of the Sun's velocity vector in the galaxy with the properties further away. Such measurements provide a forecast of the impending conditions in the interstellar medium.

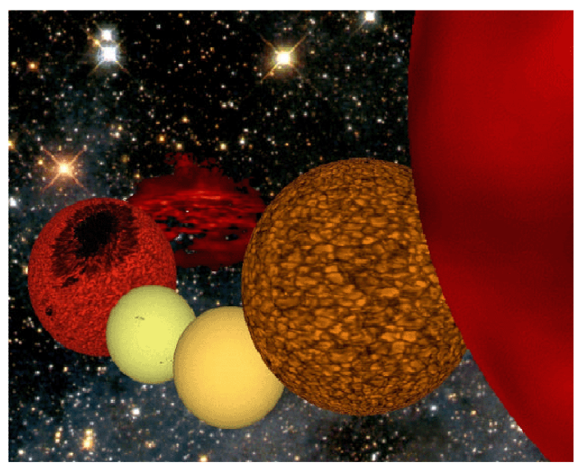


Figure 2.17 The Sun's evolution over ~10 billion years, from a protostellar disk to the magnetically active Sun of today to a red giant. Later in the Sun's life, magnetic activity will likely decrease, well before the red giant stage. This can be studied by observing appropriate solar analogs. Understanding the decay of magnetic activity is important for determining the implications on the Earth's climate.

2.4 Additional Science Objectives

The breadth of the SEC Division science extends beyond the three primary science objectives. SEC missions directly address many other Space Science Enterprise science objectives through connections to astrophysics, astrobiology, and planetary physics. The following sections describe Research Focus Areas that have direct application to other Space Science Enterprise science objectives.

2.4.1 Understand the structure of the universe, from its earliest beginnings to its ultimate fate.

(a) Develop helioseismological constraints on the structure of the Sun as a star.

Solar activity has its origin in a dynamo that generates and processes magnetic field in an interaction of rotation and convection. Much of the magnetic field involved in the dynamo is thought to be generated in, or at least stored in, the layer immediately below the convective envelope; convection pumps magnetic field into these layers as it overshoots the boundary, and that field is subsequently stretched in the rotational shear in this layer (also known as the tachocline). This layer is currently studied by helioseismic techniques from a single, ecliptic vantage point. This vantage point allows only limited depth and latitude resolution and longitudinal structure is poorly tracked. By adding a second vantage point well away from the Earth, the analysis of combined data from the two observatories allows unambiguous derivation of information along all ray paths accessible to the observatories. A mission out of the ecliptic that would reach at least mid-latitudes (or even a polar vantage point) will allow detailed exploration of the seat of the dynamo at a few optimal phases in the orbit and mapping of the flows within the convective envelope. A dedicated mission to a point some 120 degrees trailing the Earth in its orbit would allow exploration of the changes in the tachocline that are induced by the Sun's processes driving solar activity. That mission would also provide imaging of the deep interior to explore the magnitude of the core's magnetic field (likely related to neutrino flavor oscillations), the importance of gravitational settling of relatively heavy elements in the core, and the core's rotation rate.

2.4.2 Learn how galaxies, stars, and planets form, interact, and evolve.

(a) Determine the roles magnetic dynamos and angular momentum loss play in how stars and planetary systems form and evolve.

Stars form (most frequently in pairs) from cool molecular clouds that collapse under their own gravity. The final collapse into a star is hampered by even the smallest amount of rotation within these huge clouds. As the cloud contracts, material spins up more and more rapidly. Unless much of the rotational energy is lost from the center of the cloud, centrifugal forces would prohibit the ultimate formation of a star. Magnetic fields offer one efficient mechanism that may explain the dissipation of rotational energy and the associated transport of angular momentum in this phase. Better understanding is needed of the astrophysical dynamo processes that generate these fields. With this better understanding, models can be produced that provide information on what fraction of rotational energy is destroyed or removed from the cloud, and what fraction remains available for the formation of a planetary system or a stellar binary companion (or both). Knowledge about the dynamo process in stars is obtained by detailed studies of the interior dynamics and dynamo of the Sun and very-high-resolution imaging of other stars and star forming regions. This knowledge is also obtained by studying magnetized planets. Among the magnetized planets, Jupiter is the closest analog to this astrophysical application. Its magnetosphere and intense aurora are powered primarily by planetary rotation, rather than through the energy in the solar wind. Through detailed *in situ* particle and field measurements and imaging of the aurora, a link will be estabilished between magnetosphere-ionosphere coupling processes and astrophysical magnetic torquing processes.

(b) Determine the current state of the local interstellar medium and its implications for galactic evolution.

Until recently, the only direct samples of matter from beyond our solar system came from galactic cosmic rays. However, the properties of the Local Interstellar Medium (LISM) -- its density, temperature, magnetic field, cosmic ray distribution, dust properties, composition, and ionization states – can be determined through *in situ* measurements and by sampling its neutral components that penetrate into the heliosphere. These measurements hold essential clues to galactic history and would help to determine the properties of the Local Interstellar Cloud in which the heliosphere resides. For example, isotopic and elemental abundances in the LISM reflect the current state of matter in the galaxy, whereas the isotopic and elemental abundances from the material in the solar system reflect the state of matter during the solar system's formation. Over time, the interstellar medium becomes increasingly enriched in heavy elements released from stars through stellar winds, supernovae, and novae. The rate of enrichment is a direct measure of star formation and the nucleosynthetic processes occurring in the galaxy. Measurements of this medium follow a logical progression as technology develops. Precursory missions take advantage of the penetration of the interstellar medium into the heliosphere (neutral interstellar atoms penetrate to within ~4 AU, become ionized, picked up by the solar wind, and are observed as so-called pickup ions). High-resolution measurements of these pick up ions and the neutral atoms themselves are needed to determine the composition of the LISM. These precursor missions set the stage for properly instrumented spacecraft to break through heliospheric boundaries and explore the medium that pervades the galaxy.

(c) Determine the interaction between the interstellar medium and the astrospheres of the Sun and other Stars

The interaction between the Sun (or other stars) and the interstellar medium results in well-defined and important boundaries --a bow shock, heliopause and termination shock that bounds the heliosphere (the Sun's astrosphere). Astrospheres are in fact common in the galaxy. However the detailed properties of the Sun's astrosphere are not well understood. For example, the location of the termination shock has been revised considerably in recent years as the search for it continues with the Voyager mission. Measurements of anomalous cosmic rays (and galactic cosmic rays), low frequency radio emissions, high-resolution EUV imaging, and energetic neutral atom imaging are needed to remotely probe heliospheric boundaries. These measurements provide information on the properties of the LISM and the changing interaction of the LISM with the heliosphere. Remote sensing of the heliospheric boundaries provide the precursory preparation for proper instrumentation of a true interstellar explorer spacecraft.

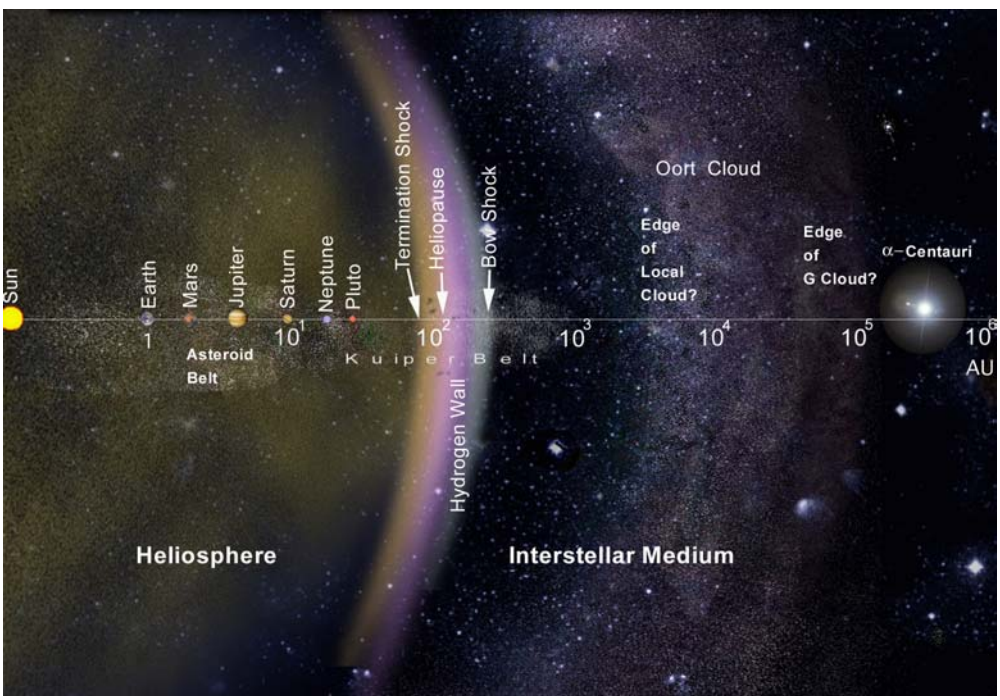


Figure 2.18 Outer boundaries of the heliosphere and LISM on a logarithmic scale. The exact locations of these boundaries are poorly known because conditions in the local interstellar medium are poorly known.

2.4.3 Understand the formation and evolution of the solar system and Earth within it.

a) Explore the role of planetary magnetic shielding in establishing diverse atmospheres of Earth, Venus, and Mars.

Recent observations show that the Earth's atmosphere is not a passive absorber of energized magnetospheric plasma that precipitates into the upper atmosphere during solar storms. In response to power input into the upper atmosphere that can measure in the hundreds of gigawatts during a typical magnetic storm, the Earth loses approximately 100 tons of oxygen from its upper atmosphere at high latitudes. While this oxygen loss is insignificant even on geologic timescales, its mechanism is nevertheless the only effective oxygen loss mechanism at Earth. Conditions at Mars and Venus are significantly different than those at Earth because of their lack of a strong planetary magnetic field to stand off the solar wind. At these planets, there is direct entry of the interplanetary magnetic field and solar wind into the atmosphere. Understanding the influence of the space environment on planetary atmospheres is important for understanding the formation and evolution of atmospheres that support life. Conditions in the Earth's near space environment may have been significantly different during the early stages of the formation of the Earth's atmosphere than they are now. Some of these differences may be reflected in current planetary magnetospheres (such as Venus and Mars). Furthermore, there are periods in the past when the Earth's magnetic field orientation has switched. During the reversal, there may be a period when the magnetic field is nearly zero, producing a solar wind interaction that is more Venus-like. Understanding this type of interaction by investigating the atmosphere-solar wind interactions at Venus and Mars helps understand the influence the space environment has on the formation and evolution of the Earth's atmosphere.

2.4.4 Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our solar system.

(a) Explain the role of varying solar activity in the past, when life developed, and the controlling factors for habitability, climate, and life since then.

When planets form around a young central star, they are subjected to intense X-ray and ultraviolet radiation and are embedded in strong stellar winds and magnetic storms. The X-ray brightness is up to 1000 times higher, and the ultraviolet brightness ten to 100 times higher, than that of the present Sun. Spots in young, active stars cover as much as half a hemisphere (Figure 2.17), resulting in strong modulations of the irradiance of the planets. Studies of other stars, stellar evolution, and dynamo mechanisms are required to understand both the pathways by which these variations affect the origin of life and the continued habitability of the planets and how the solar activity varied and waned over the 5 billion years since the planetary system formed.

(b) Search for molecules and the building blocks of life from comets, Kuiper Belt objects, and dust in the heliosphere.

One of the foremost questions concerning the existence of humankind and the possibility of life elsewhere is the origin of life on Earth. Did the building blocks for life originate on Earth, or were they transported to the planet from another source? Or a combination of both? There is a diverse spectrum of bodies in the heliosphere, from minute grains on the smallest size scales to planets on the largest scales. The chemical, isotopic, and molecular composition of these bodies carry clues about their formation and evolution, clues to the synergistic relationships between these bodies, and finally clues as to whether these bodies carry the very building blocks of life. Better sampling techniques of the bodies within the heliosphere on all size scales must be devised and executed to solve these riddles. Future studies will include direct rendezvous with comets and asteroids by deep space probes; direct and indirect determination of the composition of objects and grains in the Kuiper belt; direct and indirect determination of the composition of interplanetary and interstellar grains; and, finally, the determination of the composition in all of these objects through measurement of pickup particles, created when material is evaporated or sputtered, subsequently ionized, and finally carried out by the solar wind plasma.

(c) Understand the effects of energetic particles on the evolution and the persistence of life.

The ubiquitous presence of very energetic charged particles throughout space has consequences for life. For life on Earth, the heliosphere, magnetosphere and atmosphere provide three different and important shields from the harmful effects of these naturally occurring radiations. Also, one of the major hazards for manned space travel is recognized to be the flux of energetic charged particles and cosmic rays. Intense solar flares produce extremely high transient fluxes (over a period of hours to days) of dangerous radiation which can adversely affect life in the short term, and the always present, higher-energy cosmic rays from the galaxy provide a significant long-time harmful background which is dangerous on longer-duration manned missions. The existence and evolution of life on Earth depends both on the shielding by the heliosphere and magnetosphere and on the constantly occurring mutations which are thought to be significantly influenced by the same radiations. Certainly, a significant increase in the cosmic radiation caused by a dramatic change in the shielding effect of the solar wind and heliosphere could adversely affect life (variations in the local interstellar medium for example could cause major changes in the Sun's astrosphere). A significant change in cosmic rays in the environment could change the rates of evolution, and affect the viability of life. In addition, current speculations on panspermia must deal with the reality that radiation in space can make the transfer of life very difficult. These facts illustrate the importance of quantitative understanding and prediction of the energetic particle environment. This understanding is needed through the entire chain of factors that influence these particles.

2.4.5 Chart our destiny in the solar system.

(a) Explain the role of varying solar activity in the future of terrestrial climate and habitability.

A multitude of physical processes couple the Sun's variability to the Earth's climate. This is in addition to those processes within the Earth's atmosphere that contribute to climate variability. Which processes, if any, are important in changing Earth's climate, and how they magnify or weaken each other's actions in this complex climate system have not been determined. Key to understanding climate variability is the measurement of those solar properties which are either known to affect climate or most likely do; these include the solar spectral irradiance, and the properties of the heliospheric magnetic field and disturbances such as CMEs traveling within it. Also critical is the ability to forecast solar activity on long time scales, from decades to centuries. Theoretical models and efficient knowledge sharing with studies of activity on Sun-like stars of a range of activity levels are essential for the development and validation of long-term forecasting of solar activity. Finally, understanding the role of varying solar activity in the future of terrestrial climate requires a detailed understanding of the coupling between solar activity and the Earth's magnetosphere. This coupling modifies the effects of solar activity on the Earth's atmosphere.

3.0 SEC Mission Roadmap Introduction

Sun-Earth Connection (SEC) missions traditionally fall into one or more of four broad disciplines: solar, heliospheric, magnetospheric (including comparative magnetospheres), and Ionospheric/ Thermospheric/Mesospheric (ITM), representing each of the major disciplines in the Division. Missions within the Sun-Earth Connection Division can also be categorized by different measurement techniques. Solar missions sense the Sun remotely via imaging and spectroscopy over a variety of scale lengths and wavelengths. Heliospheric and magnetospheric missions generally return *in situ* measurements of particles, fields, and plasmas. ITM missions use both remote sensing (e.g., auroral imaging) and *in situ* measurements to determine atmospheric and ionospheric parameters.

Achieving SEC science objectives will necessitate changes in the conduct of new missions. Understanding the Sun, heliosphere, and planetary magnetospheres, ionospheres, and atmospheres as a single coupled system requires a melding of SEC missions and correspondingly distinct changes in measurement techniques. Because of this requirement, there is an evolution from single-point or widely spaced multi-point SEC missions employing only one or a few measurement techniques to coupled, multi-point missions that employ a variety of measurement techniques.

Solar physics has traditionally relied on remote sensing. Because of the inherent difficulty in performing *in situ* observations very near the Sun, new missions in the SEC continue to rely on these measurements. However, addressing key science questions also requires some important changes in the way these missions are designed. Two significant changes in new solar missions will be a dramatic increase in accumulated data (to accommodate the necessary increases in temporal and spatial resolution) and important changes in the observation vantage points. The dramatic increase in data will require new analysis and modeling techniques. Many new missions will not be confined to vantage points near the Earth. For example, they will image active regions from heliosynchronous orbits, keeping the same perspective of the active region under investigation. In addition, multi-spacecraft missions will provide continuous imaging of the entire solar surface. One of the most significant changes in solar physics will be the strengthening of ties between the solar and heliospheric communities. Inner heliospheric missions will use a combination of solar imaging and *in situ* measurements to directly link activity on the Sun with consequences in the heliosphere. Further, the region between a few solar radii and 0.3 AU (>60 solar radii) will be explored for the first time using *in situ* measurements supported by imaging to resolve critical science questions.

Heliospheric physics will undergo a similar revolution. Study of the inner heliosphere will benefit from the first heliospheric mission specifically designed to provide multi-point measurements. Study of the heliosphere at high latitudes will build upon the results obtained from Ulysses by combining *in situ* measurements with imaging of the Sun's polar regions. New SEC missions will combine multi-point, remote sensing of CMEs with multi-point *in situ* measurements of the particles accelerated in these structures. This combination will reveal how CMEs change as they propagate away from the Sun and will link these changes with the origin of the structure in the solar atmosphere. Gobal imaging of the outer heliosphere will be followed by new missions providing *in situ* measurements of the previously unexplored inner and outer boundaries of the heliosphere.

Recent multi-point and global imaging missions signal the path to advance magnetospheric physics. These missions demonstrate the need to distinguish spatial from temporal phenomena via multi-point measurements throughout the magnetosphere. The new magnetospheric missions will employ focused multi-point measurements, global imaging, or both these techniques to answer key science questions. Magnetospheric physics will also benefit significantly from comparison with the results from missions to other planets with similar magnetospheric and ionospheric processes.

ITM missions have traditionally benefited from a combination of imaging and *in situ* measurements. New missions will also use these techniques, but like their magnetospheric counterparts, they will employ multi-point measurements to distinguish spatial from temporal phenomena. ITM missions, like solar missions, will continue to benefit from ground-based observations. These observations provide critical contextual measurements of regions surrounding a low Earth orbiting spacecraft. Finally, although there has always been a strong link between atmospheric, ionospheric, and magnetospheric physics, new missions will be specifically targeted to operate in concert in all regions to answer important questions concerning the coupling among the regions.

Of all the changes, the most important is the emphasis on the Sun, Earth, and heliosphere as a single, highly coupled system. Thus, while the individual missions that are described below address directly the objectives of the SEC Division, many of these objectives are attained best by operating missions in concert with one another. Furthermore, theory and modeling play an important role in interpreting the observations from near- and intermediate-term multi-spacecraft missions and driving the development of future long-term missions. Our specific technology needs are discussed in Section 4.

Table 3.1.1: Near-, intermediate-, and long-term missions for understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

Near-Term Missions (2003 – 2008)	Intermediate-Term Missions (2009-2014)
Solar B - How is the photosphere magnetically coupled to the corona? **Solar-TErrestrial RElations Observatory (STEREO)** - What are the origins and consequences of CMEs? - What processes control CME dynamics and evolution? - How and where are energetic particles accelerated in CMEs? **Geospace Electrodynamic Connections (GEC)** - How does the Earth's ionosphere-thermosphere (I-T) system respond to magnetospheric forcing? - How is the I-T system coupled to the magnetosphere? **Solar Probe** - What are the origins of the fast and slow solar wind? - Why is the Sun's corona hot?	**Magnetospheric Constellation (MC)** - How does the magnetotail control energy flow in the magnetosphere? - What processes control magnetotail structure and dynamics? - How do physical processes and regions of the magnetosphere couple over the hierarchy of scales? **Telemachus** - What is the large scale, 3-dimensional structure of the heliosphere? - How is the heliosphere reconfigured over the course of single and multiple solar cycles? **Ionosphere Thermosphere Mesosphere (ITM) Waves Coupler** - What are the global characteristics, variability, and sources of small-scale waves in the Earth's upper atmosphere? - What are the consequences of wave-induced transport between the upper and lower atmosphere? **Heliospheric Imager and Galactic Observer (HIGO)** - What is the nature, size, and variability of the heliospheric boundaries? - What is the composition of interstellar gas?
Long-Term Missions (2015 – 2028)	
Auroral Multiscale (AMS) - How is the Earth's high latitude ionosphere electrodynamically coupled to the magnetosphere? **Geospace System Response Imager (GSRI)** - How is mass and energy transported between the ionosphere and magnetosphere under both quiescent and active conditions? **Interstellar Probe** - What is the nature of the interstellar dust and gas that interacts with the solar system? - How is the elemental composition of the interstellar medium distributed between solid (dust), neutral (gas), and plasma (ionized gas) states? **Neptune Orbiter** - What are the structure and solar wind interactions of a planetary magnetosphere whose spin axis and magnetic dipole axis are in very different directions? **SCOPE** - How are processes in the magnetospheres and upper atmospheres of the planets similar to those observed at Earth? **Solar Polar Imager** - How do active regions on the Sun form and evolve at high latitudes? - What is the nature of the velocity vector field below the surface of the poles of the Sun?	

Table 3.1.2 Investigations for understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments and their relationships to near-, and intermediate-term missions.

	Near-Term Missions				Intermediate-Term Missions			
Investigation	**Solar B**	**STEREO**	**GEC**	**Solar Probe**	**MC**	**Telem-achus**	**ITM Waves Coupler**	**HIGO**
(a) Understand the transport of mass, energy, and magnetic fields within the Sun and into the solar atmosphere	P	S		S				
(b) Determine through direct and indirect measurements the origins of the solar wind, its magnetic field, and energetic particles		P		P		S		
(c) Determine the evolution of the heliosphere on its largest scales		S		S		P		S
(d) Determine the interaction between the Sun and the galaxy						S		P
(e) Differentiate among the dynamic magnetospheric responses to steady and non-steady drivers			S		P			
(f) Explore the chain of action/reaction processes that regulate solar energy transfer into and through the coupled magnetosphere-ionosphere-atmosphere system			P				P	

P = Primary science investigation for the mission
S = Secondary science investigation for the mission

3.1 Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

Understanding the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments depends critically on an understanding of the strong and complex linkages between regions. Consequently, this science objective requires a linked set of missions to systematically establish the flows from their source (or sources), through the regions where they evolve, to their ultimate destinations. The SEC Division has a set of near-, intermediate-, and long-term missions (discussed below) that systematically and deliberately focus on each of the key regions, the most important and relevant processes occurring in these regions, and the ways by which these regions and processes are linked. While the missions described below are each stand-alone and significant, by virtue of the story that they tell together, their collective value is greater than the sum of their parts.

3.1.1 Near-Term Missions

Solar B

Solar B will characterize the magnetic coupling between the Sun's photosphere and corona through high temporal and spatial resolution imaging of active regions. It is a single spacecraft mission in Sun-synchronous orbit around the Earth. The mission is a joint undertaking of the Japanese Institute of Space and Astronautical Science (ISAS), NASA, and the UK that is being led by and launched by Japan. The objectives of Solar B are to analyze creation and destruction of the Sun's magnetic field, luminosity modulation, X- and UV-radiation variation, and eruptions in the Sun's atmosphere. The instrument complement includes a visible light spectrograph and vector magnetograph, an X-ray telescope, and an imaging UV spectrograph. The fields of view of the imagers will cover an active region including full vector magnetic field measurements with a resolution a factor of 10 better than currently available.

Solar-TErrestrial RElations Observatory (STEREO)

STEREO will describe the 3-D structure and evolution of coronal mass ejections (CMEs) from their eruption on the Sun through the inner heliosphere to Earth's orbit. The mission will employ remote sensing and *in situ* measurements from two spacecraft drifting in opposite directions away from the Earth at 1 AU to triangulate CME-driven shocks, detect preceding shock-accelerated particles, and analyze *in situ* CME and solar ejecta signatures, including heavy ion mass and charge states. The instrumentation package on each spacecraft includes a coronal and heliospheric imaging package (with an EUV imager, two coronagraphs, and heliospheric imager), a set of radio wave receivers, and an array of *in situ* measurements for measuring the solar wind, energetic particles, and interplanetary magnetic fields.

Geospace Electrodynamic Connections (GEC)

GEC will define the dynamic nature of the joint ionospheric and thermospheric response to magnetospheric forcing. This multi-spacecraft mission will focus on the hitherto relatively unexplored lower reaches of the ionosphere and thermosphere from 100 to 150 km, where the neutral atmosphere plays a preeminent role in processing and dissipating the electromagnetic energy received from the magnetosphere. GEC will discover the spatial and temporal scales at which magnetospheric energy input is important, determine the scales for the response of the IT system to this input of energy, and quantify the altitude dependence of the response. The GEC spacecraft will be identically instrumented to sample *in situ* the ionized and neutral gases of the upper atmosphere and to measure the electric and magnetic fields that couple the IT system to the magnetosphere. They will use onboard propulsion to plunge repeatedly to altitudes below the nominal 185 km perigee. During these low-perigee excursions and at other times, GEC and ground-based measurements will be coordinated to provide both global and local perspectives.

Solar Probe

Solar Probe will enter the solar atmosphere to identify the source regions for the solar wind, determine the mechanisms leading to the solar wind and other stellar winds, and trace the flow of energy from the corona into the solar wind. The distribution functions of particles, the properties of waves, the structure of boundaries and discontinuities, the energetic particles, and the elemental composition will be measured at spatial resolutions of ~100 km or less. These will be compared with photospheric and magnetogram images with similar resolution to determine the mechanisms that accelerate the solar wind and produce energetic particles.

3.1.2 Intermediate-Term Missions

Magnetospheric Constellation (MC)

MC will employ a constellation of ~50 spacecraft to describe the temporal and spatial structure of complex processes occurring throughout vast regions of the Earth's magnetosphere. *In situ* plasma, magnetic field, and energetic particle observations, and possibly imaging, will be used to distinguish between nonlinear internal dynamics of the magnetosphere and global responses to varying solar wind conditions. The data will be provided on spatial and temporal scales sufficient to enable close cooperation with state-of-the-art numerical simulations capable of describing where magnetic flux, mass transport, energy conversion, and dissipation occur. By removing the spatial and temporal ambiguities that limit single spacecraft or clustered spacecraft missions, MC will reveal the global pattern of changes within the magnetosphere to quantify the location and extent of the instabilities that trigger the explosive release of solar wind energy and mass stored in the magnetosphere, and how these quantities are transported between regions.

Telemachus

Telemachus will define the large scale, 3-D structure of the source region for most of the solar wind and magnetic field in the heliosphere. At 0.2 AU perihelion, Telemachus will determine the physics of the strongest stream/stream plasma interactions and transient shocks in the inner heliospheric region where they first form. On each ~0.4 AU polar pass, it will observe the high-latitude distribution of radio and x-ray emission from all solar longitudes simultaneously and use helioseismology to study the coupling of convection and rotation and the accumulation of magnetic flux in the polar regions. During the remainder of its orbit, the out-of-ecliptic vantage point of this mission will be used to understand the evolution of the solar wind transition to the outer heliosphere and determine the 3-D structure of the heliosphere with time.

Ionosphere-Thermosphere-Mesosphere Waves Coupler

The ITM Waves Coupler will determine the characteristics and effects of gravity waves in the upper atmosphere on a global scale. The ITM Waves Coupler mission will define the global characteristics, variability, and sources of small-scale gravity waves originating in the lower atmosphere and their influence on mesospheric, lower thermospheric, and ionospheric circulation. The mission will also quantify the effects of the circulation, composition, and transport between the thermosphere and lower atmosphere on the water budget, on the influences of polar mesospheric clouds, and the distribution of chemically-active constituents of the upper atmosphere. These objectives will be accomplished by integrating *in situ* and remote-sensing measurements from two spacecraft on low- and high-apogee orbits with state-of-the-art modeling tools. The imagers on both spacecraft will observe the elusive small-scale waves that determine energy input into the upper atmosphere. On the high inclination spacecraft, infrared spectroscopy will determine transport associated with the waves by measuring chemical composition.

Heliospheric Imager and Galactic Observer (HIGO)

HIGO is the first step into the interstellar medium. It is a single spacecraft in an eccentric orbit around the Sun with 1 AU perihelion and >4 AU aphelion. The mission will determine the 3-D structure and temporal evolution of the interaction region between the heliosphere and the local galactic environment, determine the nucleosynthetic status of a present-day sample of the galaxy. It explores the implications of this environment for Big Bang cosmology, galactic evolution, stellar nucleosynthesis, and the birthplace of the Sun. It searches for molecules and the building blocks of life from pickup molecules (generated through sputtering or sublimation, ionization, and subsequent pickup by the solar wind) left by comets and dust in the heliosphere and interstellar medium. Beyond 4 AU, the heliospheric boundaries may be imaged using Energetic Neutral Atoms (ENAs) and EUV emissions. Instruments will sample pickup ions produced from the neutral galactic matter, thereby determining isotopic and elemental composition of the Local Interstellar Medium and other heliospheric sources. The major neutral components of the interstellar gas will be directly sampled to provide more accurate measurements of the temperature and bulk flow velocity of the local interstellar gas. These measurements will be an important precursor to the follow-on mission that will directly sample the interstellar medium outside the termination shock.

3.1.3 Long-Term Missions

Auroral Multiscale (AMS)

AMS will define the electrodynamic connection between the Earth's auroral ionosphere and the magnetosphere. It utilizes four or more spacecraft that fly in formation through the auroral acceleration region at varying altitudes between 600 and 7000 km. Spacecraft separations vary between ~1 km to 1000 km. Each spacecraft samples the physical processes occurring within the auroral acceleration region (plasma, DC and AC magnetic and electric fields) with time resolution appropriate for the phenomena (from seconds to tens of milliseconds). The spacecraft also obtain high-resolution ultraviolet images of the consequences of those processes within the aurora at the magnetic footpoints of the spacecraft cluster. The combination of four spacecraft provides the unique ability to separate spatial and temporal effects and to measure the magnetic field-aligned electric current for varying conditions.

Geospace System Response Imager (GSRI)

GSRI characterizes the global-scale coupling throughout geospace. It is a combined high and low altitude, multi-spacecraft mission, leveraging innovative imaging capabilities. The high altitude component of GSRI, is composed of two identically instrumented nadir-viewing spacecraft in identical circular polar orbits. These will provide nearly continuous stereoscopic ENA and EUV imaging of the magnetosphere, determining the hot plasma morphology and energy content and global electric field distribution. Auroral and airglow imaging instruments on the high-altitude spacecraft will provide nearly continuous and conjugate remote observation of the ionosphere and thermosphere, allowing measurement of the distributions of precipitating electron energy flux, ionospheric electron density, and thermospheric neutral density, composition and temperature. The important components missing from the high altitude measurements will be obtained using GSRIs low altitude component, which consists of two minimally instrumented spacecraft in identical circular low Earth orbits. These spacecraft do regional conjugate imaging of ionospheric plasma convection and neutral wind patterns, augmented with ground-based observations. They provide global specification of the ionospheric electric field and electric current patterns in both hemispheres, essentially completing the electrodynamic picture at low altitude and matching this picture to the one imaged at high altitudes. This mission will also investigate the little-understood role of inter-hemispheric asymmetry (due to the tilt of the dipole and rotation axes) on the global system behavior.

Interstellar Probe

Interstellar Probe is the first mission outside of the Sun's heliosphere. It is a single spacecraft that will use an advanced in-space propulsion system such as a solar sail or nuclear electric propulsion to reach the upstream interstellar medium at a distance of 200 AU within about 15 years. This spacecraft will carry the first payload specifically designed to determine the characteristics of the local interstellar medium, including dust, plasma, neutral gas, energetic particles, and electromagnetic fields. On its way, it will provide only the second opportunity after Voyager to directly observe the thick interaction region between the heliosphere and the interstellar medium extending from the termination shock to the heliopause. Eventually, Interstellar Probe may cross an external bow shock, should that shock exist. Additional advanced instrumentation will determine the nature and chemical evolution of organic molecules in the outer solar system and interstellar medium and perhaps expose the cosmic infrared background (CIRB) radiation normally hidden by the Zodiacal dust.

Neptune Orbiter

Neptune Orbiter will determine the characteristics of a magnetosphere that is considerably different from the Earth's magnetosphere. It is a single spacecraft mission in a moderate inclination, eccentric orbit around Neptune. From this vantage point, it will determine the nature of the Neptune magnetosphere, which is unique in the solar system because its magnetic dipole tilt varies dramatically over Neptune's 16-hour spin period and is significantly different from its rotation axis. The *in situ* plasma and magnetic field measurements will determine the interaction of this unusual magnetosphere with the solar wind and will determine if Triton has an intrinsic magnetic field and interacts with the magnetosphere.

Solar Connections Observatory for Planetary Environments (SCOPE)

SCOPE explores the range of planetary magnetospheres and upper atmospheres of the planets. It is a set of Hubble Space Telescope-class, state-of-the-art remote sensing telescopes to carry out a broad program in comparative magnetosphere and upper atmospheres, producing a global-systems view of the response of planetary environments to the variations in the solar wind, the Sun's ultraviolet radiation, and internal processes. When SCOPE telescopes are pointed back toward Earth, advanced detector capabilities and precision filters, designed for the challenge of planetary auroral and airglow observations, provide an exciting advance in the spatial and spectral resolution of global auroral images and make the first-time ever global observations of the energy and flux of precipitating oxygen ions, a tracer of the coupling between the Earth's upper atmosphere and magnetosphere. SCOPE will map, monitor, and compare terrestrial and other planet auroral mass and energy deposition patterns, magnetospheric plasma processes, coronal emissions, and upper atmospheric structure and circulation, with proven techniques of wide and narrow field of view (FOV) spectro-imaging and line profile measurement.

Solar Polar Imager

Solar Polar Imager will define a critical missing component in the understanding of the solar cycle. It is a single spacecraft mission that uses solar sails to achieve a final 0.48 AU circular orbit with a 60° inclination to the ecliptic. This orbit is in 3:1 resonance with Earth. The spacecraft carries a Doppler imager for high-resolution helioseismology measurements, a solar magnetic field imager, *in situ* particles and fields instrumentation and a solar irradiance monitor. The 3:1 resonance permits this mission to also carry out the helioseismology measurements on the far side of the Sun from the Earth. This combined imaging and *in situ* instrument suite will make high-resolution helioseismology measurements of the Sun's polar regions down to the equator, tracing the complete life cycle of active regions and coronal holes on the Sun and placing far greater constraints on the deep structure of the Sun.

3.2 Explore the fundamental physical processes of space plasma systems.

A plasma is governed by fundamental physical properties related to its ability to support electric and magnetic fields. Among these properties, there are three that are important for understanding Sun-heliosphere-planet connections and, not by coincidence, are part of other astrophysical phenomena.

These are: creation, annihilation, and reconnection of magnetic fields, acceleration of charged particles, and cross-scale coupling. Missions within the SEC Division investigate these fundamental properties and determine their physical origin as well as their generality in other places in the universe. These missions are listed in Table 3.2.1.

Table 3.2.1 Near-, intermediate-, and long-term missions that explore fundamental properties of plasmas.

Near-Term Missions (2003 – 2008)	Intermediate-Term Missions (2009-2014)
Magnetospheric Multiscale (MMS) - Why do magnetic fields reconnect? - What is the nature of turbulence in geospace? - How are magnetospheric particles accelerated? **Bepi-Colombo** -How do planetary magnetic fields interact with the solar wind in the absence of an ionosphere?	**Jupiter Polar Orbiter (JPO)** - How similar and different are fundamental auroral acceleration processes at Jupiter and Earth? - How does auroral coupling moderate the transfer of momentum by magnetic fields in astrophysical systems? **Reconnection and Microscale (RAM)** - What mechanisms lead to reconnection in the solar corona? - Where are regions of particle acceleration? - What micro-scale instabilities lead to global effects?

Long-Term Missions (2015 – 2028)
Dayside Boundary Layer Constellation (DBC) - What is the global magnetic field topology of the Earth's dayside magnetopause? - How does turbulence in the magnetosheath or at the magnetopause modify plasma transfer across the magnetopause boundary? **Io Electrodynamics** - What are the energy coupling processes operating in a magnetosphere with an active moon? **Magnetosphere-Ionosphere Observatory (MIO)** - How is energy tapped from the Earth's magnetosphere to power auroral arcs in the high-latitude ionosphere? **Mars Aeronomy** - How is the upper atmosphere of Mars electromagnetically coupled to the solar wind? **Particle Acceleration Solar Orbiter (PASO)** - How are the most energetic particles accelerated and transported in and around the Sun? **Venus Aeronomy** - What are the electrondyamic interactions of the solar wind with a planet without an intrinsic magnetic field?

Table 3.2.2 Investigations for exploring the fundamental physical processes of space plasma systems and their relation to near- and intermediate-term missions.

	Near-Term Missions		Intermediate-Term Missions	
Investigation	MMS	Bepi-Colombo	JPO	RAM
(a) Discover the mechanisms for creation, annihilation, and reconnection of magnetic fields	P			P
(b) Determine how charged particles are accelerated to enormous energies	S		S	S
(c) Understand how small scale processes couple to large-scale dynamics	S	S	S	S
(d) Test the generality of processes in diverse plasma environments		P	P	

P = Primary science investigation for the mission
S = Secondary science investigation for the mission

3.2.1 Near-Term Missions

Magnetospheric Multiscale (MMS)

MMS will determine the fundamental physical properties of magnetic reconnection. It is a four spacecraft mission designed to study magnetic reconnection, charged particle acceleration, and turbulence (cross-scale coupling) in key boundary regions of the Earth's magnetosphere. The primary goal of the mission is to use high time resolution, *in situ* plasma and fields measurements to determine the micro-scale processes in the exceedingly small (perhaps <100 km thick) diffusion region, where the electrons in a plasma become decoupled from the magnetic field, and the field reconnects. This region is found at the Earth's magnetopause and in the magnetotail, but has never been visited by spacecraft with proper *in situ* instrumentation. The close spacecraft spacing will also enable exploration of the cross-scale coupling of plasma turbulence in the Earth's magnetosheath, at the magnetopause, and in the magnetotail. Finally, charged particle acceleration processes associated with magnetic reconnection, turbulence, and electric fields in the outer magnetosphere will be determined using direct measure of the plasma and waves that cause the acceleration.

Bepi-Colombo

Bepi-Colombo will explore Mercury and its interaction with the solar wind. It is a two-spacecraft ESA mission done in cooperation with Japan. The instruments on the Bepi-Colombo Mercury Planetary Orbiter (MPO) will consist of cameras and spectrometers for high-resolution imaging and spectroscopy of the surface, including emissions from the surface and energetic neutral atoms produced by solar wind-surface interactions. The Mercury Magnetospheric Orbiter (MMO) will carry detectors to observe Mercury's magnetic field and its interactions with the solar wind. Despite significant differences between the atmospheres, magnetic fields, and magnetospheres of Mercury and the Earth, there is evidence that Mercury undergoes a substorm-like solar wind interaction. Magnetic field, wave and particle measurements from MMO will determine the similarities and differences between the magnetospheric processes at Mercury and Earth.

3.2.2 Intermediate-Term Missions

Reconnection and Microscale (RAM)

RAM will reveal the mechanisms leading to reconnection in the solar corona. It is a single spacecraft, Earth orbiting mission that uses a suite of narrow-band and spectroscopic imaging telescopes to take very high resolution images of the solar atmosphere and corona. It improves the resolution of solar atmosphere and corona imaging by a factor of more than 1000 over current measurements. These high resolution measurements will be used to determine the topology of reconnection regions on the Sun, infer the mechanisms that lead up to reconnection and the micro-scale instabilities that lead to global effects, and determine the regions of particle acceleration. The mission takes advantage of geosynchronous orbit for nearly continuous monitoring of the Sun and a large bandwidth downlink for the high spatial and temporal resolution data. To image the small-scales of reconnection and the large-scale consequences of the process, RAM combines extremely high spatial resolution in the corona (~10 km) with intermediate scale (~70 km) large field-of-view observations at several complementary passbands/temperatures. The spectroscopic instruments are a high resolution (~70 km spatial, ~5km/s velocity) imaging EUV spectroscopy and a photon counting (~700 km, ~10 km/s velocity, ~50 ms time) imaging X-ray micro-calorimeter array.

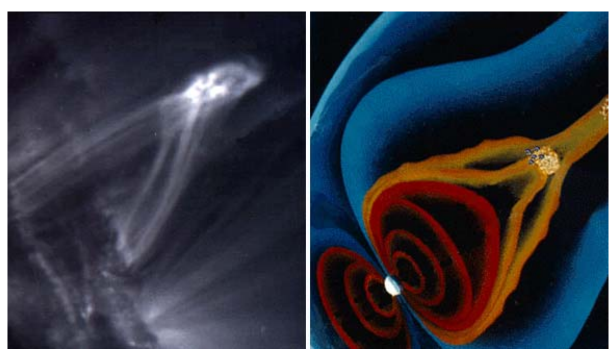


Figure 3.1 (Left side) An arc structure on the Sun undergoing reconnection (Right side) shows the Earth's magnetosphere on the same scale as the arc structure. MMS will determine the micro-scale processes responsible for reconnection in the Earth's magnetotail through high time resolution *in situ* measurements. RAM will determine the global topology and infer the micro-scale processes of reconnection using images of the solar atmosphere and corona with resolution more than 1000 times better than shown here.

Jupiter Polar Orbiter (JPO)

JPO will develop a unique understanding of the electromagnetic connection between the planet's magnetosphere and ionosphere. It is a single spacecraft in polar orbit around Jupiter. Through comparison with results from previous Earth-orbiting missions, JPO will distinguish those aspects of the field-aligned coupling phenomena that are characteristic of astrophysical plasmas in general and those that are unique to the special conditions that prevail at each planet. With its polar orbit, the JPO spacecraft flies repeatedly through the northern and southern hemisphere auroral acceleration regions, similar to what spacecraft have done at Earth. JPO measures *in situ* magnetic fields (inferring field-aligned currents), plasmas, energetic particles, and waves and images the aurora in UV. Radio occultations are used to probe the ionosphere and the thermosphere. JPO will achieve at Jupiter what other spacecraft have achieved at Earth: the most complete characterization of the auroral and magnetosphere- ionosphere coupling possible from a single spacecraft. Planetary science objectives will be included with additional instrumentation, specifically those instruments needed to probe the internal structure of Jupiter, the magnetic dynamo of Jupiter, and atmospheric dynamics.

3.2.3 Long-Term Missions

Dayside Boundary Layer Constellation (DBC)

DBC will determine the global topology of magnetic reconnection at the magnetopause. It is a network of ~30 Sun-pointing, spinning, small spacecraft, separated by ~1 R_E, that skim both the dawn and dusk sides of the dayside magnetopause. The multi-spacecraft provide simultaneous comprehensive observations of boundary phenomena including turbulence over a wide range of latitudes and local times. Three spacecraft are boosted to have apogee outside the bow shock to provide continuous monitoring of the foreshock-preconditioned solar wind input. In effect, DBC spacecraft image the variable geometry of magnetic reconnection much the same way that high-resolution images of the Sun (e.g., from the RAM mission) reveal the location and topology of reconnection and particle acceleration.

Io Electrodynamics

Io Electrodynamics will determine the coupling of an active moon to its planetary magnetosphere. It is a single spacecraft mission in eccentric equatorial orbit around Jupiter. It makes repeated flybys of Io in order to determine how this active moon couples to the Jovian magnetosphere. The spacecraft measures the particles and electric and magnetic fields necessary to determine the field-aligned currents that couple Io and its torus to the Jovian ionosphere. An understanding of this process enhances the understanding of the magnetosphere-ionosphere coupling at the Earth and serves as a bridge to understanding of other multiple component astrophysical systems.

Magnetosphere-Ionosphere Observatory (MIO)

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

Mars Aeronomy Probe

Mars Aeronomy Probe will determine the direct, dynamic coupling of a dusty atmosphere with the solar wind. It is a single spacecraft that will orbit Mars. Instruments will measure the composition, thermal profile, and circulation in the Martian upper atmosphere. Mars Aeronomy will determine the sources and sinks of ionospheric plasma, its coupling to other regions of the atmosphere, and its to the solar wind.

Particle Acceleration Solar Orbiter (PASO)

PASO will determine how the most energetic particles are accelerated and transported in and around the Sun. It is a single spacecraft that follows active solar regions for extended periods by virtue of the spacecraft's heliosynchronous orbit (from 0.2 to 0.3 AU) in the ecliptic plane. This orbit is achieved through the use of a solar sail. The spacecraft uses a combination of *in situ* and remote sensing instruments to measure the energy spectrum and composition of ions from below 1 MeV to above 100 MeV/nucleon, the neutron energy spectrum above 5 MeV, the Gamma-ray spectrum with sufficient resolution to resolve nuclear lines, and the *in situ* solar wind electrons, ions, and magnetic fields. Key to the mission is the extended measurement of nuclear lines with sufficient resolution to determine particle directionality (by Doppler shift) and track changes in spectral evolution and composition in a solar flare. The energy spectrum and composition of the particles accelerated out of the flare will then be measured directly with the *in situ* instrumentation.

Venus Aeronomy Probe

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

3.3 Define the origins and societal impacts of variability in the Sun-Earth connection.

Solar variability has significant short-term and long-term impact on society. The Living With A Star program is a long-term effort to determine the physics behind those aspects of the connected Sun-Earth system that directly affect life and society. It advances the understanding of the network of processes that couple the activity-generating processes within the Sun to the responses within geospace, down to the Earth's atmosphere. The magnitude of the problem requires dedicated NASA/LWS missions, comprehensive modeling and data assimilation, as well as intra-agency, inter-agency, and international collaboration. Development of this program requires several phases, where significant progress is already made in the near-term (during the rise of the next solar cycle, or Phase I) using a combination of solar and geospace missions. The solar mission focuses on the physics behind solar variance and its impact on society while the geospace missions focus on the geospace environment causing spacecraft charging, single event upsets, human exposure to radiation, disturbances to radar, communications, and navigation and errors in orbital prediction.

In the intermediate-term, Phase 2, deeper understanding of the complex coupling of the Sun-heliosphere-Earth system is developed, with particular emphasis on the evolution of solar disturbances in the inner heliosphere inside 1 AU and the linking of solar/magnetospheric forcing of the Earth' ionosphere with forcing from the lower atmosphere. Finally, in the long-term, missions prepare for an "operational" mission by investigating the ability to extend forecasting of solar disturbances, completing an understanding of the full, end-to-end links of the Sun-heliosphere-Earth system, and investigating long-term solar variability.

Table 3.3.1 Near-, Intermediate-, and Long-term missions that define the origins and societal impacts of variability in the Sun-Earth connection.

Near-Term Missions (2003 – 2008)	Intermediate-Term Missions (2009-2014)
Solar Dynamics Observatory (SDO) - What mechanisms drive the quasi-periodic 11-year cycle of solar activity? - What solar magnetic field configurations lead to CMEs, filament eruptions, and flares and can these events be forecasted? - Where do variations in the Sun's total and spectral irradiance arise? **<u>Geospace Storm Probes:</u>** • **Ionosphere Thermosphere (IT) Storm Probes** - What is the contribution of solar EUV to ionospheric variability? - How does the middle- and low-latitude IT system respond to geomagnetic storms? - How do ionospheric storms develop, evolve, and recover? - How are ionospheric irregularities produced? • **Radiation Belt Storm Probes** - Which physical processes produce radiation belt enhancements? - What are the dominant mechanisms for relativistic electron loss? - How does the ring current affect radiation belt dynamics?	**Inner Heliosphere Sentinels** - How does the global character of the solar wind and energetic particles in the inner heliosphere change with time? - What is the distinction between flare and shock accelerated particles? **Solar Orbiter** - What are the links between the solar corona and the heliosphere? - What is the nature of the inner heliosphere solar wind? **Inner Magnetospheric Constellation** - How do the radiation belts, ring current, and plasmasphere couple to produce changing energetic particle populations? - What is the origin, dynamics, and consequences of day/ night and dawn/dusk asymmetries in the inner magnetosphere? **Tropical ITM Coupler** - How are the mesosphere, thermosphere, ionosphere and plasmasphere coupled? - How does the ionosphere and thermosphere respond to forcing from the lower atmosphere? **Magnetic Transition Region Probe (MTRAP)** - What is the dynamics of the Sun's magnetic transition region between the photosphere and upper chromosphere? - What processes control the stability of large-scale coronal structures and high density filaments that result in CMEs?
Long-Term Missions (2015 – 2028)	
L1-Diamond - How does large-scale turbulence modify the "geoeffectiveness" of solar disturbances? - Can *in situ* forecasting of solar disturbances be extended to regions closer to the Sun than L1? **SIRA** - What is the global structure of CMEs and other transient and co-rotating regions in the outer corona? **Stellar Imager** - What are the characteristics of stellar activity in stars like the Sun? - What are the signatures of solar activity on time-scales of years to decades? **Sun Earth Energy Connector (SEEC)** - How do solar irradiance variations affect geospace? **Sun-Heliosphere-Earth Constellation** - What are the end-to-end links of solar variability in the Sun-heliosphere-Earth system?	

Table 3.3.2 Investigations for defining the origins and societal impacts of variability in the Sun-Earth connection and their relation to near- and intermediate-term missions.

	Near-Term Missions			Intermediate-Term Missions				
Investigation	SDO	IT Storm Probes	Radiation Belt Storm Probes	IHS	Solar Orbiter	IMC	Tropical ITM Coupler	MTRAP
(a) Develop the capability to predict solar activity and its consequences in space.	P			S	P			P
(b) Develop an understanding of the evolution of solar disturbances, how they propagate through the heliosphere, and affect the Earth.	S		S	P	S	S		S
(c) Develop the capability to specify and predict changes to the radiation environment.		S	P			P		S
(d) Develop an understanding of the upper atmosphere and ionosphere variability to solar forcing and coupling from the lower atmosphere.		P	S				P	
(e) Understand the connection between solar variability, the Earth's upper atmosphere, and global change.		S					S	
(f) Develop the capability to predict the long-term climate of space.	S	S	S					S

P = Primary science investigation for the mission
S = Secondary science investigation for the mission

3.3.1 Near-Term Missions (Phase I)

The Phase I LWS missions are designed to make significant progress on specific LWS objectives including the origins and consequences of magnetic activity on the Sun, the radial dynamics of the radiation belts, and the formation and evolution of ionospheric irregularities.

Solar Dynamics Observatory (SDO)

SDO will discover the mechanisms that drive solar variations that affect the Earth. It is a single spacecraft that images the Sun from Earth orbit. SDO will be the first mission to view the entire domain of the Sun where magnetic fields originate and cause the variations that affect life and society. Its two principal functions are to make measurements of solar parameters that are necessary to provide a deeper understanding of the mechanisms that lie at the foundation of the Sun's variability on all time scales, and to provide measurements of the radiative, particulate, and magnetized plasma output of the Sun that affect the terrestrial environment and the heliosphere in which it is embedded. To do this, SDO focuses on the dynamics of the solar magnetic field and of the plasma contained in it. It carries a helioseismic/magnetic imager with high spatial and temporal resolution and continuous full-disk coverage, an Atmospheric Imaging Array, providing full disk imaging at different levels in the solar atmosphere, a white light coronagraph, and a spectral irradiance investigation. The spacecraft will be in geosynchronous orbit for nearly continuous solar monitoring and to take advantage of significant downlink capability. Key to the mission is the unprecedented temporal cadence and spatial resolution of the solar imaging. With this imaging, SDO performs helioseismic measurements to assess changes in the structure and dynamics of the solar interior associated with magnetic fields; it images the entire coronal atmosphere at high spatial, temporal, and thermal resolution; it observes the irregularities traveling into the heliosphere; and it measures the spectral irradiance in the EUV. Thus it provides, for the first time, a comprehensive view of the entire magnetic system of the Sun.

Geospace Storm Probes:

- **Ionosphere Thermosphere Storm Probes**

The IT Storm Probes specify the ionospheric irregularities that affect communications, navigation, and radar systems, by understanding how the variability of Sun and magnetosphere affect the ionospheric electron density and its irregularities. Two spacecraft will fly in middle-inclination orbits around 400 km in altitude, with ascending node separations varying from 2 to 20 degrees. In this orbit, the spacecraft traverse the mid-latitude ionosphere, a critical region for ionospheric irregularities. These spacecraft carry *in situ* instruments to measure, for example, ionospheric density with height, density irregularities, scintillations, plasma drifts (or electric fields), and the density, composition, and bulk displacements (winds) of the neutral particle population. Key to this part of the IT mission is the use of more than one satellite to resolve the spatial extent of ionospheric irregularities and distinguish spatial and temporal variations in these structures. It is desirable to support these two LEO spacecraft with an ionosphere-thermosphere imaging instrument on a geosynchronous platform to measure the global oxygen to nitrogen ratio and electron density. This imager establishes the global response to solar and geomagnetic forcing as well as context information for the in-situ measurements.

- **Radiation Belt Storm Probes**

The Radiation Belt Storm Probes will determine the processes responsible for dynamic changes in the radiation belts. It is a pair of spacecraft in low-inclination geostationary transfer orbits, with particle and field instruments to carry out comprehensive in-situ measurements of the radiation belts and ring current in the inner magnetosphere. These spacecraft will determine the processes responsible for radiation belt enhancements, the dominant mechanisms for relativistic electron loss, and the role of the ring current. The spacecraft orbits are chosen such that the instruments sample a range of conditions within the radiation belts. Two or more spacecraft are required to resolve temporal and spatial variations, particularly in the direction radially away from the Earth. These spacecraft measure the acceleration and transport processes and investigate the temporal and the radial spatial structure of the electric and magnetic field variations responsible for acceleration of particles. Measurements include the radiation belt particle fluxes at a variety of radial separations, pitch angle distributions, ring current ion composition, and electric and magnetic fields.

Combined LWS missions in the Near-Term

One of the important elements of the LWS program is the study of the Sun-heliosphere-Earth as a system. It is only through study of this highly coupled system that an understanding of the societal impacts on solar variability will be developed. Thus, the LWS missions in Phase I are designed to have overlapping operation within the geospace mission as well as between the geospace and solar missions.

The joint operation of the Ionosphere Thermosphere and the Radiation Belt Storm Probes allows measurement of the interaction between magnetosphere, ionosphere, and thermosphere, including how magnetospheric particle populations and ring-current changes affect the lower-altitude plasmasphere, and how particles from the ionosphere couple to the magnetospheric population.

The joint operation of the Geospace missions and the Solar Dynamics Observatory allows determination of the forcing from the sun on the upper atmosphere. In particular, the irradiance instrument(s) on SDO provide essential, simultaneous measurements of the EUV spectral irradiance that couples directly to the evolution of density and composition of the ionosphere. Similarly, the geospace missions provide context for the study of the solar activity that gives rise to geoeffective events such as drastic changes in the radiation belts during some intense solar storms.

3.3.2 Intermediate-Term Missions (Phase II)

In Phase II, progress is made on additional LWS objectives and links between regions are determined. There are three areas of study that have high priority. The first is the characterization of the inner heliosphere once the evolution of CMEs near the Sun is determined by SDO. The second is the combined radial and longitudinal dynamics of the inner magnetosphere and the links between the radiation belts and the outer magnetosphere once the radial dynamics are determined by the Radiation Belt Storm Probes. The third is the coupling of the ionosphere, thermosphere, and magnetosphere including forcing from the lower atmosphere once the solar forcing of the ionosphere is determined by the Ionosphere Thermosphere Storm Probes. Upon completion of this set of missions, LWS will have attained a minimal systems approach that is needed to study the many couplings and interactions within the entire Sun-Earth system. Four new missions are needed to reach the next phase of implementation of the LWS program:

Inner Heliosphere Sentinels

IHS will determine the initial evolution of geoeffective disturbances. It is a multi-spacecraft mission with four small spacecraft that have *in situ* experiments (including high-energy particle spectrometers) complemented by a single, larger spacecraft that also carries a high-energy imager. These spacecraft fly in 4 different, highly eccentric orbits in the inner heliosphere designed to give good coverage in solar longitude and distance at all times during the mission. These multi-point measurements are used to investigate the structure of the solar wind and embedded magnetic field, the evolution of perturbations as they propagate from the Sun to Earth, and the generation of shocks and associated energetic particles.

Solar Orbiter

Solar Orbiter delineates links between the solar corona and the heliosphere. It is a European Space Agency (ESA), single-spacecraft mission that makes unprecedented observations in heliosynchronous segments at heliocentric distances near 0.2 AU out of the ecliptic plane to heliographic latitudes of 30° – 38°. It will use a combination of *in situ* particle and field measurements, radio sounding, and visible UV, and EUV imaging. With this instrument complement and a heliosynchronous perspective, Solar Orbiter will investigate the inner workings of the solar dynamo, track the birth and evolution of solar activity, and make the first out of the ecliptic images of CMEs during their creation and early evolution stages. The combined Inner Heliospheric Sentinels and Solar Orbiter missions will provide a powerful tool for determining the global, 3-D structure of the inner heliosphere and the evolution of solar disturbances within it.

Inner Magnetospheric Constellation

IMC will determine the interaction among the radiation belts, outer magnetosphere, and plasmasphere. It is multiple spacecraft in at least two ecliptic plane “petal” orbits. This spacecraft fleet focuses on detailed specification of the orbital environment of most spacecraft and manned missions, to determine in detail the origin and evolution of particle populations and their interaction with the evolving electro-magnetic field during magnetic storms. The in-situ measurements from these multiple positions allow the construction of comprehensive “weather maps” of the inner magnetosphere (1.5-12 Earth radii) that evolve in response to Sun-induced disturbances. These observations extend the radiation belt storm probe results by making simultaneous maps of the radial as well as the longitudinal variations in the radiation belts. Large day/night and dawn/dusk asymmetries exist in the inner magnetosphere and complicate the global specification of particles and fields. Through simultaneous measure of radial and longitudinal variations in the radiation belts, the temporal and spatial asymmetries will be resolved.

Tropical ITM Coupler

Tropical ITM Coupler will determine the lower atmosphere forcing of the ionosphere at low latitudes. It is a multi-spacecraft mission where two spacecraft are in highly elliptical, equatorial orbits that have conjugate apogee and perigee so that one is at 1500 km apogee while the other is at 150-250 km altitude. A third spacecraft is at intermediate, circular low-inclination orbit. The intermediate altitude spacecraft provides remote sensing of the Earth's lower atmosphere, including waves, winds, airglow, and lightning and tropical thunderstorm monitors. The two spacecraft in highly elliptical orbit provide in-situ wind and particle measurements. This mission focuses on the dynamics of neutral and charged particles as they traverse the interfaces between the mesosphere, thermosphere, ionosphere, and inner plasmasphere at low-altitudes where the magnetic field has a largely horizontal configuration. A better knowledge is needed of the lower atmosphere coupling. Specifically how large-scale neutral winds, gravity waves produced by input from the lower atmosphere, and ion drifts are coupled and vary with solar activity.

Magnetic TRAnsition Region Probe (MTRAP)

MTRAP will discover the processes that control the appearance, transport, and destruction of magnetic fields through the transition region in the solar atmosphere. It is a single spacecraft in geosynchronous Earth orbit. The transition region controls the stability of large-scale coronal structures and is key to understanding the stability and instability of the high-density filaments that result in the most significant CMEs. MTRAP will observe sites of transition region reconnection and the generation and dissipation of high-energy particles. The mission will measure the magnetic field and the associated plasma dynamics in the chromosphere and transition region with unprecedented resolution and cadence that is attainable only from Earth orbit. The observations will consist of visible and infrared maps of vector magnetic fields and velocities in the magnetic transition region between the photosphere and the corona. It will have a large field of view (>100,000 km), high resolution (<100 km), and high sensitivity (<30G in transverse field). At higher levels in the upper chromosphere and lower transition region there will be UV maps of the magnetic field and velocity, including the full vector field if technically feasible. Finally, there will be an EUV imaging spectrograph to observe coronal structures in the field of view, with comparable resolution.

3.3.3 Long-Term Missions (Phase III)

The long-term missions of the LWS program include a multi-spacecraft mission to provide a global view of the Sun, imaging of other solar-like stars, a multi-spacecraft mission to study to multi-scale processes in the inner heliosphere, and multi-spacecraft missions to measure the evolution of small-scale irregularities within the magnetosphere and ITM environment.

L1-Diamond

L1-Diamond will determine the large scale, three-dimensional structure of disturbances that propagate toward the Earth and will determine the practicality of continuous monitoring solar disturbances from a vantage point closer to the Sun than L1. It builds on the multi-spacecraft measurements from L1 using existing assets. The mission consists of four identically instrumented spacecraft with wide separation (up to 100's of R_E) centered approximately near L1, but with at least one spacecraft closer than L1. Solar sail technology is used to maintain spacecraft separation and keep the spacecraft in non-Keplarian orbits.

Solar Imaging Radio Array (SIRA)

SIRA will determine the global structure of CMEs and other transient and co-rotating structures in the outer corona. It consists of 10-16 identical microsat spacecraft in a quasi-spherical constellation with ~100 km diameter in a nearly retrograde orbit ~10^6 km from the Earth. These spacecraft will carry radio receivers with frequency and time resolution optimized for solar radio burst detection and analysis. This will enable tracking of CMEs from the Sun to 1 AU, thus considerably improving the accuracy of space weather forecasting. In addition, imaging of type III (fast drift) radio bursts will permit the mapping of interplanetary magnetic field topology and density structures in the solar wind.

Stellar Imager

Stellar Imager will determine the long-term variability of the Sun by imaging other solar-like stars. These observations will be used to develop and test a solar dynamo model with predictive capabilities. Developing that dynamo model, and testing it for long-term predictions of solar activity is impractical if only the Sun is used, as it would take centuries to see the Sun go through only a limited part of the possible states of the nonlinear dynamo. SI will image dozens of Sun-like, magnetically active stars with sufficient resolution to see the patterns of field emergence and evolution, revisiting stars frequently over up to a decade to map out the patterns in the dynamo, and to test and validate dynamo models. It will make use of asteroseismic methods to image the internal rotation profiles of stars. The ultimate SI mission is a multi-spacecraft space-based interferometer working in the visible and UV: at least nine meter-class light collectors and a central beam-combining module, with a maximum baseline of up to 250 m, capable of frequent reconfigurations on a time scale of order 10 hours, operating in a very stable part of space, such as the Sun-Earth L2 point outside the Earth's orbit.

A pathfinder mission of two or three free flying spacecraft would be able to study the least active stars (rotating slowly with few active regions) and form a logical successor to the boom-based Space Interferometry Mission. Ideally, the SI would be a multi-directorate mission, as its imaging capabilities are of direct interest to studies of stars in particular and the universe in general.

Sun Earth Energy Connector (SEEC)

The SEEC mission will perform a comprehensive, global imaging of the solar atmosphere and the near-Earth space environment simultaneously. SEEC will determine how solar irradiance variations affect geospace. SEEC instruments sense selected bands of radiation that reveal primary physical processes occurring within the solar atmosphere and Earth's plasmasphere, ionosphere, and neutral atmosphere.

Sun-Heliosphere-Earth Constellation

The Sun-Heliosphere-Earth Constellation mission requirements depend critically on the results of the near- and intermediate-term mission results. This mission uses the knowledge acquired from these missions to place a constellation of spacecraft in each of the key coupling regions of the Sun-heliosphere-Earth system so that a complete end-to-end understanding of this system is obtained. This constellation provides the knowledge and understanding of the coupled system that is required to field an operational space weather constellation.

3.4 Inter-relationships between SEC missions

The strong coupling between elements of the Sun-heliosphere-Earth system necessitates a similar linkage between missions in the SEC Division. This combination of missions is aided by the evolution from single-point or widely spaced multi-point missions employing largely one measurement technique to coupled, multi-point missions that employ a variety of measurement techniques. As a result, many SEC missions have additional objectives that extend beyond the three primary objectives of the SEC Division. Table 3.4.1 and 3.4.2 list the SEC near and intermediate missions, their primary objectives, and their additional objectives. Missions are listed in approximately time-phased order.

Table 3.4.1 Near-Term missions and their primary and secondary science objectives

	Primary SEC Science Objectives							
Mission /Science Objective	1. Understand the changing flow of energy throughout the Sun, heliosphere, and planetary environments	2. Explore the fundamental physical processes of space plasma systems	3. Define the origins and societal impacts of variability in the Sun-Earth connection	Understand the structure of the universe from its earliest beginnings to its ultimate fate	Learn how galaxies, stars, and planets form, interact, and evolve	Understand the formation and evolution of the solar system and Earth within it	Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our solar system	Chart our destiny in the solar system
Solar B	P	S	S					
Stereo	P		S					S
SDO	S		P	S	S			S
MMS	S	P						
GEC	P		S			S		S
IT Storm Probes	S		P					S
Bepi-Colombo		P			S	S		
RB Storm Probes	S		P		S			S
Solar Probe	P	S	S			S		S

P = Primary science investigation for the mission
S = Secondary science investigation for the mission

Table 3.4.2 Intermediate-Term Missions and their Primary and Secondary Science Objectives

Primary SEC Science Objectives

Mission / Science Objective	1. Understand the changing flow of energy throughout the Sun, heliosphere, and planetary environments	2. Explore the fundamental physical processes of space plasma systems	3. Define the origins and societal impacts of variability in the Sun-Earth connection	Understand the structure of the universe from its earliest beginnings to its ultimate fate	Learn how galaxies, stars, and planets form, interact, and evolve	Understand the formation and evolution of the solar system and Earth within it	Probe the origin and evolution of life on Earth and determine if life exists elsewhere in our solar system	Chart our destiny in the solar system
JPO		P			S	S		
Solar Orbiter	S		P					S
IHS	S	S	P					S
IMC	S		P					S
MC	P		S					
Telemachus	P	S	S			S	S	
RAM	S	P	S					
ITM Waves	P		S			S		
Tropical ITM Coupler	S		P					S
MTRAP	S	S	P					S
HIGO	P	S			S		S	S

P = Primary science investigation for the mission
S = Secondary science investigation for the mission

Linking missions leads to higher science return and, in some instances, is necessary to attain a particular objective. This linking can occur because the missions are operating at the same time, or because the successful completion of one mission provides important input to the operation of a future mission. In the SEC mission roadmap, there are important combinations of missions that address more than one science objective. Focusing on the near- and intermediate-term, these mission combinations and synergisms are:

3.4.1 Mission Combinations

Connections with L1 missions:

All SEC science objectives benefit greatly from *in situ* observations of solar wind plasma and magnetic fields at L1. The *in situ* observations are used to determine arrival times and the internal structure of disturbances observed remotely in the solar atmosphere. They provide an additional vantage point to help determine the extent, evolution, and internal structure of large-scale inner heliospheric phenomena. All ITM and magnetospheric missions require L1 observations of the solar wind input.

Solar and heliospheric mission links:

Solar B, STEREO, and SDO – Deducing 3-D structures from 2-D images poses one of the most difficult problems in solar physics. By the time SDO is launched, the two STEREO spacecraft will be located at maximum separation from the Earth for the nominal science mission, enabling high resolution imaging of the Sun from three vantage points in the ecliptic plane. The combined missions place the Sun in its proper three-dimensional perspective. Solar B will provide a vector magnetic field "microscope" and x-ray imaging to complement the SDO full-sun images.

IHS, Bepi Colombo, Solar Orbiter, Solar Probe, Telemachus, RAM, and HIGO – An unprecedented fleet of spacecraft will populate the inner heliosphere at all heliographic latitudes from 4 solar radii to beyond 1 AU. Solar Orbiter will co-rotate (at times) with the Sun. Bepi Colombo will provide inner heliosphere observations from its orbit around Mercury. IHS will observe from multiple ecliptic locations, Solar Orbiter from mid latitudes, and Solar Probe and Telemachus will observe all heliographic latitudes in their pole-to-pole scans. RAM will provide very high-resolution images of the solar atmosphere that will be placed in their global 3-D context by the multi-point measurements of individual active regions on the Sun. Finally, the detailed observations of inner heliospheric phenomena provided by this fleet of inner heliospheric missions will aid HIGO in determining their evolution through the outer heliosphere. Taken together, these missions will provide unprecedented coverage of the Sun and inner heliosphere,

Magnetospheric and ionospheric mission links:

MMS, GEC, IT Storm Probes, and Radiation Belt Storm Probes – MMS spacecraft separations will be very small (~10-100 km) at apogee to resolve reconnection regions, but will spread out in other parts of the orbit. These spacecraft will provide a second "petal" orbit for the radiation belt storm probes, providing longitudinal information on radiation belt dynamics. Because the apogee of the MMS orbit will lie beyond geostationary orbit, it will be possible to use MMS and Radiation Belt Storm Probe observations to study of the interaction of the ring current and radiation belts and the inward convection of ring current particle populations. Linking the ionosphere to the magnetosphere is critical to LWS. The addition of GEC high latitude ionospheric observations to those by the IT and Radiation Belt Storm Probes will aid in understanding the creation of ionospheric irregularities at high latitudes, their propagation to mid latitudes, and their implications for magnetosphere-ionosphere coupling.

Magnetospheric Constellation, ITM Waves Coupler, Inner Magnetospheric Constellation, and Tropical ITM Coupler – This fleet of magnetospheric spacecraft will make unprecedented multi-point measurements of the inner and outer magnetosphere and the intermediate and low latitude ionosphere. With ~ 50 spacecraft in the outer magnetosphere, Magnetospheric Constellation will providing global context of the Earth's ring current on spatial scales similar to those of state of the art global simulations. This global context will be invaluable to the Inner Magnetospheric Constellation in determining the causes of longitudinal asymmetries in the radiation belts. Similarly, the unprecedented coverage in the magnetosphere and radiation belts will be important in distinguishing effects of solar forcing of the ionosphere, as determined by the magnetospheric missions, from forcing of the ionosphere from below as determined by the ITM Waves Coupler and Tropical ITM Coupler.

System-Wide Mission Links:

Solar B, STEREO, SDO, MMS, IT Storm Probes, and Radiation Belt Storm Probes – This combination of missions provides unprecedented details of the entire Sun-heliosphere-Earth system extending from inside the Sun down to the ionosphere. SDO will provide measurements of the solar interior and the development of solar disturbances, Solar B and STEREO will follow these out into the heliosphere and determine their evolution, MMS will make measurements in the outer magnetosphere that help determine the micro-scale coupling of solar disturbances to the Earth's magnetosphere, the IT Storm Probes will link the radiation belt and magnetospheric disturbances with the ionosphere, and the Radiation Belt Storm Probes will determine the direct and indirect effects of the magnetospheric response on the radiation belt population. The result will be a system-wide understanding of the physics behind solar disturbances and their geo-effectiveness. In the intermediate-term missions, a similar set of missions will focus on multi-point evolution of the disturbances in the inner heliosphere, their large-scale coupling to the magnetosphere, their global effects on the ring current, and their effects on the upper and lower atmosphere.

3.4.2 Mission Synergisms

Exploring the Sun: Solar B, RAM, MTRAP

Solar exploration follows three logical progressions related to resolution, full disk imaging, and changing vantage points.

The Solar B, RAM, and MTRAP missions provide an example of increased spatial resolution ranging from 1 arcsec EUV imaging, to ~0.001 arcsec imaging. This progression allows understanding of the morphology and dynamics of large-scale features in the solar atmosphere with increasingly finer scales elucidating the underlying mechanisms that create the dynamics. SDO and Solar Orbiter provide a progression of full disk, synoptic science and helioseismology, first from the equatorial plane, and later from higher latitudes.

Exploration of the Heliosphere: STEREO, Solar Probe, Telemachus, IHS, HIGO

The heliospheric mission sequence will study the inner heliosphere and then progress to the outer heliosphere. The initial 3-D imaging of solar disturbances and their evolution in the inner heliosphere toward the Earth will be made by STEREO. Following that mission, the multi-point measurements of the Inner Heliosphere Sentinels, Solar Orbiter and Bepi-Colombo will determine the global evolution of solar disturbances throughout the inner heliosphere. Solar Probe, Telemachus, and Solar Orbiter will describe the evolution of disturbances in the inner heliosphere out of the ecliptic including the solar polar regions. Finally, the Heliospheric Imager and Galactic Observer will image the outer heliosphere in preparation for subsequent *in situ* exploration.

Exploration of the Magnetosphere: MMS, Magnetospheric Constellation, Radiation Belt Storm Probes, Inner Magnetospheric Constellation

Because boundary layer processes occurring on the smallest scales control large-scale dynamics, the MMS mission will focus on microphysical processes at the magnetopause and inside the magnetotail current sheet: magnetic reconnection, charged particle acceleration, and microscale turbulence. It will serve as the plasma physical "microscope," investigating scales too small to be resolved by global circulation models. Parameterized results will feed into global magnetospheric models. Manetospheric Constellation will function as a "meso/macro-scope" for Earth's magnetosphere. Ultimately, it will also yield a new understanding on the magnetosphere as a complex nonlinear dynamical system by completing the exploration of scale sizes begun by MMS. Similarly, the Radiation Belt Storm Probes will focus on the radial evolution of the belts and their interaction with the mid-latitude ionosphere. Inner Magnetospheric Constellation will extend this knowledge by determining simultaneous radial and azimuthal properties of the radiation belts and their interaction with the outer magnetosphere.

Exploration of the Ionosphere Thermosphere Mesosphere: GEC to IT Storm Probes, ITM Waves, and Tropical ITM Coupler

The ITM mission sequence will determine the response of the upper and lower atmosphere and ionosphere to forcing from above (i.e., the magnetosphere and solar wind), and below (from the lower atmosphere to the upper atmosphere). The GEC mission focuses on forcing from above at high latitudes, where solar and magnetospheric effects are significant. The IT Storm Probes address forcing from above at mid-latitudes, where there are significant societal affects. Subsequent ITM Waves and Tropical ITM Couplers define forcing from below at mid latitudes and at low latitudes. The end result will be the complete specification of atmospheric forcing from above and below over the full range of latitudes.

A timeline of the near- and intermediate-term missions, grouped by program (STP, LWS, and Other), is shown in Fig. 3.2, SEC Near- and Intermediate-Term Mission Timeline.

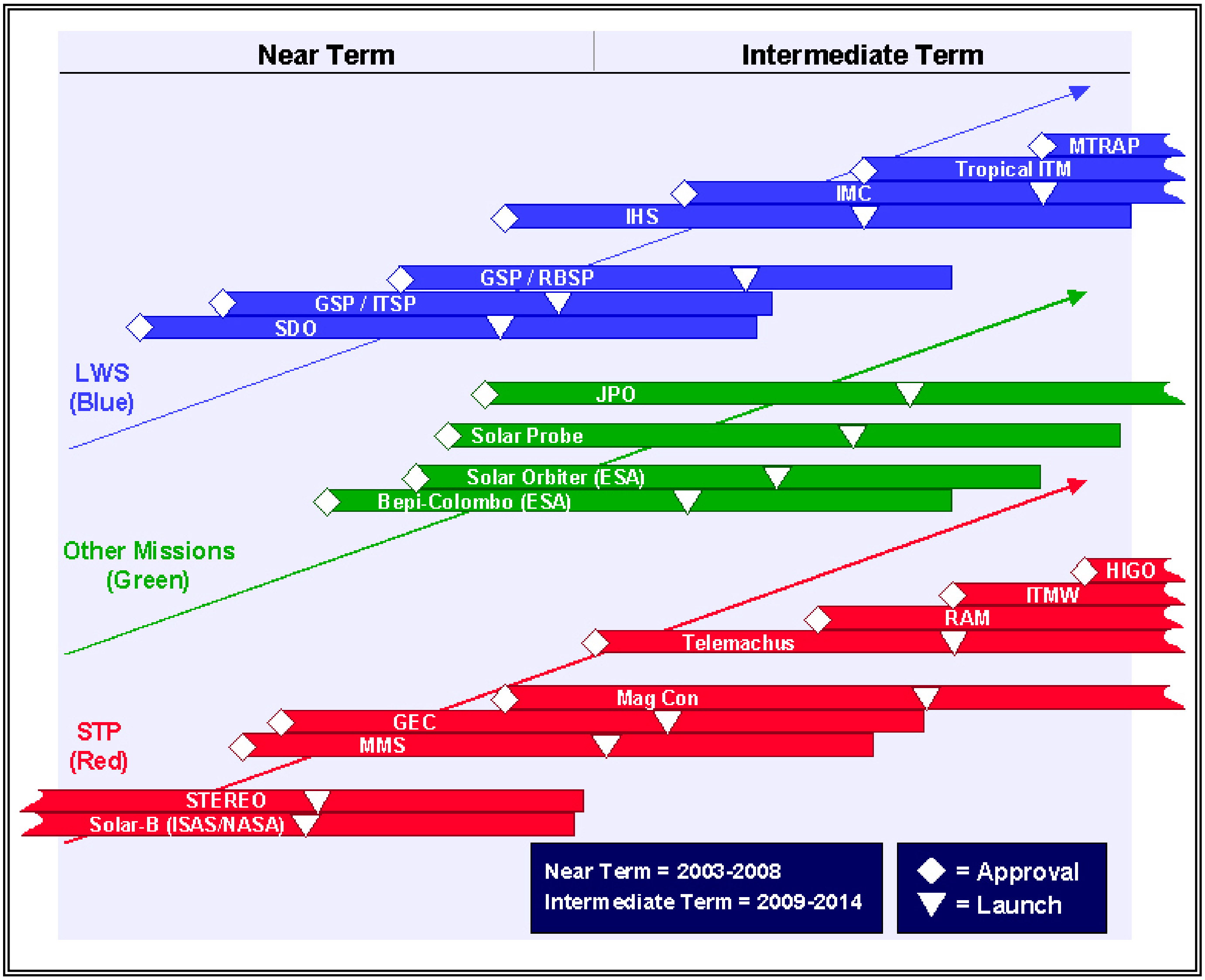


Figure 3.2 SEC Near- and Intermediate-Term Mission Timeline

4.0 Technology Introduction

Future Sun-Earth Connection missions will be made possible or improved through the development of advanced technology. Development of new *enabling* technologies may provide a presently unavailable sensor or propulsion system necessary for mission implementation. Enabling technologies may also be vital for cost reduction, e.g., technologies aimed at manufacturability and operation of multiple spacecraft. These technologies are vital for both intermediate- and long-term SEC missions and the technology program discussed below addresses both these demands.

Missions can also use *enhancing* technology. This type of technology significantly improves mission performance in some manner: e.g., increasing sensitivity, spatial or temporal resolution; improving data return; or simply reducing the cost of a particular capability. All of these enhancements provide more resources for more mission-critical elements. By definition, such enhancing technology does not enable these new missions. Nevertheless, enhancing technologies are important for continued and steady advancement in the capabilities of SEC missions.

This section of the 2003 Roadmap first identifies the vital enabling and critical enhancing technologies required for the entire suite of STP and LWS missions defined and described in Section 3. The technologies fall into four, cross-cutting focus areas; Spacecraft, IT/Autonomy, Scientific Instrumentation, and Propulsion. Within each cross-cutting focus area, the highest priority technology is discussed. Finally an implementation plan is recommended.

4.1 Enabling and Enhancing Technologies

Teams of scientists, system engineers, and technologists reviewed every mission in the SEC Roadmap. From each mission review there emerged mission-specific technologies assessed to be either enabling or enhancing. The mission enabling technologies were then further qualified. Enabling technologies were classified as "in place" if technology development programs were already firmly implemented and sufficiently funded. Other enabling technologies were classified as "planned" if development programs were planned but not yet implemented or were in place but considered insufficient. Finally, technologies were classified as "needed" if no current development plan existed. A summary of that technology identification and assessment is presented in Table 4.1.

The mission-specific technologies in Table 4.1 are shown in rows and grouped into the four broad technology areas. Red boxes indicate "needed" enabling technologies; yellow indicates "planned"; green indicates "in place." The stippled boxes indicate mission-enhancing technologies. Under the "multiple spacecraft challenges" technology, the number in the box indicates the number of spacecraft desired for that mission.

4.2 Technology Prioritization

The review teams determined what technologies were needed to enable and enhance its mission set. Within each technology area, the individual technologies were then prioritized. The overriding factors in the prioritization of a needed technology were mission impact if the technology was not available, position in the mission queue, and cross-mission applicability. Technologies that were cross-cutting, critical for mission implementation, and needed for near- or intermediate- term missions received highest ranking. The four technology areas, the highest priority technologies requiring a concurrent technology program, and a representative mission that these technologies support are listed in Table 4.2.

Table 4.2 SEC Technology Needs and Supporting NASA Technology Programs

Technology Area	Highest Priority Need	Representative Mission
Spacecraft	Multiple spacecraft – low power electronics	Magnetospheric Constellation
IT/autonomy	Data management and assimilation	Solar Dynamics Observatory
Scientific Instrumentation	Detectors	Reconnection and Microscale
Propulsion	Solar Sails	Technology Demonstration

Table 4.1 Enabling and Enhancing Technologies for SEC Roadmap Missions

Near- and Intermediate-Term Missions

		STP Missions							LWS Missions						*	Joint SSE/SEC Missions
Category	**Technology Focus area**	MMS	GEC	MC	Telemachus	RAM	ITM Waves Coupler	HIGO	SDO	Geospace Probes	IHS	IMC	Tropical ITM Coupler	MTRAP	Solar Probe	JPO
Spacecraft	Multi-spacecraft Issues (# of s/c	4	4	50			2			4	4	6	3			
	Avionics			Y	+			+	+	Y	+	R		R		R
	Communications	+		Y	+	+		+	G	+	+			Y	Y	R
	Guidance, Navigation, Control	G	+	Y	Y		+			+	+	+	+	Y	+	
	Power	+	+	Y	Y		+	+		+	+	+	+		Y	+
	Structures/Materials	+	+	+		Y	+							R	Y	
	Thermal Control		+		+	G	+			+	+		+	R	Y	
Propulsion	Solar Sails															
	Conventional	+	+	+			+				+	+	+		+	
IT/Autonomy	Information Technology	+		Y		+	+	+	Y	+	+	+	+	R	+	+
	Autonomy	+		Y		+	+	+		+	+	+	+	R	+	+
Instrumentatior	Sensors/Instruments		+	G		G	+	R	Y	+	+	+	+	R	+	R
	Space-based Optics					R			+					R	+	+

Long-Term Missions

		Joint SSE/SEC Missions				STP Missions							LWS missions				*	
Category	**Technology Focus area**	Io Electrodynamics	Neptune Orbiter =	Mars Aeronomy	Venus Aeronomy	DBC	MIO	PASO	AMS	GSRI	SCOPE	Solar Polar Imager	L1-Diamond	SIRA	SEEC	Sun-Helio-Earth Const.	Interstellar Probe	Stellar Imager
Spacecraft	Multi-spacecraft Issues (# of s/c					30	3		4	4			4	>10		5-10		30
	Avionics	R	+			+		+	+			+						
	Communications	+	Y	+	+	Y		+	+		+	+	+				+	R
	Guidance, Navigation, Control					+	+	R	+		R	R	R					R
	Power	Y	R			Y	+	R	+		+						R	
	Structures/Materials					+		R			+	R	R				R	+
	Thermal Control		+					R			+						R	+
Propulsion	Solar Sails		R=					R				R	R				R	
	Conventional	+		+		+			+		+							R
IT/Autonomy	Information Technology					Y		+	+	+	+	+			R		+	R
	Autonomy		+		+	Y		R	+	+	+	R	R				+	R
Instrumentatior	Sensors/Instruments	+	+	+		+	+	+				+	+				R	R
	Space-based Optics							+			R	+			R			R

31-Jan-2003

Legend		
	Enabling Technology, Development In P	G
	Enabling Technology, Development Pen	Y
	Enabling Technology, Gap Apparent	R
	Enhancing Technology	+

Notes	
	Table does not include Solar Orbiter, Bepi-Columbo (ESA missions);
	nor STP missions such as STEREO, Solar-B (which are in implementation).
XYZ	Approved missions are underlined.
*	Other missions.
=	Neptune Orbiter: Solar Sails (or other advanced Propulsion) & aerocapture required.

The next-tier priority technology development needs are spacecraft power systems, and communication systems. The specific details of these highest priority and next-tier technologies are provided below.

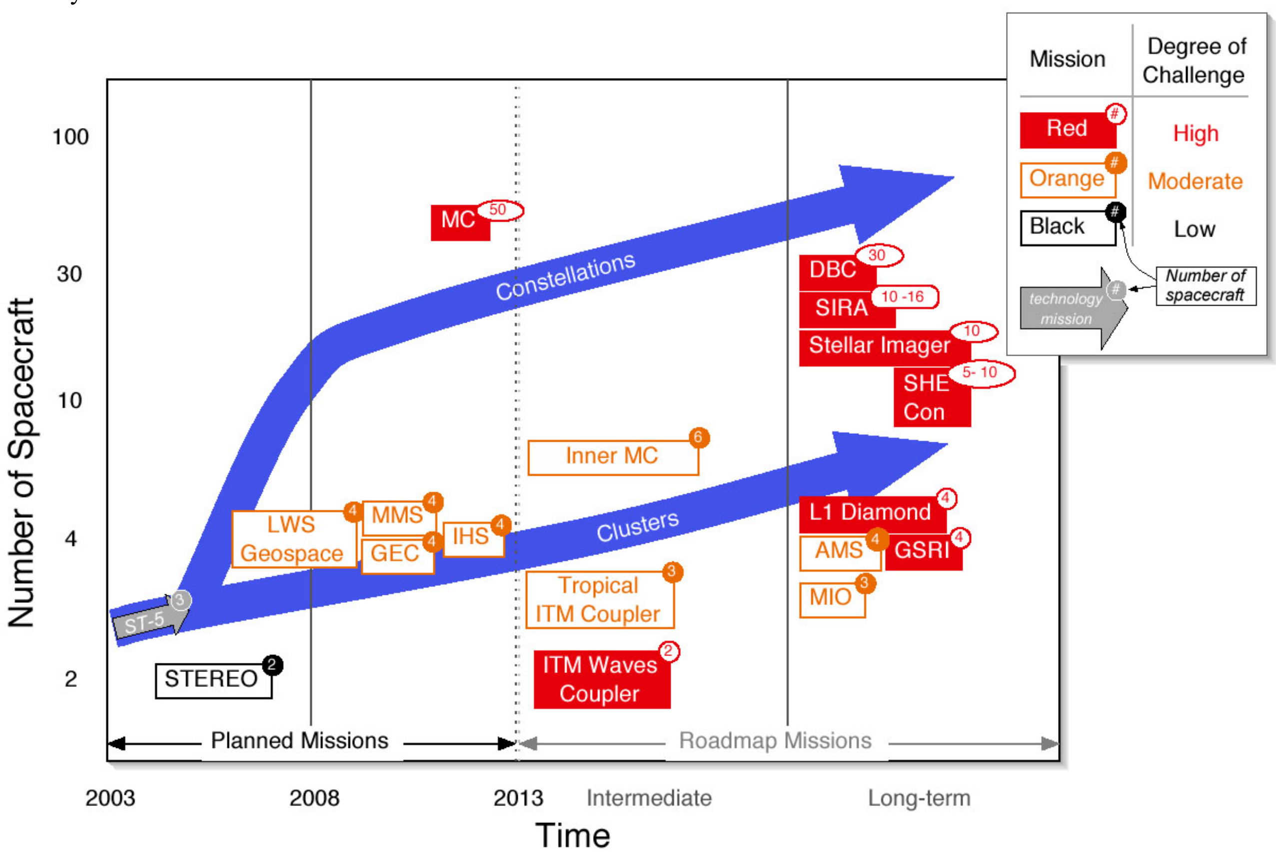
4.2.1 Spacecraft - Multiple Spacecraft Challenges and Ultra-Low Power Electronics

A large number of multiple-spacecraft missions are mandated for the future of SEC science. Cost-effective implementation of these missions could incorporate emerging technologies into highly integrated designs that are less expensive to build, test, and operate. First steps are underway to assure this vision, one example being the 3-spacecraft ST-5 mission. However, more investment will be required, and additional study will likely be needed to develop the specific aspects of a coherent theme or Enterprise investment strategy.

The multiple spacecraft challenge is motivated in the near- and intermediate-term by missions such as MMS, GEC, MagCon, GeoProbes, and IHS. Each mission has its own specific needs, but many of the challenges are cross cutting. All space missions would benefit from the availability of lower-cost platforms that provide essential spacecraft services for scientific instruments. SEC confronts the urgent requirement to reduce the unit cost of spacecraft, especially after the first one has been built. Figure 4.1 depicts this pervasive and vital need for economical spacecraft that could enable strategic SEC missions from the near to the far-term.

As part of the mission studies for this SEC roadmap, an analysis assessed the potential of enabling technologies to reduce spacecraft mass and power. Results indicate that 10 to 20% of the spacecraft cost could be saved through the evolution and application of technologies aimed at lowering spacecraft mass and power. Lower mass to orbit, in some cases multiplied by many spacecraft, can allow the use of a smaller launch vehicle, resulting then in even more substantial cost savings.

Figure 4.1 Demonstration of the overarching need for economical spacecraft. The Challenge of "Economical" Spacecraft: Develop affordable clusters and constellations of spacecraft for multi-point measurements of the connected Sun-Earth System.



System-level technologies such as ultra low power electronics and advanced packaging could bring dramatic reductions since they are applicable to both instruments and spacecraft bus. Generally, there is a direct relation between the electrical power needs of a spacecraft and total system mass. This relation is particularly important for *in situ* missions that employ body-mounted solar panel arrays. These missions often are severely power constrained because solar panel area is directly related to spacecraft size.

Ultra Low Power (ULP) electronics has the potential to dramatically reduce power requirements for flight avionics and instruments. The reduction in the voltage of logic from 5 V to 0.5 V can result in a power reduction for specific parts by a factor of 100. Early application of the technology is likely to focus on power "tall-poles" in digital logic. System-wide availability of the technology could reduce power consumption by 70% compared with conventional systems. Such power savings could be traded for reduced mass or greater data architectural flexibility (via redundancy). The first OSS flight experiment of this technology will likely be the ULP Reed-Solomon Encoder on ST-5. ULP electronics is a high priority technology with great potential. It addresses an important aspect of the multi-spacecraft challenge, and SEC should track and support its progress robustly.

4.2.2 Information Technology/Autonomy

The SEC mission set is comprised of coordinated scientific observations from spacecraft operating throughout the heliosphere. These missions are characterized by: multiple spacecraft making system-spanning measurements; instrument sets on platforms at unique vantage points; or missions making measurements with unprecedented spatial, temporal or spectral resolution. In the near-term, SEC will need flight systems able to handle data volumes unprecedented within OSS. It is vital that flight systems be developed that are capable of cost-effectively managing this data stream. Systems that loosely compress and encode high data-rate streams (thus maximizing the science return from limited bandwidth downlinks) will be needed.

SEC missions in the very near future will generate huge quantities of scientific data that will require processing, analysis, and information extraction. Thus far, data volume has kept pace with data storage capabilities, but new data volumes may tax future storage capabilities. However, data storage capacity is largely driven by needs outside of the SEC Division. Therefore, developing larger storage capacity may not hold out the promise of significant return on the investment. Instead of investing in increased storage capacity, a technology program is needed that develops the tools necessary for systematic and automatic access to large and distributed data sets and the ability to synthesize quite disparate data sets. To address all of these diverse requirements, early investments in information technology will be a high priority, in particular to promote the system understanding sought by LWS and STP missions.

In 2002, the number of spacecraft operated by SEC is 19. In 2012, it is reasonable that this number could approach 75. Much of the anticipated increase is due to the proposed fifty spacecraft of MC. Given recent history, it is safe to presume there will not be a concomitant four-fold increase in resources but rather that downward pressure on operations budgets will persist, if not intensify. For SEC to handle the increase in coming years, a technology program aimed to produce a steady and in some cases dramatic decrease in the operations cost per spacecraft is required.

4.2.3 Scientific Instrumentation

SEC scientific instrumentation performs *in situ* and remote sensing measurements. Technology challenges in the *in situ* instrumentation are largely related to the multi-spacecraft requirements of a large number of SEC missions. In particular, the development of highly integrated and compact instrument electronics is important for multi-spacecraft missions. However, aspects of this technology may be addressed by the development of low power electronics for spacecraft sub-systems, and most certainly will be aided by recently instituted, instrument development programs (see implementation section). Therefore, within the scientific instrumentation technology area, the remote sensing instrumentation should be accorded higher priority.

Remote sensing instruments have two specific technology requirements. These are large format array detectors and lightweight, precision optics and coatings. Of these two technology requirements, technology development of detector arrays derives the most benefit and is the highest priority.

Large format, fast-readout detectors offer enormous potential for performance enhancement of current remote sensing instrumentation. In particular, fast-readout, 4k x 4k, thinned, backside-illuminated CCDs are needed for SDO and ultimately 16k x 16k format CCDs will be needed for MTRAP. Active Pixel Sensor (APS) arrays offer enormous potential savings in mass, power and radiation hardness as well as variable gain readout capability, making them ideally suited for missions such as Solar Probe and RAM. Large format, energy resolved array detectors, such as microcalorimeter arrays, also offer exciting promise for soft x-ray spectroscopy on missions such as RAM, providing the ability to make simultaneous two dimensional spectral imaging observations of high temperature plasmas. Included in the technology necessary to develop these arrays are improved mechanical cryo-coolers for extended operational life.

Technology development in lightweight, precision optics and coatings also offers the potential for exciting enhancements in future remote sensing missions. In particular, large (>1 meter), lightweight, precision optics are required for MTRAP and precision, super-polished UV optics are needed for RAM and other missions. New, innovative coating technologies continue to be needed to expand spectral observing domains in the UV, EUV, X-ray and Gamma-ray, and enhance instrument efficiency on essentially all future remote sensing missions.

4.2.4 Propulsion - Solar Sails

For geospace missions, chemical propulsion will likely remain the standard means of achieving an observational station. However, solar sails remain a high technology priority for SEC, enabling unique vantage points in and outside the heliosphere wholly unavailable by other means. Such vantage points include: observing the Sun from high-inclination, heliocentric orbit (Solar Polar Imager); leaving the heliosphere to determine the nature of interstellar space (Interstellar Probe); observing the origin of high-energy solar particles from heliosynchronous orbit (Particle Acceleration Solar Orbiter); and making sustained measurements from otherwise inaccessible, non-Keplerian, near-Earth orbits (L1 Diamond). Furthermore, solar sails offer a unique advantage over other propulsion systems. These sails can be used as an active element in a spacecraft sensor array. For example, wire imbedded in the solar sail could be used as the antennae for an electric field instrument. Other propulsion systems (e.g., nuclear-powered propulsion) may be studied for other applications (e.g., planetary missions, where the ability to decelerate a spacecraft is as important as the ability to accelerate it). With the advent of the In-Space Propulsion and Nuclear Systems Initiatives, SEC should continue to closely monitor developments in nuclear electric and solar electric propulsion, and periodically assess whether these technologies could enable our deep-space missions. However, solar sails remain the highest technical priority for spacecraft propulsion for the SEC Division.

Given the challenge inherent in deploying and controlling a large, gossamer solar sail, a technology demonstration mission will be required. Successful demonstration of a 50-m class (root-area) solar sail would enable measurements upstream of L1 (such as NOAA's Geostorm concept or SEC's L1 Diamond) and by straight-forward scale-up to sizes in the 100-m class, such a demonstration would make Solar Polar Imager possible. Following this development, the technology would have to be adapted for application to the near-solar environment for missions like PASO (0.17 AU). This would likely require use of advanced thermal control techniques for the lightweight structure and membrane materials suitable for high-temperature use. Meeting the challenge of flying close to the Sun would feed in naturally to the next sail mission: Interstellar Probe. It will require the development of a 300-m-class solar sail, and likely incorporating technology from PASO, will use a solar gravity assist (perihelion ~ 0.25 AU).

4.3 Next-tier Priority Technologies – Power and Communication Systems

Power Systems

Exploration of the outer heliosphere in practice is contingent on the availability of radioactive power sources. While the SEC Division supports renewed prospects for advanced radioactive power sources, the vast majority of SEC missions will continue to rely on photovoltaic systems. Operations with photovoltaics as far as Jovian orbit require deployable, low-intensity, low-temperature solar arrays. In addition, photovoltaic systems able to cope with the high-temperature, high flux of the near-solar environment (< 0.4 AU from the Sun) will be needed. The theme has unique interest in the development of new lower-cost, electrostatically clean solar arrays.

Communications

Because of the large link distances, spacecraft in deep-space face communications challenges. SEC has some unique needs in this regard such as systems that provide for high data rate communications from spinning spacecraft in deep space. Specific technology needs include: Hi-EIRP telecom "cloverleaf", adaptive feed/uplink Beacon, Ka-band transmit network, and DSN 70-m equivalent with Ka-band downlink.

4.4 Other Notable Technologies

The SEC identifies other notable technologies that are mission enhancing. These include:

Avionics

High-performance flight avionics will play an increasingly important role in SEC missions. A number of factors contribute to this development: progressively higher-resolution and higher-cadence imaging of the Sun; multi-spacecraft missions making complex, system-wide measurements of dynamic phenomena at affordable cost; missions that must cope with severe environments; and those operating far from the Earth that face severe limits on communications.

Guidance, Navigation, and Control

Future SEC missions have some distinctive characteristics: single spacecraft operating at unique vantage points (often in severe environments); multiple spacecraft making coordinated measurements of a region of interest; or an instrument platform (or set of platforms) with unprecedented sensitivity, and/or temporal, spatial or spectral resolution. Each class of mission will require advances in the art and practice of guidance, navigation, and control.

Structures & Materials, Thermal Control

Materials, devices, and schemes for near-solar thermal management will be needed to enable *in-situ* measurements near the Sun. Solar Probe will need a phenomenally robust, carbon-carbon thermal shield, able to withstand temperatures up to 1,800°C with no appreciable sublimation of material. Solar sails and other spacecraft structures must be able to withstand thermal environments near and far from the Sun (the solar thermal input ranges from 0.04 Suns at 5 AU to 2800 Suns at 0.02 AU).

4.5 Technology Implementation Plan

Until quite recently, technology investment in SEC largely has been managed and funded on a mission-by-mission basis. However, the resources and time available to a mission in formulation is quite limited, and leads to focus on one or two key challenges. This approach yields a frustratingly low rate of technology infusion in general and cross-mission infusion of technology in particular. Our ambitious new missions require a new approach to technology development. Advancement of SEC-specific technology requires a broad and sustainable program with a cross-mission perspective.

Recently, two elements of ROSS NRAs have helped to bolster SEC technology investment, namely the SEC and LWS Instrument Development programs. These opportunities provide resources to the science community for the enabling scientific instrumentation demanded by future missions. However, this new program is relatively small and at present unproven given that the first funding cycle is still underway. No such parallel program exits for systems-level technology development, although NMP does play a significant role in many ways (e.g., development of nanosatellite technologies through ST-5). Other traditional and new sources of technology development programs for supporting SEC needs are: LWS Space Environment Testbed (SET), In-Space Propulsion, PRT, and SBIR.

LWS Space Environment Testbeds will provide flight opportunities for new hardware and design/operations tools whose performance is sensitive to solar variations. The testbeds will also fly instrument technologies of interest to SEC. Technologies will be competitively selected, with flight opportunities beginning in 2004 and recurring every two years thereafter. The experimental nature of the testbeds and potential for frequent access to space, make it a valuable resource for SEC strategic missions.

Continued advocacy within the agency for developing technology for SEC needs should focus on several different fronts. One area needing promotion is the publication of technology requirements as a means of facilitating dialog and improving alignment of technology providers. Another is in the area of partnering – competitively selected technologies are strongly preferred with directed efforts used solely to guide adaptation of technology previously selected through competition. Another area of significant impact would be the moderation of the current technology-averse policy in place for mission development.

A new theme technology program should be small and focused, serving clear, persistent technology needs within our program lines. Technology selected and developed within these programs must have potential for reasonable near-term return on investment but also high programmatic impact. Because such funds will always be vulnerable and have alternative usages, implementation will require impeccable Enterprise focus, competitive procurements, partnering, periodic assessment of the program, and the ability make periodic adjustments.

5.0 Theory and Modeling Introduction

In SEC research, the systems under study are typically of great complexity. Furthermore, they can be sparsely sampled or have good sampling only over a narrow spatial, temporal, or spectral range. Using these observations of complex systems, the SEC researchers seek to develop the capability to predict the behavior of the combined system under well-defined conditions and verify this development using new observations. Such an endeavor requires well-tailored development of abstractions of the system, in the form of theories or models. Thus, the intrinsic nature of SEC research necessitates a strong theory and modeling program.

Currently, SEC study of the Sun-heliosphere-planet system is undergoing three substantial changes. One of these changes lies in the markedly increased complexity of present and planned future missions, especially those based on clusters of spacecraft. The second and perhaps more fundamental change involves an evolution from a discovery-driven investigative mode to one motivated by quantification and the desire to verify concepts of understanding. This paradigm shift is especially evident in the goal to understand the coupling between elements in the Sun-heliosphere-planet system. Finally, the Space Weather element of the Living With a Star program requires the development of physics-based models that provide predictive capability. These transformations result in a much closer and much more essential tie between scientific flight missions and accompanying activities in theory and modeling of space plasmas. Thus the role of theory and modeling emerges in a new, prominent light within the SEC Division and has become central to the SEC strategic science objectives. Sections 5.1, 5.2, and 5.3, discuss the tie between theory and modeling and the three primary SEC science objectives. Section 5.4 presents a brief summary.

5.1 Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.

The transport of matter and energy, together with magnetic flux and momentum, over huge distances, poses a grand challenge problem to Sun-Earth Connection research. Theory and Modeling forms an essential element of this research. The analysis and description of the vast and complex Sun-heliosphere-geospace system mandate tools for integration between missions addressing different aspects of the transport problem. Due to the sheer size of the domain, such a glue can only be provided by large-scale models.

Large-scale models, such as those developed for the solar corona or ionosphere-thermosphere, fulfill a set of needs in SEC research. Traditionally, such models have been utilized to provide the overall context for the interpretation of spacecraft measurements. This highly useful function will continue in the future. In addition, large-scale models now can also provide high-quality estimates of the connection between individual measurements, separated in space or in time. As an example, the overall structure of the solar wind, involving currents sheets separating different magnetic fields, determines whether coronal ejecta or energetic particles arrive at the Earth or not. Comparisons like this example are essential to extend the value of measurements beyond the local environment, and to develop better, model-based manifestations which reflect the level of understanding. The interplay between model predictions and spacecraft measurements thus provides a new avenue of space research, combining new windows into the workings of the SEC system through direct feedback between mission data analysis and modeling.

Beyond this overarching role, large-scale models directly support specific missions. For example, global models of the corona and solar wind are used to interpret and predict, co-rotating interaction regions, propagation of cosmic rays in the heliosphere, and the propagation characteristics of CMEs. These models are important for STEREO and Solar-B, and, in the absence of true global measurements, are important for Telemachus. Other examples of mission support through modeling are GEC and MagCon, where data assimilation techniques into large-scale models provide, for the first time, a comprehensive map of properties, dynamics, and transport in geospace and in the ionosphere.

5.2. Explore the fundamental physical processes of space plasma systems.

In a growing area of space research, investigations are moving away from the basic morphological studies of the discovery period to more detailed and targeted probing of the inner workings of key physical processes. Better understanding of the overall morphology generates the need to understand key physical processes, which determine the overall system state and dynamics. Accordingly, mission-based research often aims at distinguishing between different candidate mechanisms, or at least understanding of a single process, which fundamentally determines system behavior. Often, these processes are driven by micro-scale instabilities. Understanding of the processes on the micro-scale typically requires basic theory supported and enhanced by kinetic and hybrid modeling.

This basic theory and modeling is playing an increasing role in SEC missions. Typically, plans for missions are based on prior knowledge, obtained from prior missions. In the future, mission conception, tailoring, and execution will focus increasingly on the verification or falsification of understanding. In particular, many future missions will have as their goal to test the veracity of a prediction of fundamental plasma system behavior, obtained from theories and models. The conception of such flight missions, their execution, and the enhancement of understanding require the establishment and maintenance of strong theory and modeling activities.

Following the prediction phase, fundamental plasma models will be intricately involved in the preparation and execution of missions. An example of the interplay between theory and observations is the study of magnetic reconnection. MMS will study this process at microscopic levels of detail heretofore only accessible by modeling. Thus the concept underlying MMS, as well as its design relied heavily on results from modern models and theory. During the flight phase, MMS will involve a close interaction between observations and models to bring closure to the operation of reconnection in geospace. Reconnection in the solar coronal environment has been, to date, even less accessible to direct measurements. Therefore, Theory and Modeling will play a similarly fundamental role in the conception and execution of RAM. Modeling will also play an important role in understanding cross-scale coupling such as turbulent transport. Here, kinetic and/or hybrid models must be developed for large-scale systems approaching the global magnetohydrodynamic models.

5.3 Define the origins and societal impacts of variability in the Sun-Earth connection.

The Space Weather element of the Living With a Star program requires research and development targeted at the basic physics needed to create space weather forecasting capabilities. With the exception of very few simple causal relationships, forecasting is based on modeling the future behavior of the space environment based on known present conditions. Such models are necessarily physics-based in that the underlying physics, developed from theory and guided by observations, provides the key ingredient for forecasting capability. Finally, the testing of candidate models against new measurements takes on an additional and very important role of validating progress. These models will combine global modeling and local modeling approaches such that the physics included in the global model will be derived from local models and theory, which is in turn driven by targeted LWS observations.

The close-knit relation between model development and observations will benefit all LWS missions. Specifically, SDO will provide scientific insight, inputs to models, as well as the data against which solar interior, coronal, and heliospheric models can be evaluated. The close linkage between observations and models will also answer one of the most pressing questions underlying space weather modeling; the question of which information has to be provided to models for precision forecasts of the future space environment. Modeling plays a similar role within the geospace segment of LWS, consisting of Radiation Belt Storm Probes, and Ionosphere Thermosphere Storm Probes and Inner Heliospheric Sentinels. Here models and theory will, through mapping techniques and data assimilation, extend a set of multi-point measurements to large-scale specification. Subsequent comparisons between predicted and actual futures will lead to the scientific understanding and forecasting capabilities.

5.4 Summary of Theory and Modeling in the SEC Division.

This discussion elucidates the growing importance of theory and modeling for the SEC Division. Theory and modeling is suitably implemented in four forms. First, the success and value of basic scientific research renders the SEC Theory Program highly valuable. In order to address national needs in the space weather area, a targeted and well-planned research activity is required, which also needs to be integrated with LWS missions. This activity should also include a plan for the transitioning of research results and models to the operational agencies. The needs of other missions also mandate that suitably sized theory and modeling activities be established alongside instrument and spacecraft subsystem development. The roles of supporting innovative ideas and approaches have been successfully filled by a strong supporting research and technology program.

6.0 Education and Public Outreach Introduction

NASA's mission is to inspire the next generation of explorers. The Office of Space Science (OSS) has identified a specific enterprise goal to "share the excitement and knowledge generated by scientific discovery and improve science education", with specific objectives: (1) to share the excitement of space science discoveries with the public; (2) to enhance the quality of science, mathematics, and technology education, particularly at the precollege level; and (3) to help create our 21st century scientific and technical workforce.

OSS provides significant funding across the enterprise to support the achievement of these objectives. As a result of these investments over the past 5 years, EPO is now well integrated throughout all elements of the SEC theme. The Sun-Earth Education Forum and regional Broker/Facilitator institutions work together to develop and support partnerships between SEC scientists and education professionals in formal and informal settings as well as to encourage coordination of activities.

Sun-Earth Connection Education Forum

The Sun-Earth Connection Education Forum (SECEF) provides a national coordination and support structure for the SEC theme. A partnership between NASA's Goddard Space Flight Center and UC Berkeley's Space Sciences Laboratory, SECEF

- Facilitates the involvement of SEC scientists in education and outreach
- Helps identify high leverage opportunities
- Coordinates nationally and synthesizes the education and outreach programs undertaken by SEC flight missions and individual researchers
- Arranges for the widest possible dissemination and long-term sustainability of SEC education and outreach programs and products, and
- Identifies and disseminates best practices in education and public outreach.

6.1 Sharing our Science with the Public

In the modern age, space exploration continues to thrill the public with new discoveries that help them build a better understanding of the Sun, near Earth space, the solar system, and the Universe. Whether encouraged through news releases highlighting solar events, high production value films bringing excitement of SEC science and research to life, PBS documentaries, innovative planetarium shows, museums, science centers, or rich website environments, a significant fraction of the US population retains an abiding fascination with space exploration and discovery that can be used to facilitate the achievement of the EPO objectives identified by OSS.

The SEC Division has significant science resources to share with the public. However, sectors of the education and outreach community remain ill-prepared to take advantage of them. The large majority of K-12 educators are not prepared with sufficient science-based content knowledge to effectively develop students understanding and engagement with SEC related science themes. And yet, it is through the educational system that students are prepared for the workforce of tomorrow. Current demographic trends show that the US is facing a critical shortage of workers prepared with sufficient science, math, and technology knowledge to continue the technological leadership the US now enjoys, and which has also been responsible for the ability to dramatically expand SEC science knowledge over the past 50 years. It therefore becomes critical, for the health of the OSS enterprise and SEC science, to share science, enhance K-14 education, and assist in the development of our workforce.

6.2 Partnerships and Leverage

In order to achieve these objectives, the OSS EPO infrastructure is working to identify optimal ways to support the needs of multiple audiences – students, K-14 teachers, museum-based educators, community educators, the public, and policy makers. By targeting high leverage opportunities and partnerships, OSS SEC EPO activities can have a significant impact on large audiences that are difficult to reach through direct interactions alone. Resources and programs available from SEC can become integrated into ongoing programs through participation in and support of education initiatives and professional organizations, providing amplified impact. Professional development workshops for educators are a highly effective example of educational outreach. Results are particularly dramatic when educators are required to provide in-district training to their colleagues.

Innovative Partnerships

The National Parks provide a natural venue where the interests of the NASA Earth Science Enterprise, the Office of Space Science, and the National Park Service can complement and support each other in EPO efforts. Programs offered to the public by park rangers in these settings can be enriched by SEC science content. Examples range from supporting 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.

High visibility for SEC EPO efforts is achieved by building on existing programs, institutions, and networks and by coordinating activities within NASA and other institutions. Promising opportunities for partnership exist with programs underway across NASA enterprises (for example, the NASA Space Grant Program and the Earth Science Enterprise Education Program), with programs under development externally through funding from NASA and other agencies, foundations, non-profits, and industry. Through partnerships with educators and educational organizations, planetaria, museums, science centers, national parks, community groups, publishers and the media, SEC science can be shared through existing networks and infrastructures, developed by specialists in each of these EPO venues. In this way, the special strengths of the Division can be utilized – SEC science discovery, the excitement of SEC missions, and SEC scientists and engineers. Through these partnerships, and a careful analysis of existing resources, SEC EPO can avoid reinventing the wheel, and ensure EPO funds are invested for highest impact.

High Impact Video Programming

The "LIVE FROM" series, developed by Geoffrey Haines-Stiles' Passport to Knowledge program, is a highly respected and high impact program supporting science education and literacy through broadcast media. With strong established relationships on PBS network stations, "LIVE FROM" EPO collaborations with this established program ensure a high visibility product that has been shown to have a positive impact on student learning. Successful programs include LIVE FROM THE HUBBLE SPACE TELESCOPE, LIVE FROM THE SUN, LIVE FROM A BLACK HOLE, LIVE FROM THE EDGE OF SPACE AND TIME, MARS 2002. In 2003, LIVE FROM THE AURORA is planned to highlight Sun-Earth Connections science through the beauty and dynamics of Earth's aurora.

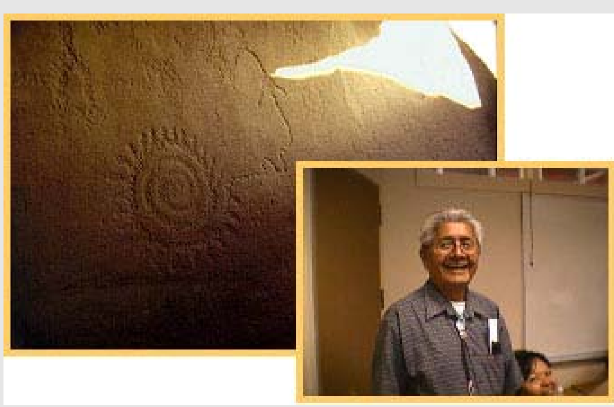
6.3 EPO Highlights - Examples of Successful Programs

There are now numerous examples of successful EPO products and programs highlighting SEC science and discovery. Over the past 3 years, SECEF has focused on development of resources for K-12 and informal education, including curriculum guides, educational materials, and workshops for educators, exhibits, planetarium shows, and the SEC web portal. In addition, SECEF has played a major role in facilitating organization and programming for events associated with solar eclipses and Sun-Earth Day.

In addition to these activities, SECEF has been active providing infrastructure support to EPO activities within OSS, including supporting development of the Space Science Education Resource Directory, facilitation of space science product and website review, as well as support of national conferences.

Sun-Earth Days

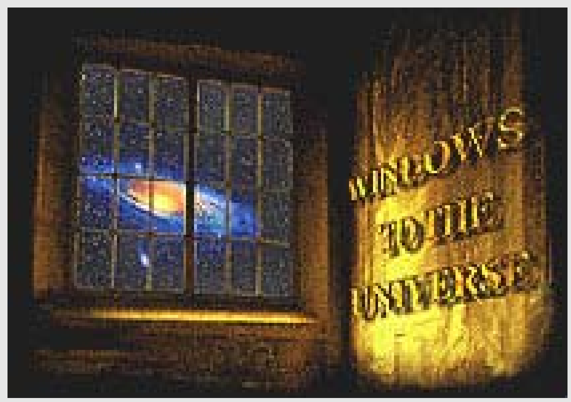
During Sun-Earth Day, 2001 (April 27-28), over 100 events were scheduled nationally, involving 200,000 formal education participants. All NASA education offices were involved in workshops, special events, classroom visits, and other dissemination opportunities. Sun-Earth Day, 2002 (March 20) combined a Native American connection and equinox theme for a multifaceted successful event. Resources included grade-level appropriate classroom activities, a central website, a Sun-Earth Day kit distributed through NASA Core, and a NASA Quest webcast with scientists and featured activities.



EPO efforts for future missions should build upon this heritage, and identify new opportunities to share the excitement and relevance of our science to society, with educators, students and the public.

High Impact Web Portals

Web sites developed over the past several years with funding from NASA and other agencies provide high leverage venues for further education and outreach efforts, due to their large existing audiences and content bases. The award-winning Windows to the Universe project, now in its 8th year of development, serves over 4 million users per year, and is used extensively in the K-12 classroom by students and teachers. Supported primarily through the OSS Information Technology Research Program in partnership with the Earth Science Enterprise, this existing high-leverage web resource is now being used to support new OSS missions and research programs.



6.4 EPO Themes for the Future

Missions in the near- and intermediate-term across the STP and LWS lines share several common thematic elements for the purposes of education and public outreach – magnetic fields, plasmas, the Sun and its impact on the near Earth space environment. For these audiences, the details of the physics explored in each mission are likely to be beyond the scope of understanding for most people. The common themes identified here, however, are highly relevant to both the public as well as to students and educators, invite their curiosity and provide vehicles for showcasing exciting scientific discovery at the forefront of mission research.

All SEC missions share an emphasis on space plasmas and the role of magnetic fields. From the perspective of the public, students, and educators, near-term missions (Stereo, Solar B, and SDO) and intermediate-term missions (Telemachus, Solar Orbiter, RAM, Solar Probe, and Inner Heliospheric Sentinels) will highlight the Sun, phenomena on the Sun, their variability, and their impact on the inner heliosphere. MMS, GEC, MagCon, Radiation Belt Storm Probe, Ionosphere Thermosphere Storm Probe, Inner Magnetospheric Constellation, and Tropospheric ITM Coupler focus on the detailed structure and dynamics of planetary magnetospheres and plasmas, in the case of GEC and Tropical ITM Coupler extending to the coupling of the magnetosphere with the ionosphere and atmosphere of Earth. Similarly, although JPO targets the Jovian magnetosphere/ionosphere system, the fundamental processes involved mirror those under investigation with the Earth magnetosphere/ionosphere focused missions mentioned above. For the purposes of EPO, the potential to compare and contrast results from JPO with MMS, GEC, and Magnetospheric Constellation is very powerful.

The high impact themes described below are recommended as those that will be particularly fruitful for EPO activities, based on their cross-cutting nature and relevance to educational needs. Each supports multiple missions described in the Roadmap, has strong links to the NSES, and have significant potential for high public impact due to the inherent nature of the theme and the quality of imagery available.

High Impact EPO Themes

Voyage to a Star – A focus on missions to the Sun will highlight science in extreme environments. EPO activities connecting to this theme will support multiple missions described in this Roadmap document and connect strongly with content standards described in the NSES. Solar and celestial events can be used as the focus of high impact public events that can delve further into the science.

Magnetic Fields – Magnetic fields are central to SEC research and numerous missions described in the Roadmap. The invisible nature of this force, acting at a distance, is inherently fascinating to young people, yet also is poorly understood by educators and the public. In addition, magnetism appears prominently in the NSES.

Solar Variability – Variability of the Sun on different temporal scales in the past, present, and the future has particular relevance to the public. Whether focusing on solar eruptive events or the Maunder Minimum, the variability of the Sun and it potential impact on the Earth's environment connects directly with society. With strong connections to the NSES and linkages to climate, this is a topic of high societal relevance and public interest.

Space Debris – Public interest and concern about space debris can be used to provide educational resources on gravity, variable atmospheric effects (drag) related to space weather effects, and satellite orbits and tracking. This topic has strong links to the NSES, and there is the possibility of events associated with incoming debris.

Voyage to the Unknown – Continuing trek of Voyager and Pioneer to the edges of the solar system is a fascinating concept for students and the public. This provides a window to outer heliospheric topics, and has connections to the NSES.

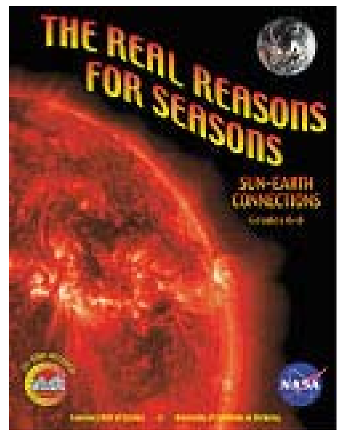
6.5 EPO Program Elements for Future Emphasis

The lack of diversity in the professional scientific workforce has recently been recognized as a critical national issue for the future of science. In the face of imminent large-scale retirements at high levels across industry, federal agencies, and academia in science, declining numbers of the “traditional” scientific workforce is pursing scientific careers. Although some fields have had moderate success attracting minorities and women to fill this gap, the geosciences lag behind all other fields of science in recruitment of underrepresented scientists. EPO efforts developed through SEC can contribute to the objective of attracting underrepresented students to our field through examination of existing programs and best practices. Opportunities range from working in collaboration with after-school programs for K-12 students, supporting outreach programs at museums in urban settings, working with schools in inner city settings, to providing enrichment to academic bridging programs at institutions such as community colleges and Minority Serving Institutions.

Connecting Sun City with Sun-Earth Connections Minority Partnership

Through a mix of school-year and summer activities, "Connecting Sun City with Sun-Earth Connections" will encourage El Paso-area Hispanic students to pursue science careers and assist teachers and university faculty in providing improved science education to their students by using space science as a thematic vehicle to create enthusiasm for science and mathematics. University of Texas at El Paso (UTEP) faculty in all departments of the College of Science will participate in the program in conjunction with teachers from area schools. Activities include summer inquiry institutes for teachers, shorter school-year workshops, and school visits for teachers as well as summer science camps for students.

Additional opportunities to bring our science to students in K-14 settings arise when we use our science in examples of mathematical, geographic, historical, and social contexts. Likewise, our science is rich in examples of complex systems, processes, and models that can be used to address NSES requirements to develop student understandings of unifying concepts and processes. Another rich area for EPO development is technology and engineering. SEC missions provide exciting examples of complex technologies and amazing engineering concepts that can excite students through research/design experience.



7.0 Critical Factors and External Assessment Introduction

Successful execution of the SEC roadmap depends upon several factors beyond the control of the Division. Major factors are: access to space, collaboration within NASA and with other organizations, and infrastructure issues.

7.1 Access to Space

7.1.1 Launch cost and availability

All SEC missions require uninhibited access to space. Launch costs for Solar Terrestrial Probe missions currently comprise approximately one fourth of the total mission cost. Reductions in launch costs would enhance science returns by shifting money currently spent on launch vehicles into enhanced spacecraft and scientific instrument capabilities. Continued availability of launch vehicles for small payloads is being questioned. There are several ways to reduce launch costs and increase launch vehicle availability.

Direct procurement of US launch services

NASA should negotiate directly with launch providers to obtain, for example, complete packages of spacecraft, integration, and launch services at reduced rates for individual missions.

Additional launch vehicles

NASA should broaden the range of launch vehicles to fill gaps in capability. For example, they should encourage a range of intermediate launch capabilities between the small and large launchers already available. This would increase competition for launch capabilities, provide a variety of launch options, and allow launch capabilities to be tailored to particular missions.

Foreign launch vehicles

NASA should pursue the option of selecting foreign launchers for certain missions. This opens up the possibility of additional competition, thereby reducing launch costs for both foreign and domestic launchers.

Secondary payloads

NASA should develop the ability to purchase secondary payload space on US and foreign launch vehicles, in some cases for entire missions and in others to enhance mission capabilities. A dedicated secondary payload program increases access to space, reduces overall mission costs, and provides the opportunity to perform test bed-like development projects with greatly reduced launch costs.

7.1.2 Importance of the Explorer, Discovery, Sub-Orbital, and Testbed Programs to SEC

The explorer, discovery, and sub-orbital programs fill a critical niche in SEC science. They perform specific, focused scientific investigations on SEC themes using the latest technology, accepting a greater degree of risk than SEC missions like the Solar Terrestrial Probes or Living With a Star. This enhanced risk often results in a higher science to mission cost ratio. Furthermore, the specific, focused science investigation of these missions reduces the time for mission development. As a result, the Explorer and Sub-Orbital programs greatly enhance the SEC Division's overall science return. Adding a Space Testbed program to these programs would permit the development of spacecraft subsystems and reduce overall mission costs. Finally, the shorter schedules of all these focused programs encourage the training of young scientists and engineers who will become essential personnel on future SEC missions.

Explorer Program

NASA should strive to maintain the Explorer program originally conceived by alternately selecting small and medium SEC-theme Explorer missions each year. Similarly, it should launch either a medium or a small explorer mission each year.

Discovery Program

NASA's Discovery program provides the planetary community with access to relatively low cost missions. While these missions focus upon planetary themes, NASA and the planetary community should remain open to including Discovery missions that address comparative planetary environments. In the past, this approach has resulted in greatly enhanced scientific return.

Sub-orbital Program

The NASA Sub-orbital Program has produced outstanding science throughout its lifetime. Many phenomena have been discovered using rockets, rockoons and balloons and many outstanding problems brought to closure, particularly when teamed with ground-based facilities. Unique altitude ranges and very specific geophysical conditions are often only accessible to sounding rockets and balloons, particularly in the campaign mode. Furthermore, the extremely short sounding rocket schedule provides an excellent training ground for young scientists and engineers, including the opportunity for a student to be in a project from cradle to thesis. This short schedule also allows for significantly higher risks, with correspondingly greater scientific returns. NASA should strive to maintain and enhance the funding of the sounding rocket program and continue to develop cost savings measures that place additional responsibility and resources in the hands of the sounding rocket PI institutions.

Space Testbeds

The SEC's strategic plan increasingly emphasizes missions that employ fleets of satellites to provide multi-point diagnostics of the Solar-Terrestrial interaction. If the standard percentage scheme for development margin is used for all the satellites, the resulting costs will be prohibitive. SEC needs a flight test program to lower the programmatic risks for these missions and to allow a quick, high-risk test of the first prototype spacecraft or at least the key sub-systems of such spacecraft. Some of these functions are accommodated in the sub-orbital program (limited in flight duration, but critically important), and also the Space Technology series (e.g., ST-5). However, higher profile programs that do not have a specific technology focus tend to receive higher public attention, particularly when the program "fails". As a result, costs continue to increase for programs providing rapid access to space. NASA should consider teaming with other US Government agencies, in particular the Air Force Space Test Program, to implement a quick, low-cost orbital program enabling rapid access to space to test missions and mission concepts in a low-profile environment.

The LWS Space Environment Testbeds, described in Section 4.5, Technology Implementation Plan, provides a step in this direction by utilizing teaming opportunities with interagency and international partners. The flight testing provided by these low profile Space Environment Testbeds will enable the infusion of new technology thereby reducing both risk and excessive design margins for future space missions.

7.1.3 Large Missions

The SEC mission roadmap contains some missions that are outside of the typical funding limitations of Solar Terrestrial Probes and Living With a Star mission cost caps. One of these missions is Solar Probe, which is a very high priority mission that accomplishes SEC science that is not possible with any other mission. For this mission and some others, NASA needs to be flexible in determining overall mission cost caps. For its part, the SEC community must realize most missions must stay within particular mission cost cap requirements or future missions will be impacted.

7.2 Collaborations Within NASA and With Other Organizations

7.2.1 Vital Need for L1 Observations

All SEC missions benefit greatly from solar wind particle and field measurements at the L1 libration point. Given the budget limitations for SEC missions, the STP and LWS mission lines assume that L1 monitoring will continue. ACE, WIND, and SOHO currently fulfill most needs of the observational and modeling communities for L1 monitoring. The capabilities of these spacecraft could be greatly extended at low-cost by launching TRIANA. (The primary science objective of this mission is in the Earth Sciences directorate; however, it does carry solar wind monitoring instruments). The measurements of these four spacecraft could be used to calculate vector particle and field gradients, as well as the internal structure, of large- and small-scale heliospheric disturbances aimed towards the Earth's magnetic shield. Since the SEC has no plans for subsequent missions to make these critical measurements, NASA should work closely with other government agencies to develop low-cost "operational" L1 missions that provide real-time solar wind data for space weather forecasts (e.g., those provided by the NOAA Space Environment Center) in addition to data for scientific study of the solar wind and its effects.

7.2.2 Intra-agency Collaboration – heliospheric observations on planetary missions

Historically, the major advances in both heliospheric physics and comparative magnetospheres resulted from collaboration between the Sun-Earth Connection and Solar System Exploration. In fact, there have only been three stand-alone heliospheric missions: Helios (a German mission), Ulysses (joint US and ESA mission), and ACE (a US Explorer mission). The remaining heliospheric missions and all of our comparative magnetospheric missions have resulted from the inclusion of space physics instrumentation on planetary missions such as Mariner, Pioneer, Voyager, Galileo, and Cassini. The payoff of these complementary payloads has not been just one-way. For example, Voyager's discovery of volcanic activity on Io and the Io plasma torus showed the importance of understanding Jupiter as a system, including the planet, its moons, and magnetosphere. With the revolution of 'faster-better-cheaper' missions, the planetary missions have become smaller and more focused. NASA needs to continue to encourage the Solar System Exploration and Sun-Earth Connection themes to collaborate on new planetary and SEC missions.

7.2.3 Inter-agency Collaboration – DOD, NOAA, NSF, etc.

The goals of the SEC's Living With a Star program necessitate close collaboration with other agencies such as the DoD and NOAA. For example, the LWS program assumes that there will be hard and soft X-ray monitors (on GOES spacecraft and its successors) to supply data essential to the Earth-atmospheric aeronomy and climate studies. In return the LWS and Solar Terrestrial Probe missions provide important data for other agencies. For example, the real-time ACE and IMAGE data provided to the NOAA Space Environment Center have revolutionized space weather forecasting. NASA should initiate and maintain close collaboration with other government agencies to maximize scientific return from its missions and maximize the government and private sector return on its space investments. This collaboration becomes increasingly important as the LWS program begins to make significant progress on the physics behind those aspects of space variability that affect society.

7.2.4 Ground-based observations

Historically, SEC missions have benefited significantly from coordination with ground-based observations, typically under the auspices of the National Science Foundation. Ground-based radars, all-sky imagers, riometers, and magnetometer chains provide the global context of the ionosphere and upper atmosphere for magnetospheric and ITM missions. Many missions require ground-based coordination to complete their science objectives. NASA should initiate and maintain close collaboration with NSF and other agencies that design, develop, and implement ground-based observing systems.

7.2.5 International Collaboration on Missions

SEC missions receive significant scientific leverage from international partners. This participation depends on continued NASA and US policies supporting scientific cooperation. NASA should initiate and maintain close collaboration with other space agencies. The most significant policy that affects this international participation is the International Traffic in Arms Regulations (ITAR)

7.2.6 International Traffic in Arms Regulations (ITAR)

ITAR places significant burdens on scientists and program managers engaged in SEC science investigations that are international in scope. The regulations cast a wide net, affecting virtually all space flight hardware. Compliance levies additional burdens and stresses on program managers and scientists who must prepare applications for Technical Assistance Agreements (TAA). The regulations can become self-defeating in certain cases. For example, foreign collaborators can be barred from operation centers (regardless of existing TAAs), making them unavailable for important and sometimes critical decision processes. In other cases, the TAA may not be approved until after the Phase A period of the project, effectively preventing team meetings from being held during that important formative period of the mission life cycle.

NASA can take constructive steps in the ITAR arena to facilitate efficient mission planning and execution. For example, NASA could adopt a more proactive role and brief the State Department regarding a particular mission early in the project life cycle (i.e., during pre-Phase A studies). This could result in the granting of a blanket approval for appropriate activities associated with individual missions or, at a minimum, an expedited approval procedure. Short of that, NASA may be able to negotiate with the State Department to obtain TAA approvals during the proposal evaluation phase, thereby enabling teams with international components to commence team level meetings and planning during Phase A.

7.3 Infrastructure Issues

7.3.1 Spacecraft Communications - DSN

Although much SEC science is done near the Earth, significant science in this roadmap requires spacecraft in solar orbits far from Earth or orbits about other planets. Furthermore, some of these missions require large downlink telemetry rates. This represents a departure from traditional SEC missions whose tracking requirements could be met by small ground stations. The new suite of missions will require the state-of-the-art capabilities of an already fully subscribed Deep Space Network. To realize the potential gains from these new missions, it is necessary for NASA to continue to upgrade and expand the capabilities of the DSN to be able to track more spacecraft and with larger telemetry bandwidths.

7.3.2 Information Technology

The information technology infrastructure has enabled broad access to NASA databases. It addresses the problem of how to compare data from different sources, at different locations, and on different computer systems. Most NASA scientific data is in the public domain and maintaining the reliable and user-friendly information technology infrastructure has made this a reality rather than an ideal. In the future, far greater demands will be placed on this infrastructure by the large volumes of data produced many of the SEC missions. NASA should continue to maintain and incorporate developing technology into this infrastructure to meet these mission needs.

7.3.3 Human Resources – Need for Scientists and Engineers

The 25-year roadmap plan assumes that adequately trained scientists and engineers will be available to carry out the missions. This assumption depends on the existence of clear paths by which technically trained people can join NASA projects. Paths currently exist, for example, through special training programs, college and university investigator opportunities, and private industry. NASA should continue to support and enhance current paths and explore new training paths. Enhanced development of joint NASA-University collaborations is one of many examples of ways NASA can strengthen engineering and scientific participation in NASA programs.

7.3.4 Supporting Research and Technology (SR&T) program

The Supporting Research and Technology (SR&T) program has been of immense value to the mission of the Sun-Earth Connection Theme. The Sun-Earth Connection requires a mechanism to support innovation in both research and technology development. Furthermore, the value of present and past research missions benefit greatly from research not directly tied to a mission or mission line, but from one that permits integration of research across mission lines and data sources. Finally, developing SR&T proposals helps young scientists career development. NASA should maintain a healthy SR&T program and continue to provide easy access to mission data for these types of studies.

Appendix A
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Appendix B
SEC Roadmap Acronyms

1D	One Dimensional
3-D	Three Dimensional
AC	Alternating Current
ACE	Advanced Composition Explorer
ACRs	Anomalous Cosmic Rays
AMS	Auroral Multiscale
APS	Active Pixel Sensor
AU	Astronomical Unit
CCD	Charge Coupled Device
CIRB	Cosmic Infrared Background
CIRs	Corotating Interaction Regions
CMEs	Coronal Mass Ejections
CRRES	Combined Release and Radiation Effects Satellite
DBC	Dayside Boundary Layer Constellation
DC	Direct Current
DoD	Department of Defense
DSN`	Deep Space Network
ENA	Energetic Neutral Atom
EPO	Education and Public Outreach
ESA	European Space Agency
EUV	Extreme Ultraviolet
eV	Electron Volt
FOV	Field Of View
FUV	Far Ultraviolet
GEC	Geospace Electrodynamic Connections
GMIRs	Global Merged Interaction Regions
GNC	Guidance, Navigation and Control
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
GSRI	Geospace System Response Imager
H	Hours
H	Hydrogen
He	Helium
Hi-EIRP	Effective Isotropic Radiated Power
HIGO	Heliospheric Imager and Galactic Observer
IHS	Inner Heliospheric Sentinels
IMAGE	Imager for Magnetopause-to Aurora Global Exploration
IMC	Inner Magnetospheric Constellation
IMF	Interplanetary Magnetic Fields
ISAS	Japanese Institute of Space and Astronautical Science
IT	Information Technology
IT	Ionosphere Thermosphere
ITAR	International Traffic in Arms Regulations
ITM	Ionosphere / Thermosphere / Mesosphere
JPO	Jupiter Polar Orbiter
°K	Degrees Kelvin
km	Kilometer
LEO	Low Earth Orbit
LISM	Local Interstellar Medium
LWS	Living With a Star
MagCon	Magnetospheric Constellation
MC	Magnetospheric Constellation
MeV	Million Electron Volts
MHD	MagnetoHydro Dynamics
M-I	Magnetosphere-Ionosphere
MIA	Magnetosphere-Ionosphere-Atmosphere
MIO	Magnetosphere-Ionosphere Observatory
MMO	Mercury Magnetosphere Orbiter

MMS	Magnetospheric Multiscale
MPO	Mercury Planetary Orbiter
MTRAP	Magnetic TRAnsition Region Probe
NOAA	National Oceanographic and Atmospheric Administration
NASA	National Aeronautics and Space Administration
NEP	Nuclear Electric Propulsion
NMP	New Millennium Program
NO	Nitric Oxide
NRA	NASA Research Announcement
NSES	National Science Education Standards
NSF	National Science Foundation
O/N2	Oxygen/Nitrogen Dioxide Ratio
OSS	Office of Space Science
PASO	Particle Acceleration Solar Orbiter
PRT	Pioneering Revolutionary Technology
RAM	Reconnection and Microscale
Re	Earth Radii
RFA	Research Focus Area
ROSS	Research Opportunities in Space Science
SBIR	Small Business Innovative Research
SCOPE	Solar Connections Observatory for Planetary Environments
SDO	Solar Dynamics Observatory
SEC	Sun-Earth Connection
SECEF	Sun-Earth Connection Education Forum
SEEC	Sun-Earth Energy Connector
SHEC	Sun-Heliosphere-Earth-Constellation
SI	Stellar Imager
SIRA	Solar Imaging Radio Array
SOHO	SOlar and Heliospheric Observatory
SR&T	Supporting Research and Technology
ST-5	Space Technology-5
STEREO	Solar-TErrestrial Relations Observatory
STP	Solar Terrestrial Probes
TAA	Technical Assistance Agreements
TRACE	Transition Region And Coronal Explorer
ULP	Ultra Low Power
US	United States
UTEP	University of Texas at El Paso
UV	Ultraviolet

Appendix C: Comparison between the 2003 Sun-Earth Connection Roadmap and the 2002 Solar and Space Physics Decadal Survey

The 2003 SEC Roadmap Report and the 2002 Solar and Space Physics Decadal Survey Report (The Sun to the Earth and Beyond: A Decadal Research Strategy in Solar and Space Physics) were developed independently. There were no members of the main Decadal Survey Panel that were also members of the Roadmap team. Furthermore, because of National Research Council requirements, the Decadal Survey report remained confidential until August 2002, when the Roadmap report was in its final stages of development. Nevertheless, there were several Roadmap team members that were also members of the various sub-panels of the Decadal Survey. Thus, overlap was inevitable between the two reports.

Although overlap was expected, it was also expected that the Roadmap and Decadal Survey reports should have some differences. After all, the Roadmap report focuses on Sun-Earth Connection research conducted through strategic missions over an extended interval whereas the Decadal Survey report has a much broader audience including the National Science Foundation, NOAA, and the Department of Defense. The following compares those elements of the Roadmap and Decadal Survey that are similar, but use different terminology. This comparison is intended to illustrate that the two reports are similar when the parts of the Decadal Survey that pertain to the Sun- Earth Connection Division are considered.

Science Issues

Both the Roadmap and Decadal Survey describe "science objectives" for the "coming decade and beyond". That is, the Decadal Survey recognizes that the objectives listed in its executive summary are multi-decadal, similar to the Roadmap science objectives. In the Roadmap, these objectives are called Primary Science Objectives, while in the Decadal Survey, they are called Science Challenges. The Roadmap Primary Science Objectives are further divided into Research Focus Areas, which are approximately decadal in duration. When compared side-by-side as in Table C1, it is apparent that the Science Objectives and Research Focus Areas in the Roadmap and the Science Challenges in the Decadal Survey are very similar. In particular, the first three Science Challenges of the Decadal Survey and the first three research focus areas of the Roadmap are very similar. The next two Science Challenges in the Decadal Survey are similar to the second and third Science Objectives in the Roadmap. The most significant difference between the Science Challenges and the Roadmap objectives is in the fifth Challenge and third Science Objective in Table C1. The Roadmap Science Objective focuses on the targeted basic research in the Living With a Star program that will lead to an understanding of the impacts of variability in the Sun-Earth connection. The Decadal Survey Science Challenge goes further to develop near-real-time predictive capability for understanding the impacts of variability in the Sun-Earth connection. This difference reflects the broader institutional nature of the Decadal Survey when compared to the Roadmap. In the Decadal Survey, the Science Challenges extend to other government institutions such as NOAA, which has typically had the responsibility of developing and maintaining "operational" space missions (e.g., the GOES spacecraft). In contrast, the Roadmap is focused on the Science Objectives of the Sun-Earth Connection Division, which does not typically have responsibility over "operational" space missions.

Table C1. Comparison of the Roadmap Primary Science Objectives and Research Focus Areas and the Decadal Survey Science Challenges.

2003 SEC Roadmap Primary Science Objectives	2003 SEC Roadmap Research Focus Areas	2002 Solar and Space Physics Decadal Survey Science Challenges
Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.	- Understand the structure and dynamics of the Sun and solar wind and the origins of magnetic variability.	1. Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona
	- Determine the evolution of the heliosphere and its interaction with the galaxy.	2. Understanding heliospheric structure, the distribution of magnetic fields and matter throughout the solar system, and the interaction of the solar atmosphere with the local interstellar medium
	- Understand the response of magnetospheres and atmospheres to external and internal drivers.	3. Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences
Explore the fundamental physical processes of space plasma systems.	- Discover how magnetic fields are created and evolve and how charged particles are accelerated. - Understand coupling across multiple scale lengths and its generality in plasma systems.	4. Understanding the basic physical principles manifest in processes observed in solar and space plasmas
Define the origins and societal impacts of variability in the Sun-Earth connection.	- Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere and affect the Earth - Specify and enable prediction of changes to the Earth's radiation environment, ionosphere, and upper atmosphere. - Understand the role of solar variability in driving space climate and global change in the Earth's atmosphere.	5. Developing near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in the Earth's magnetosphere.

Mission Issues

Nearly all of the missions in the Decadal Survey are found in the Roadmap under the same name. The Decadal Survey lists missions in priority order. Such a prioritization is not done in the roadmap. Furthermore, the Decadal Survey considers missions from a variety of sources in its prioritization. Thus, there are some differences in the Decadal Survey and Roadmap missions. These differences are delineated in Table C2. Aside from name changes, there are few differences in the missions. One exception is the Stereo Magnetospheric Imager (last row in Table C2) and the Geospace System Response Imager (GSRI). GSRI incorporates elements of the Stereo Magnetospheric Imager mission in its mission design; however, these two missions are different.

Finally, there are several missions in the Roadmap that do not appear in the Decadal Survey. This difference should not be surprising considering that the Decadal Survey has a much shorter time horizon than the Roadmap. The placement of the missions in the two reports is also somewhat different. The Roadmap missions are placed in three categories (near-, intermediate-, and long-term) based on the start of mission phase C/D. In contrast, the Decadal Survey discusses missions with launch dates within the next decade.

Table C2. Comparison of Missions in the Roadmap and Decadal Survey.

Roadmap Mission	Decadal Survey Mission	Comments
Solar Probe	Solar Probe	Both the Roadmap and Decadal Survey recognize this as a "large" mission of high importance.
Magnetospheric Multiscale	Magnetospheric Multiscale	Identical in the two reports
Radiation Belt Storm Probes/ Ionosphere Thermosphere Storm Probes	Geospace Network	Identical missions in the two reports, only differences in the names
Jupiter Polar Orbiter (JPO)	Jupiter Polar Mission	Essentially identical missions in the two reports, with slightly different names
Inner Heliosphere Sentinels (IHS)	Multi-spacecraft Heliospheric Mission	Nearly identical missions in the two reports, only differences in the names
Geospace Electrodynamic Connections (GEC)	Geospace Electrodynamic Connections (GEC)	Identical in the two reports
Magnetospheric Constellation (MC)	Magnetospheric Constellation	Identical in the two reports
L-1 Diamond	Solar Wind Sentinels	Similar missions in the two reports (differing in the number of spacecraft)
Geospace System Response Imager (GSRI)	Stereo Magnetospheric Imager (SMI)	GSRI incorporates some of the elements of SMI, but these missions are different

Appendix D
SEC Roadmap Mission Fact Sheets

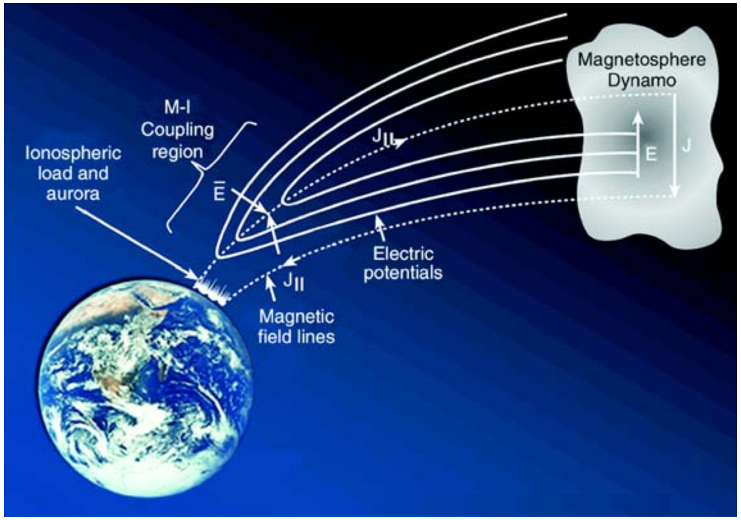
The following pages contain the SEC Mission Fact Sheets in alphabetical order. These missions include the STP and LWS missions in formulation and development, supporting international missions, and the SEC Roadmap Missions for the intermediate-term and the long-term.

Appendix D
SEC Near-, Intermediate-, and Long-Term Missions

Alphabetical Listing:

- Auroral Multi-Scale (AMS)
- Bepi-Colombo
- Dayside Boundary Layer Constellation (DBC)
- Geospace Electrodynamics Connections (GEC)
- Geospace Storm Probes
  - Ionosphere Thermosphere Storm Probes
  - Radiation Belt Storm Probes
- Geospace System Response Imager (GSRI)
- Heliospheric Imager and Galactic Observer (HIGO)
- Inner Heliosphere Sentinels (IHS)
- Inner Magnetospheric Constellation (IMC)
- Interstellar Probe
- Io Electrodynamics
- Ionosphere Thermosphere Mesosphere Waves Coupler
- Jupiter Polar Orbiter (JPO)
- L1-Diamond
- Magnetic TRAnsition region Probe (MTRAP)
- Magnetospheric Constellation (MC)
- Magnetosphere-Ionosphere Observatory (MIO)
- Magnetospheric Multiscale (MMS)
- Mars Aeronomy Probe
- Neptune Orbiter
- Particle Acceleration Solar Orbiter (PASO)
- Reconnection and Microscale (RAM)
- Solar-B
- Solar Connection Observatory for Planetary Environments (SCOPE)
- Solar Dynamics Observatory (SDO)
- Solar Imaging Radio Array (SIRA)
- Solar Orbiter
- Solar Polar Imager
- Solar Probe
- Solar-TERrestrial RElations Observatory (STEREO)
- Stellar Imager
- Sun-Earth Energy Connector (SEEC)
- Sun-Heliosphere-Earth Constellation
- Telemachus
- Tropical ITM Coupler
- Venus Aeronomy Probe

Auroral Multi-Scale



Minimum Technology Design was baselined

- No "enabling" technology required
- New enhancing technology should reduce spacecraft cost by 10%

Science Objectives

To understand the electrodynamic connection between Earth's ionosphere and magnetosphere

- What structures accomplish the connection?
- What is the electrical impedance and how is it established?
- What is the role of ionospheric feedback?
- How does magnetospheric dynamics affect the coupling?

Mission Description

- Four spacecraft flying in formation through the mid-altitude M-I coupling region, supported by on-board auroral UV imaging
- 600 X 7,000 km orbits
- Small orbital maneuvers to achieve near tetrahedral configuration at desired point in orbit

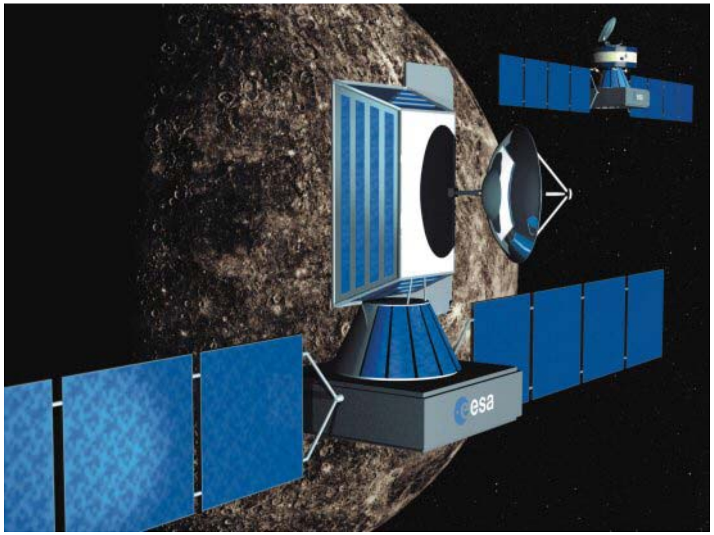
Measurement Strategy

- Measure j: B & precision attitude (0.02° maximum error)
- Measure ϕ: DC E-field, particle distribution, || B necessary
- Distinguish waves, static structures: ~10 μsec timing
- Identify kinetic processes via established signatures

UV Auroral imaging

- Establish context: motions, forms, and conductivity structures
- FOV focused along magnetic foot-point
- Daytime and nighttime imaging needed

Bepi-Colombo



Technology

- Solar Electric Propulsion will be demonstrated on ESA's technology mission, SMART-1 (2003)
- High Temperature (HT) MLI, HT coatings
- HT, high intensity GaAs solar cells
- HT, 2-axis large amplitude antenna articulation mechanism
- HT X/Ka high gain antenna reflector and feeds
- Miniaturized integrated electronics for HT environments
- Mercury Horizon Sensor, HT Sun Sensors
- Lander

Science Objectives

- Measure the composition, state and distribution of mass within Mercury's interior.
- Map Mercury's intrinsic magnetic field and determine the nature of its interaction with the solar wind.
- Measure the composition, density, and dynamic variations in the charged particles that populate Mercury's magnetosphere.
- Image the entire surface of mercury at a resolution <100 m and determine its composition.
- Determine if water ice exists in deep craters in Mercury's polar regions.
- Measure the composition and density of Mercury's tenuous exosphere.

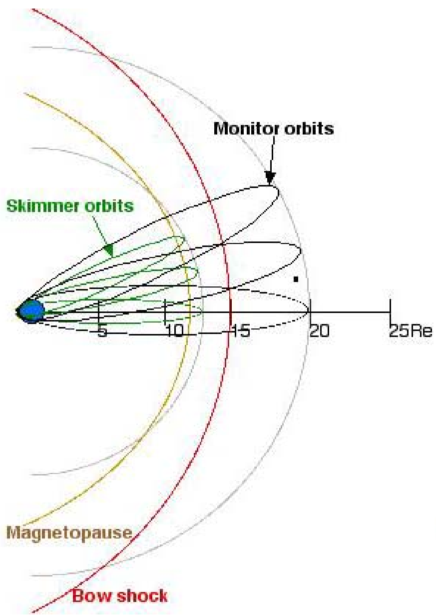
Mission Description

- 2-3 ESA/ISAS spacecraft using SEP and gravity assist (Moon, Venus, Mercury) to orbit Mercury
  - (MPO) Mercury Polar Orbiter (ESA) (3AS)
  - (MMO) Magnetospheric Orbiter (ISAS) (Spinner)
  - (MSE) Mercury Surface Element (ESA (if approved)
- Option 1: 2 spacecraft on 2 separate Soyuz-Fregat Launchers as much as 1 year apart
- Option 2: 3 spacecraft on 1-Ariane V
- Launch 2009-1010

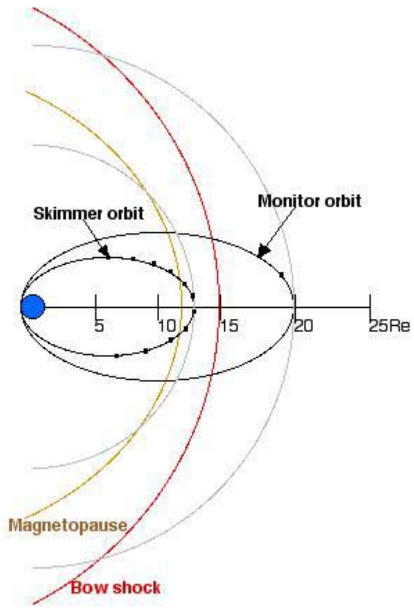
Measurement Strategy

- Planetary orbiter (MPO):
  - 3-axis stabilized
  - Visible/near IR camera, photon spectrometers (IR, UV, X-ray, gamma-ray), neutron spectrometer, accelerometer, K-band transponder
- Magnetospheric orbiter (MMO):
  - Spin-stabilized
  - Magnetometer, ion spectrometer, ion/electron analyser, cold plasma detector, energetic particle detector
- Surface element (MSE):
  - Physical properties and geochemistry package, camera, seismometer
- MPO remote sensing

Dayside Boundary Constellation



Equatorial View



Polar View

Minimum New Technology

- No “enabling” technology required
- Low level long duration thrust needed for orbit precession – small solar sail potential

Science Objectives

- Measure highly asymmetric and dynamic bow shock and magnetopause structures which regulate the solar wind’s impact on the magnetosphere.
- Establish the casual relationship(s) between these boundary phenomena and corresponding solar wind, foreshock, and magnetosheath drivers.

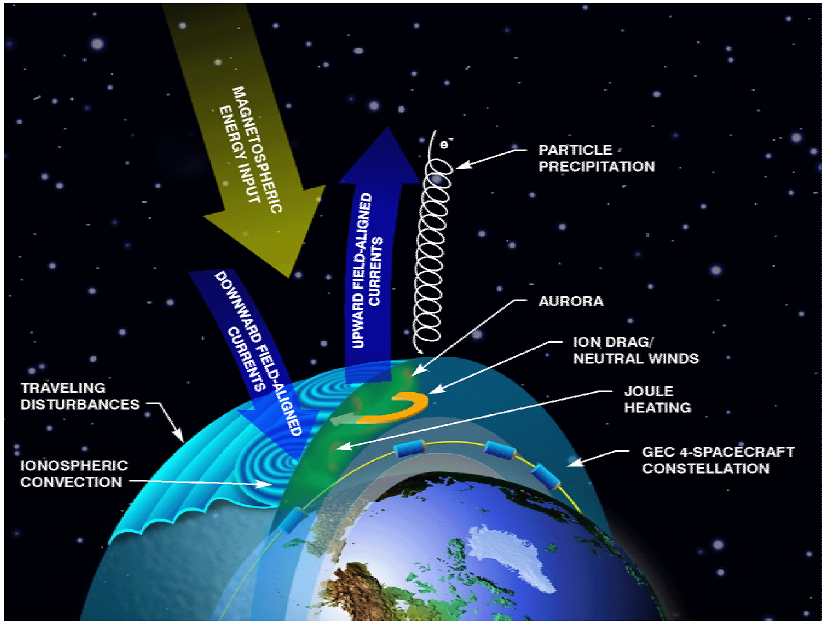
Mission Concept

- Orbits: 3 orbit planes near equator with 30 deg separation
  - Active precession to keep apogee on earth sun line
  - 11 “skimmers”per plane with 11 to 12 Re apogee
  - 1”monitor” per plane with ~ 20 Re apogee
- “Skimmer” separations range from 1 to 5 Re near apogees in phase with those of “monitors”

Measurement Strategy

- **Minimum measurement compliment to**
  - Identify boundary layer, magnetopause and shock crossings
  - Determine timing over ~Re separations: $\Delta t \sim 60$ seconds between SC
  - Measure solar wind & IMF (monitors)
- **Vector magnetic field**
  - ~0.5 nT accuracy, ~0.1 nT resolution
  - 0.1 sec resolution (required to despin)
- **Plasma**
  - Ions: density, flow, temperature. ~5 sec resolution
  - Electrons: 50 eV to 1 keV. ~5 sec resolution.

Geospace Electrodynamic Connections (GEC)



Key Mission Enhancing Technologies

- Aerodynamic Structures & Materials
- Low Magnetic & Electric Field Emissions
- Body Mounted Solar Arrays (ESC) with Lightweight/Rigid Booms
- Precise formation flying

Science Objectives

- Understand the response of the Ionosphere-Thermosphere system to Magnetosphere forcing
- Resolve the dynamic coupling of the Ionosphere-Thermosphere system to the Magnetosphere

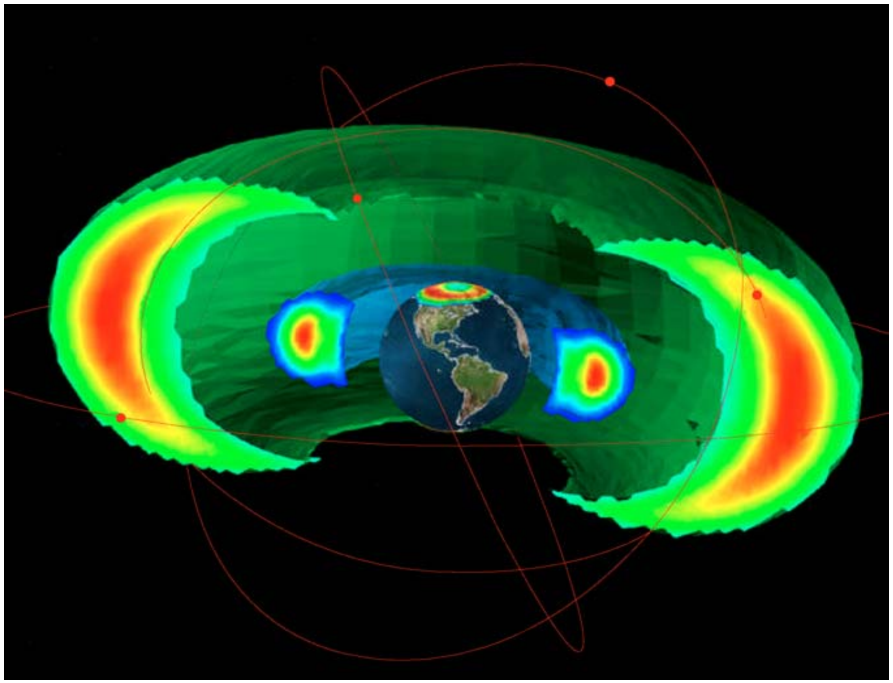
Mission Description

- A constellation of four spacecraft flying in formation (Pearls-On-A-String) each carrying identical sets of nine instruments.
- 185 X 2,000 km; 83 degree inclination parking orbit
- Orbital maneuvers, at select times, to lower perigee to an altitude of ~ 130 km, lasting up to one week

Measurement Strategy

- Measure in-situ all relevant plasma-neutral coupling parameters
- Spacecraft cross important high latitude magnetosphere-ionosphere coupling regions
- Unequal, variable spacecraft spacings to resolve different scales
- Low dips to altitude where atmosphere begins to dominate the plasma dynamics.

Geospace Storm Probes



Minimum Technology Design was Baselined

- Enabling technology development in high-radiation avionics pending
- New enhancing technology should reduce spacecraft cost for multiple-spacecraft investigations

Science Objectives

- Characterize and understand acceleration, global distribution, and variability of the radiation belt electrons and ions that produce the harsh environments for spacecraft and humans
- Characterize and understand mid-latitude ionospheric variability and irregularities that affect communications, navigation, and radar systems

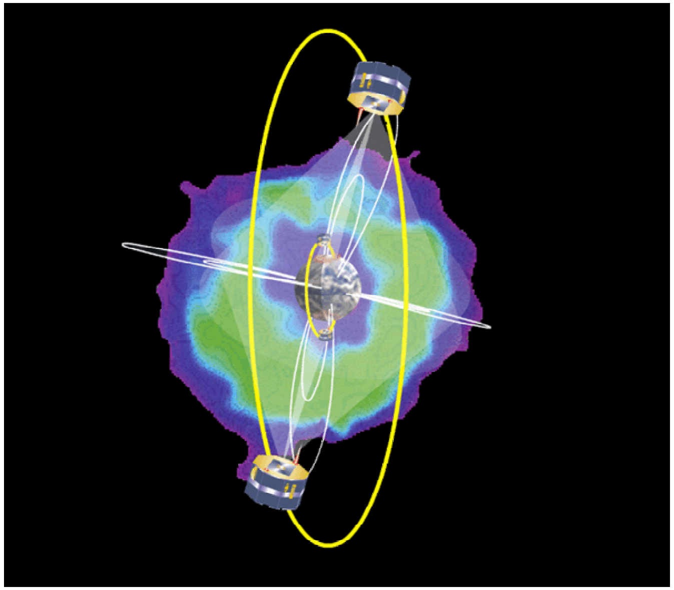
Mission Description

- Ionospheric-Thermospheric Storm Probes (ITSP)
  - Two spacecraft in nearly identical, 60°-inclination, circular orbits at a nominal altitude of 450 km
  - Both spacecraft identically instrumented to characterize the dynamic response of the I-T system to variable solar EUV flux and geomagnetic storms
- Radiation Belt Storm Probes (RBSP)
  - Two spacecraft in nearly identical, low-inclination (<18°, 12° goal), highly elliptical (500 km × 5.5 R_E) "chasing" orbits for magnetic shell coverage
  - First spacecraft fully instrumented for in situ measurements of radiation belt particles, fields, and background environment
  - Second spacecraft with subset of instruments for simultaneous multipoint measurements in radiation belts
- Global Mid-Latitude UV Imaging
  - UV imager on a non-LWS geosynchronous spacecraft

Measurement Strategy

- Ionospheric-Thermospheric Storm Probes (ITSP)
  - DC electric fields (ion drifts), neutral wind vector, plasma density and fluctuations, plasma density altitude profile, neutral density and mass composition, neutral temperature, scintillations
- Radiation Belt Storm Probes (RBSP)
  - Radiation belt electrons, vector magnetic field, ring current particles, AC magnetic fields, DC/AC electric fields
- Global Mid-Latitude UV Imaging
  - Ultraviolet measurements of O/N_2 ratio and electron density
- Concurrent observations by RBSP, ITSP, the Global Mid-Latitude UV Imaging, and a Solar Dynamics Observatory EUV imager

Geospace System Response Imager (GSRI)



Measurement Strategy

- Two high altitude spacecraft with global ENA and EUV imaging magnetosphere, and high high resolution global spectroscopic FUV and x-ray imaging of the I-T system – all data available real-time
- Two low altitude spacecraft with Fabrey-Perot interferometers and in-situ field and particle measurements
- Ground radar measurements coordinated with space-based sensors

Minimum Technology Design was baselined:

- No "enabling" technology required
- New enhancing technology should reduce spacecraft cost by 10%

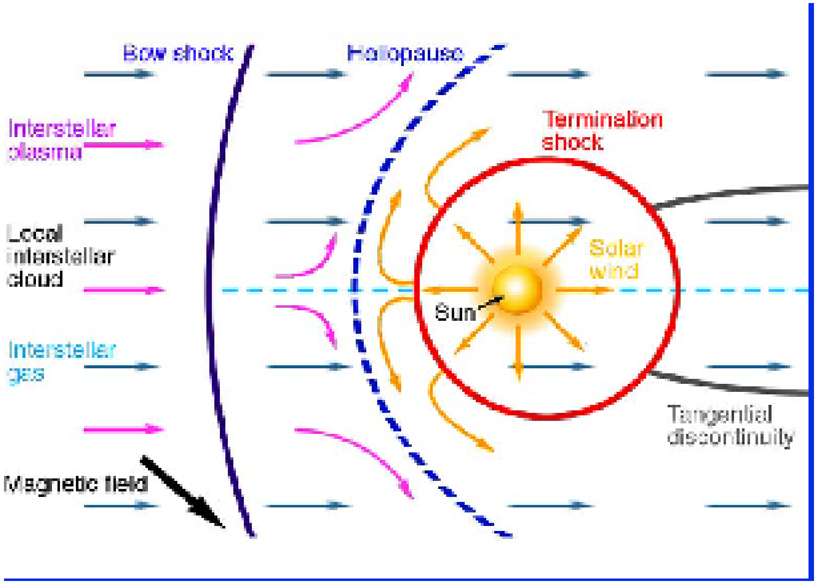
Science Objectives

- Determine dynamic coupling between ionosphere and magnetosphere
- Determine how magnetospheric energy is dissipated in the Ionosphere-Thermosphere (I-T) system
- Determine the important feedback mechanisms from the I-T system to the magnetosphere
- Determine global magnetospheric dynamics
- Determine causes and consequences of magnetospheric storms and sub-storms

Mission Description

- Mission Design
  - 2 Low Altitude Spacecraft (LAS) in 500-km sun-synchronous (97.4-degree inclination)
  - 2 High Altitude Spacecraft (HAS) in 8Re circular orbit also at 97.4-degree inclination
  - Ground-based radar network covers 30 to 90 deg north and south latitudes
  - 2 year life
- Payload
  - LAS F-P Interferometer plus in-situ ions and Mag field instruments nadir and RAM oriented
  - HAS 8 Imaging instruments nadir pointing with roll about nadir
  - 10 ground radar installations with 2 antennas each

Heliosphere Imager and Galactic Observer



Enabling Technology Development

- High resolution diffuse EUV Spectrometer
- Advancing anti-coincidence noise suppression technique
- Negative Ion Conversion Surface

Science Objectives

- Establish the 3-D Structure of the Interaction Region Between the Heliosphere and the Local Galactic Environment
- Determine the Nucleosynthetic Status of a Present-Day Sample of the Galaxy and Explore the Implications of this Knowledge for Big Bang Cosmology, Galactic Evolution, Stellar Nucleosynthesis, and the Birthplace of the Sun
- Characterize the Physical State of the Local Interstellar Cloud and the Nature of its Interaction with the Heliosphere
- Map the Location and Establish the Characteristics of the Extended Inner Source of Neutrals in the Heliosphere, and Set Limits on the Dust Density in the Heliosphere
- Search for molecules and the building blocks of life liberated by sublimation of small comets, asteroids and grains (detectable through measurement of pickup particles)

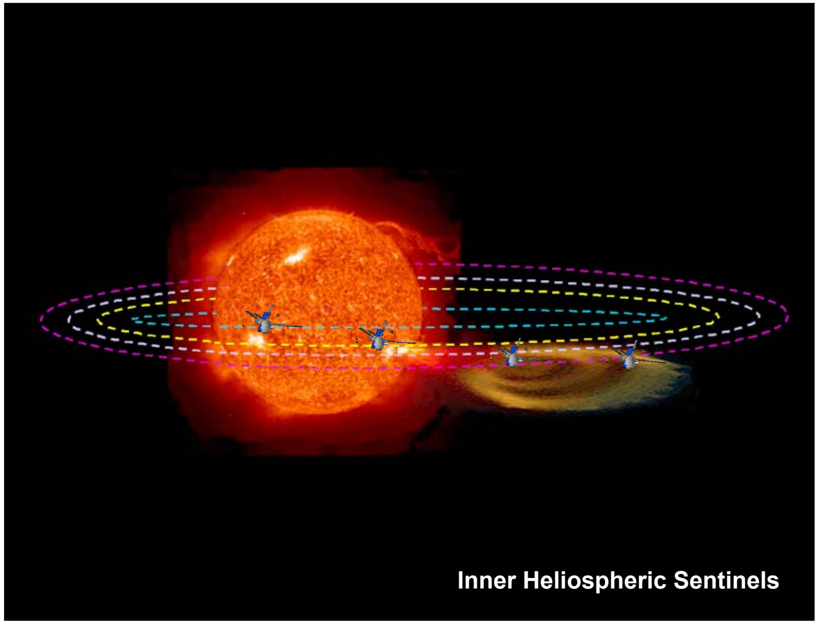
Mission Description

- Example Mission Design
  - Delta II 2925 Launch, 745 kg @ C_3 = 26.4 km^2/s^2 (25.3 min)
  - ΔV-EGA (2-) Trajectory
    - 2.8 year cruise, 2 year orbital science operations
    - 1 x 4 AU Equatorial Final Orbit
- Flight System Concept
  - Spin-Stabilized Platform
  - Solar Array Design
  - Payload: 71 kg, 62 W, 1 kbps
  - 628 m/s ΔV
  - 900 arcsec (control), 360 arcsec (knowledge)

Measurement Strategy

- Image the Heliopause using Global Sky Maps of 83.4 O+
- Image the Termination Shock using Energetic Hydrogen Atoms and Radio Detection (2-5 kHz)
- Determine the isotopic and elemental composition of the neutral portion of the interstellar gas from measurements of pickup ions and of the main neutral species
- Determine the Flow Direction, Speed and Temperature of Interstellar Atoms
- Determine Composition and Radial Profiles of Extended Inner Source Pickup Ions
- Determine Time-dependent Interactions of Large-Scale Structures with Heliospheric Interfaces through Radio Detection (2-5 kHz)

Inner Heliospheric Sentinels



Technology Development

- High Temperature Solar Arrays
- Advanced Thermal Control
- Low Mass/Power High-Density Data Storage

Science Objectives

- Determine how the global character of the inner heliosphere changes with time
- Understand how geo-effective structures (CMEs, shocks, CIRs) propagate and evolve from Sun to 1 AU
- Discover what solar dynamic processes are responsible for the release of energetic particles and geo-effective events
- Constrain heliospheric models

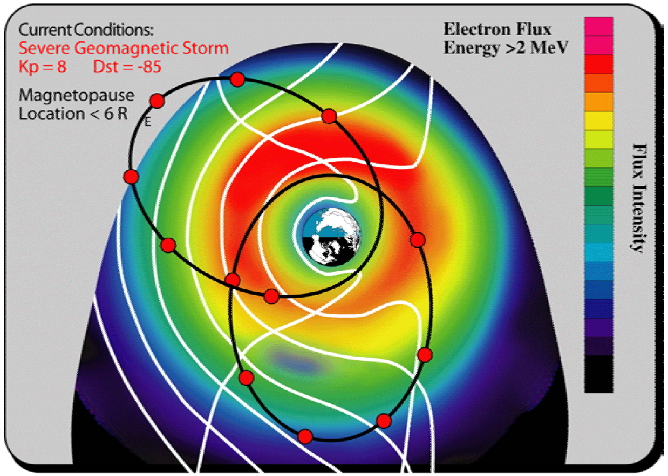
Mission Description

- Example Mission Design
  - Delta II or III Launch Vehicle
  - Trajectory:Ballistic w/ Venus Gravity Assist(s)
  - Elliptical Heliocentric Orbits
    - R_p = 0.4, 0.45, 0.72, 0.72 AU
    - R_a = 0.76, 0.79, 0.8, 0.95 AU
  - 0.5 – 1 yr cruise, 4.5 – 4 yr science ops
- Flight System Concept
  - Spin Stabilized (4 Dual-String S/C)
  - Solar Array Implementation
  - Telecom: X-band UP, Ka-band DOWN

Measurement Strategy

- Magnetic field, solar wind particle distribution, energetic particle and radio and plasma wave measurements
- Longitudinally distributed and concentrated solar observations

Inner Magnetospheric Constellation (IMC)



Science Objectives

- Create time-dependent maps of the inner magnetosphere (1.5-12 RE)
- Fully specify and understand the space environment where spacecraft and astronauts work.
- Discover the origin and dynamics of magnetospheric particle populations
- Derive the global, time-dependent magnetic and electric fields.
- Determine the development and evolution of magnetic storms.

Mission Description

- 2 “petal” low inclination orbits that maintain uniform coverage independent of precession.
- 3 satellites per orbit, 6 total.
- Instruments: 3-axis Magnetometer, Electron Analyzer, Energetic Particles, 2-axis Electric Fields

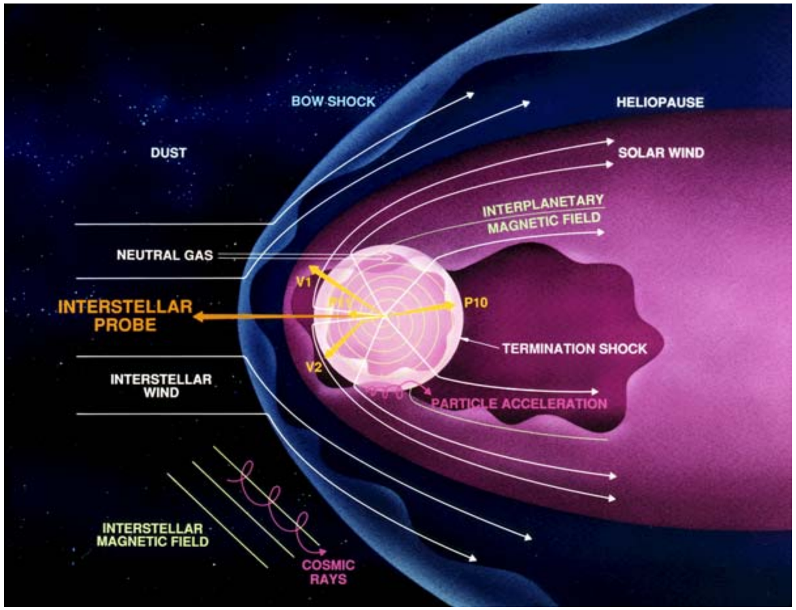
Measurement Strategy

- The large-scale equatorial electric & magnetic fields are directly measured.
- An independent measurement of the fields - integrated along particle drift paths - is obtained from the energetic particle phase space density contours.
- Different energies have different drift paths and highly constrain the construction of global synoptic “weather maps” of the inner magnetospheric response to geomagnetic disturbances originating on the Sun..
- Direct measurement of the origin and dynamics of global particle structures such as the ring current, the relativistic electron radiation belts, the plasmasphere and detached/extruded plasmaspheric populations.

Minimum Technology Design was Baselined

- No “enabling” technology required
- New enhancing technology should reduce spacecraft cost by 10%

Interstellar Probe



Technology

- Solar Sail: < 1 g/m^2, 200 m radius
- DSN 70m Subnet w/ Ka-band Uplink
- Next Generation ARPS
- Next Generation System On A Chip
- Ka-band S/C Components and Phased Array
- Hot-Gas Propulsion
- Micro-S/C Technology
- Low Mass/Power Instrumentation

* Nuclear Electric Propulsion (NEP) may be a future implementation, developments within the Nuclear Systems Initiative will be closely followed and utilized to their fullest advantage

Science Objectives

- Explore the interstellar medium and determine directly the properties of the interstellar gas, the interstellar magnetic field, low-energy cosmic rays, and interstellar dust
- Determine the structure and dynamics of the heliosphere, as an example of the interaction of a star with its environment
- Study, in situ, the structure of the solar wind termination shock, and the acceleration of pickup ions and other species
- Investigate the origin and distribution of solar-system matter beyond the orbit of Neptune

Mission Description

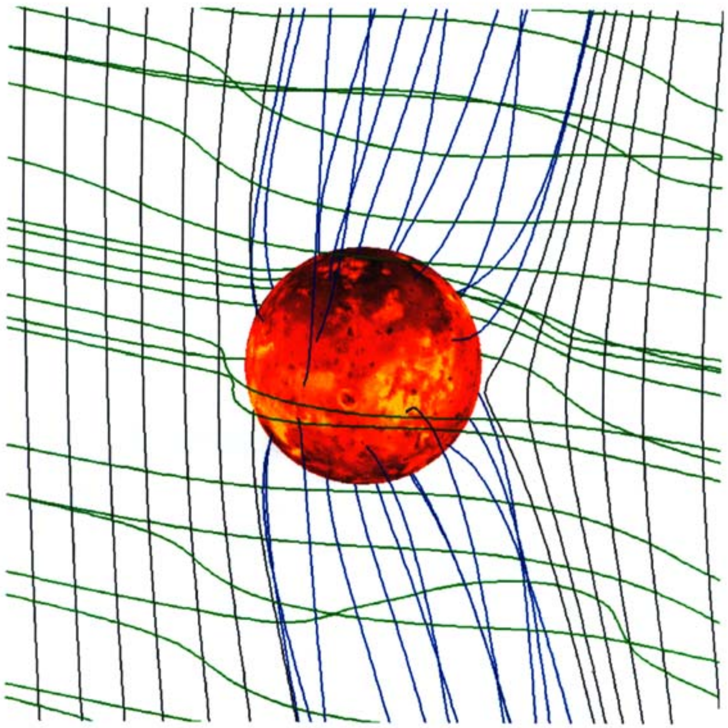
- Example Mission Design*
  - Delta II 7425 Launch (719 kg Cap., $C_3 = 0$ km^2/s^2)
  - Flight System Launch Mass: 564 kg
  - Solar Sail Trajectory Targeted for Nose of Heliosphere
    - 0.25 AU Solar Pass, 200 AU in 15 yrs.
- Flight System Concept
  - “Flying Antenna” Design Implementation (191 kg)
  - Sized for 30 year Operations
  - Payload: Fields & Particles + Imaging

Measurement Strategy

- Measure, in situ, the properties and composition of interstellar plasma and neutrals, low energy cosmic rays, and interstellar dust
- Determine the structure and dynamics of the heliosphere with in situ measurements and global imaging
- Map the infrared emission of the zodiacal dust cloud, measure in situ the distribution of interplanetary dust, and determine the radial distribution of small Kuiper Belt objects

Io Electrodynamics

Magnetic Field Lines and Flow Stream Lines Near Io



Science Objectives

- Investigate the Energy Conversion Processes in a Magnetized Plasma
- Understand Mass Transport in a Rapidly Rotating Magnetosphere
- Determine How Intense Parallel Electric Fields are Generated in a Magnetized Plasma
- Determine How Momentum is Transferred Through Field-Aligned Current Systems
- Determine the Role of Io on Radio Wave Generation at Jupiter

Mission Description

- Example Mission Design
  - Delta III Launch: Direct Trajectory
  - Elliptical Io-Resonant Equatorial Orbit
    - 5.9 R_j x 71 R_j , ~ 1 mo. Orbital Period
    - 2-Year Flight Time, 3-Year OPS
- Flight System Concept
  - Rad-Hard Spin-Stabilized Platform
  - Chem/Bi-Prop w/ ARPS Implementation
  - Payload:
    - Fields & Particles Instrumentation (Plasma, Energetic Particle, Magnetic & Electric Fields)
    - UV Imager

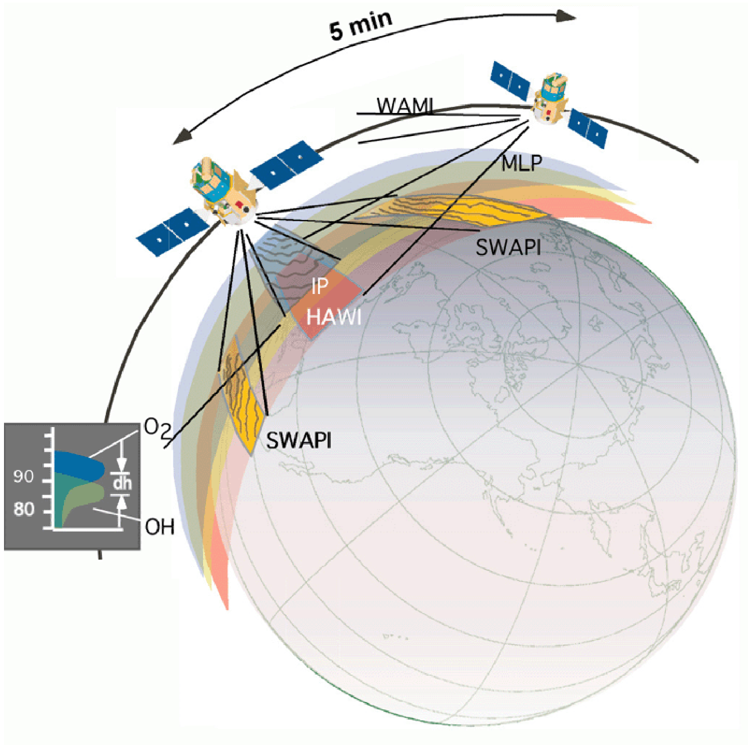
Enabling Technology Development

- Rad-Hard Electronics/ACS Sensors
- Advanced Radioisotope Power

Measurement Strategy

- Multiple Flybys of Io
- Different Science Emphasis for Each Encounter/Flyby
- High Resolution Flyby Data Stored in Mass Memory for Playback Over Post-Encounter Trajectory (Apojove)
- Image Jupiter aurora to track magnetic footprint of Io

Ionospheric-Thermospheric-Mesospheric Waves Coupler



Minimum Technology Design was Baselined

- No "enabling" technology required
- New enhancing technology should reduce spacecraft cost by 10%

Science Objectives

- Global measurements of small scale gravity waves in the Earth's MLTI region
- Determine the exchange rate of water vapor between the troposphere and thermosphere

Mission Description

- 2 satellites in 650 km circular orbits
  - 30°: 2 years lifetime beginning when both satellites are on orbit
  - 70°: 6 years lifetime for water vapor measurement (desired)
- Payload (nadir and ram pointing)
  - 5 remote sensing
  - 2 in situ instruments

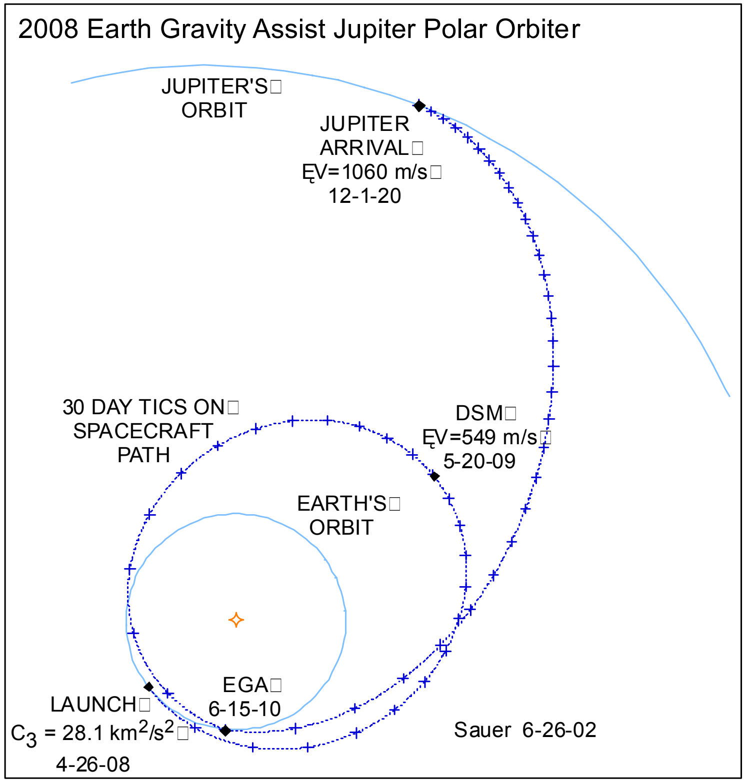
Measurement Strategy

- Type
  - Optical remote sensing of airglow emissions, cloud height, wind fields, and water vapor
  - In situ measurement of electron and ion densities

Coverage

- All latitudes and local times
- Weekly sampling periods

Jupiter Polar Orbiter



Enabling Technology Development

- Radiation Hard Components
- Adaptive Feed/Uplink Beacon
- Internal 2-axis Slow Scanning Mirror IMC
- TDI Image Synthesis and Relative Motion Cancellation
- Synchronized Shutter for Imager Radiation Shielding
- Ka-band Transponder/TWTA/Switches

Science Objectives

- The Relative Contributions of Planetary Rotation and of the Interaction with the Interplanetary Medium to Jovian Magnetospheric Dynamics
- How Global Electric and Magnetic Fields Regulate the Processes that Produce the Radiation Belts, Plasma Sheet, and the Aurora
- Identify the Particles Responsible for the Generation of the Jovian Aurora and Determine their Magnetospheric Source Regions

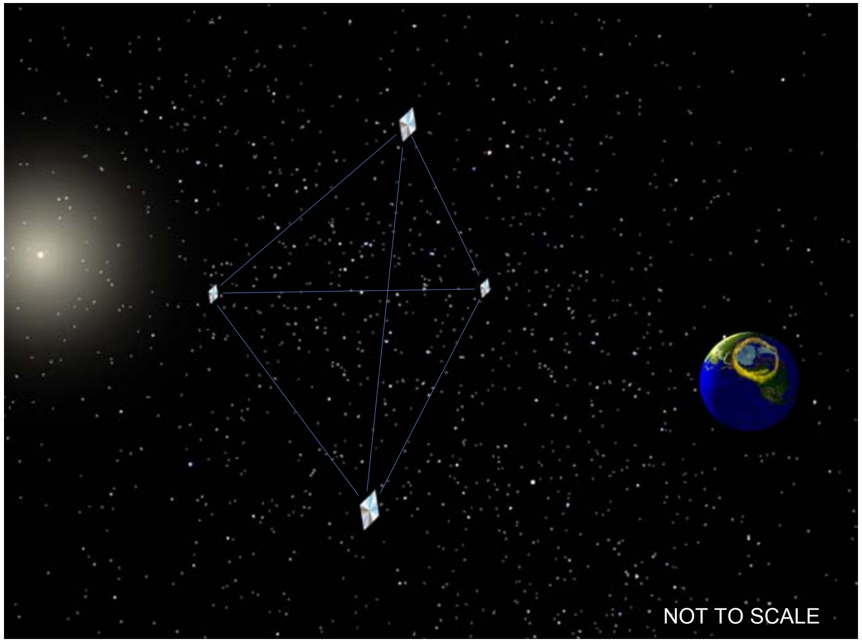
Mission Description

- Example Mission Design
  - Delta III/Star 48 Launch , 1658 kg @ C_3 = 31 km^2/s^2 (28.1 min)
  - Elliptical Polar Orbit
    - 1.1 R_j x 40 R_j, 75° inclination
    - 4.6 Year cruise, 1-Year OPS
- Flight System Concept
  - Rad-Hard Spin-Stabilized Platform
  - Solar Array Implementation
  - Payload: Field & Particles, Imagery, Radio Science
    - 55 kg, 38 W, 4 kbps
  - 1758 m/s ΔV
  - Capability Driven Design
    - 900 arcsec (control), 36 arcsec (knowledge)

Measurement Strategy

- Measure Particles and Fields In-Situ in the Auroral Acceleration Region, Along L Shells, and in Conjugate Magnetospheric Source Regions
- Radio occultations of ionosphere and upper atmosphere
- Image Aurora in the Visible and UV
- Measure the Magnitude and Configuration of the Near-Planet Magnetic Field and Map the 3-D Structure of the Radiation Belts

L1-Diamond



Enabling Technology Development

- Solar Sail
- Solar Sail Navigation Tools
- Autonomous Thrust Vector Control
- "Multi-Chip Module" (MCM) Electronics

Science Objectives

- Measure the properties of solar-wind turbulence (as seen in density, velocity vector and magnetic field) as a function of separation in space and time, ranging from the dissipation scales of perhaps hundreds of kilometers to the outer scale of millions-of-kilometers
- Direct measurements of the possible spatial symmetries of the turbulence
- Discover associations of the turbulence with suprathermal and energetic particles
- Measure the spatial variation in convected and propagating waves, shocks and other disturbances in the solar wind

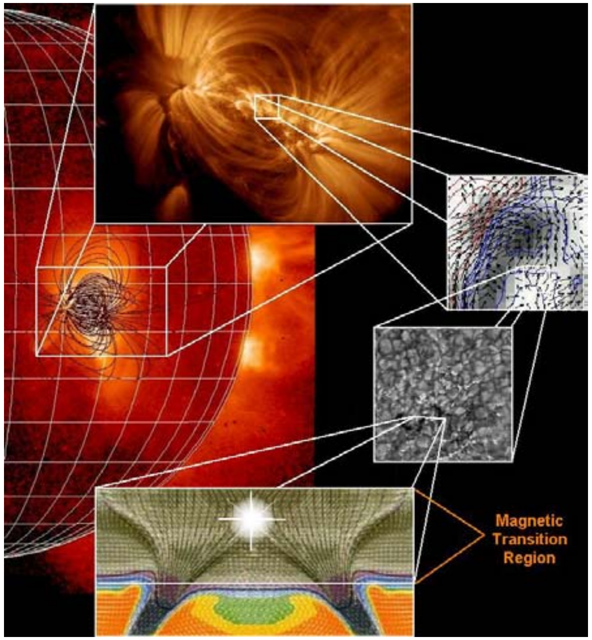
Mission Description

- Example Mission Design
- Delta IV Launch Vehicle
  - Trajectory: ballistic transfer from Earth to L1 Halo (~90 days), solar sail transition from L1 to constellation stations,
    - 3 s/c in triangle formation, centroid 280 - 500 Re sunward of Earth on Sun-Earth line, 4th s/c above the ecliptic
    - Variable constellation baseline (for 3-D structure)
  - Continuous Solar Viewing: 3 years In Final Orbit
- Flight System Concept
  - 4 solar-array powered S/C with solar sails
  - Payload: Fields and Particles (~ 15 kg/9W)

Measurement Strategy

- 4-s/c constellation with varying separations to study the full range of turbulence structures in both space and time
- High time resolution with time delays providing valuable correlations between the observed quantities

Magnetic Transition Region Probe



Enabling Technology Development

- Large, light weight, reflecting optics for use in visible near IR and vacuum ultraviolet
- Extendable optical bench
- Large format (up to 16K x 16K pixels), low power, high QE at 150 nm, multiport CCDs.
- Image motion compensation/stabilization for large apertures and EUV
- Variable Emissivity Surfaces
- High Data Volume Ground Processing
- Instrument Auto-Boresighting System
- High Stability Platform
- Compact PCI Cards
- Ka-band Transponder/TWTA/Switches

Science Objectives

- Discover, measure, and understand the 3D structure and dynamics of the magnetic transition region between the photosphere and upper chromosphere.
- Connect the structure and events in the magnetic transition region with their photospheric roots and the magnetic stressing and heating of the chromosphere and corona.
- Resolve and measure the appearance, transport, and destruction of magnetic field on the fundamental intergranular scales in the photosphere.

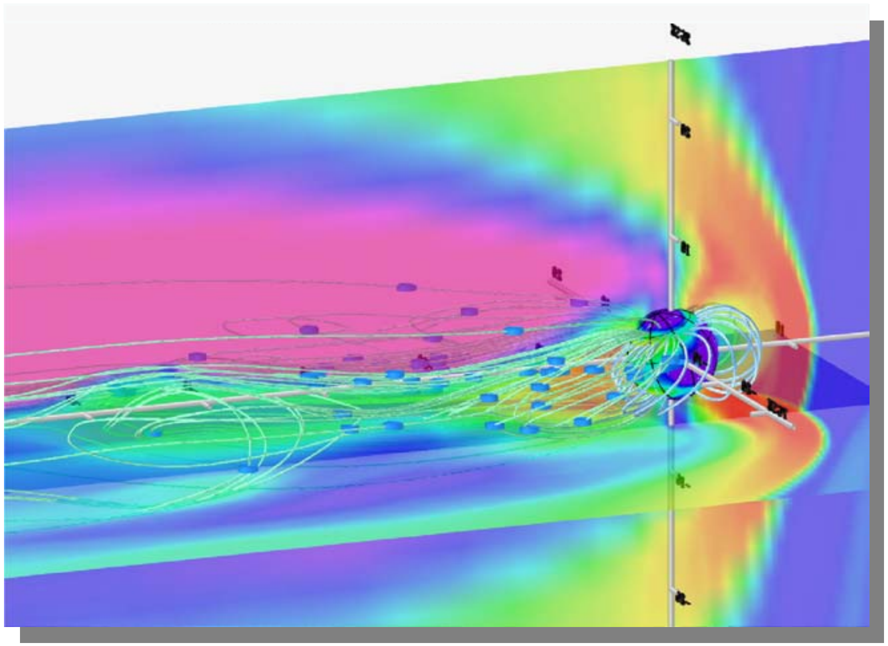
Mission Description

- Example Mission Design
  - Delta IV Launch Vehicle (due to shroud requirement)
  - Geo-synchronous, Earth-orbiting satellite
    - 3 years In Orbit
- Flight System Concept
  - 3-Axis Stabilized Solar Inertial Observatory Platform
  - Solar Arrays
  - 751 Mbps link to Ground Terminal
  - Payload: 570 kg, 330 W (peak), 750 Mbps
  - 36-as control (payload implements 10-as with 1-as knowledge)

Measurement Strategy

- Visible/infrared maps/images of vector magnetic field, intensity, and velocity in the magnetic transition region and the photosphere, with large FOV (> 100,000 km), high resolution (< 100 km), and high sensitivity (< 30 G, transverse).
- UV maps/images of line-of-sight magnetic field, intensity, and velocity in upper chromosphere/lower transition region.
- EUV images and spectra of coronal structures in and around the FOV of the magnetic transition region observations and with comparable resolution.

Magnetospheric Constellation (MC) Mission



Key Mission Enhancing Technologies

- Cost effective fabrication, assembly and testing techniques for 50-100 nano-satellites
- Miniaturized, rad-tolerant, low mass/power instrumentation and support systems for an integrated "sciencecraft"
- Advanced data synthesis and visualization techniques

Science Objectives

- Define and characterize the magnetotail's responses to external and internal drivers
- Resolve space/time ambiguities that conceal the governing physical processes.

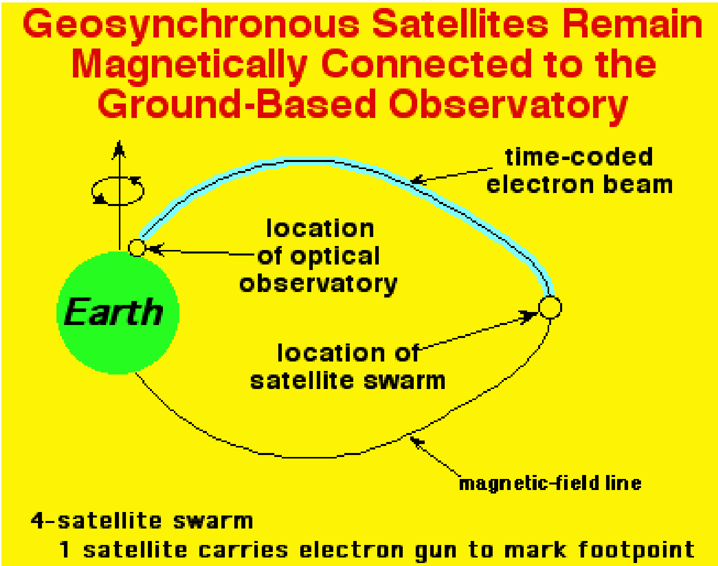
Mission Description

- A constellation of 50-100 nano-satellites distributed in 3x7 Re to 3x40 Re low inclination, nested orbits
- "Nearest neighbor" spacing peaks at 1.0-2.0 R_e for ~ 50 - 100 nano-sats

Measurement Strategy

- Systematic multi-point measurements of magnetic field, bulk plasma & energetic particle parameters
- Spacecraft deployed with optimal spatial distribution
- Prime mission conducted while in magnetotail; secondary science on flanks and dayside.

Magnetosphere-Ionosphere Observatory



Science Objectives

- Determine what causes the aurora
- Determine how 10's-100's of gigawatts of energy are extracted from the magnetotail
- Probe magnetosphere-ionosphere coupling

Mission Description

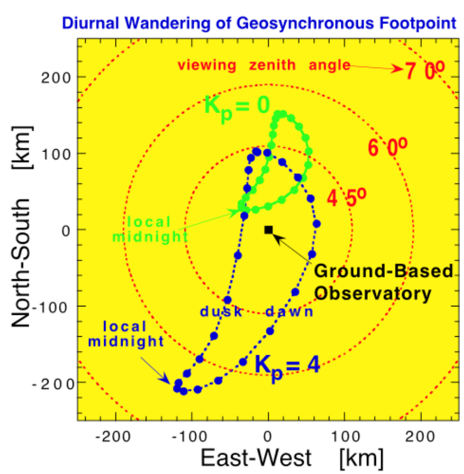
- Main spacecraft contains a high-power electron gun
- 3 satellite spacecraft in close cluster with main spacecraft
- Geosynchronous satellites remain magnetically connected full-time to ionospheric observatory
- All spacecraft carry critical measurement instruments
- Observatory locates the beamspot within the auroral ionosphere

Measurement Strategy

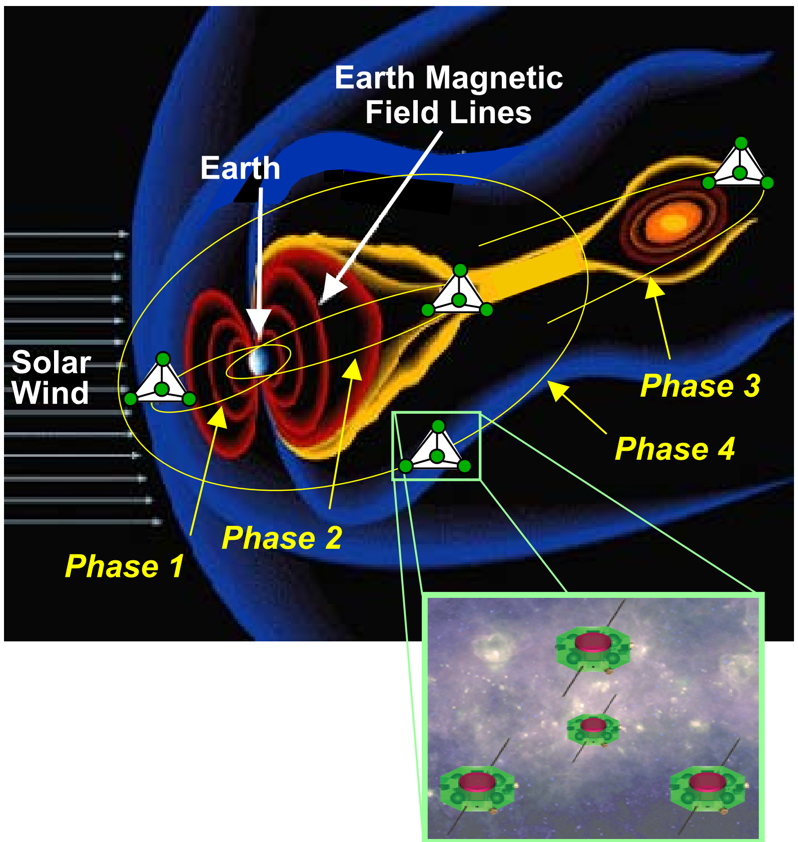
- Find the magnetospheric end of auroral arcs
- Verify position from electron-beam connection
- Measure plasma, flow, and field gradients in aurora using multiple spacecraft
- Discriminate among auroral arc theories

Minimum Technology Design was Baselined

- Exploits technologies developed by NASA's program in active space experiments.
- New enhancing technology should reduce spacecraft cost by 10%



Magnetospheric Multiscale (MMS)



Minimum Technology Design was Baselined

- No “enabling” technology is required

Science Objectives

- Understand the fundamental plasma physics processes of reconnection, particle acceleration, and turbulence on the microscale and mesoscale in the Earth’s magnetosphere.

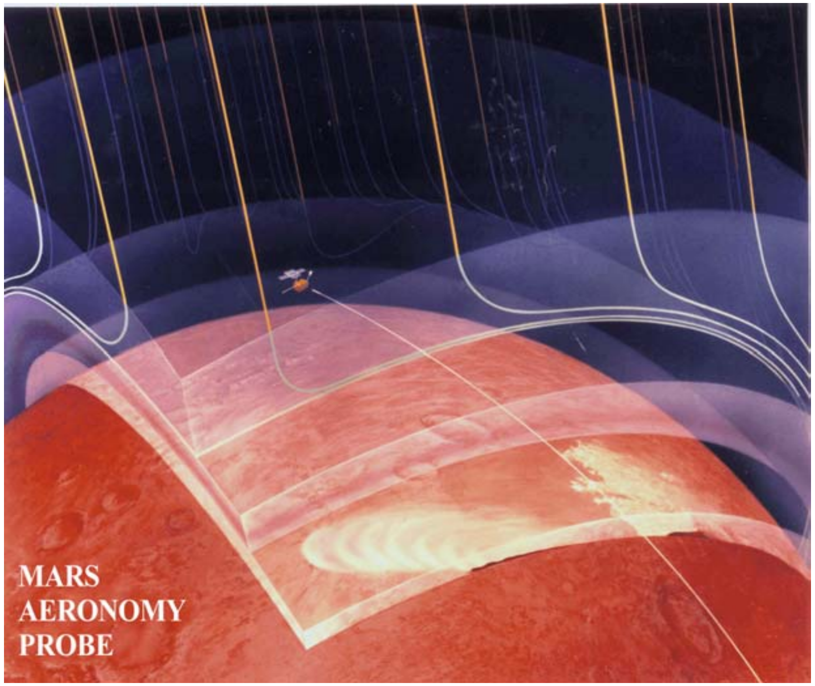
Mission Description

- 4 spin-stabilized spacecraft in a tetrahedron constellation (2 year mission)
- Inter-spacecraft ranging system
- 4 orbital phases:
  - Phase 1: 1.2 R_E by 12 R_E, 10° incl. (9 months)
  - Phase 2: 1.2 R_E by 30 R_E, 10° incl. (3 months)
  - Phase 3: 8 R_E by 100-120 R_E lunar assist maneuver to achieve ~90° orbit plane change
  - Phase 4: 10 R_E by 40 R_E, 90° incl. (11 months)

Measurement Strategy and Coverage

- 4 suites of identical instruments: electric field, energetic particles, hot plasma & magnetometer
- Measurements taken during 4 phases include:
  - Phase 1: Dayside Magnetopause: reconnection acceleration, turbulence, solar wind entry
  - Phase 2: Nightside Substorm: reconnection, plasma sheet boundry, accel., current disruption
  - Phase 3: Magnetotail: reconnection structures and dynamics, plasma escape/motion across boundary
  - Phase 4: Post-Cusp Magnetopause: northward re-connection, reverse convection, pointing flux entry

Mars Aeronomy Probe



Technology Development

- Low Mass/Power Instrumentation
- Micro-Spacecraft Components and S/S

Science Objectives

- Map the Upper Atmospheric Composition, Thermal Profile and Global Circulation
- Determine the Properties of the Ionosphere, its Sources and Sinks, Dynamical Coupling to the Neutral Atmosphere Including Dust Storms and Gravity Waves and its Electrodynamic Response to the Solar Wind
- Observe the Response of the Upper Atmosphere to Solar Variability and Model the affects of Space Weather on Satellite Drag and Aerocapture
- Explores the processes for atmospheric escape

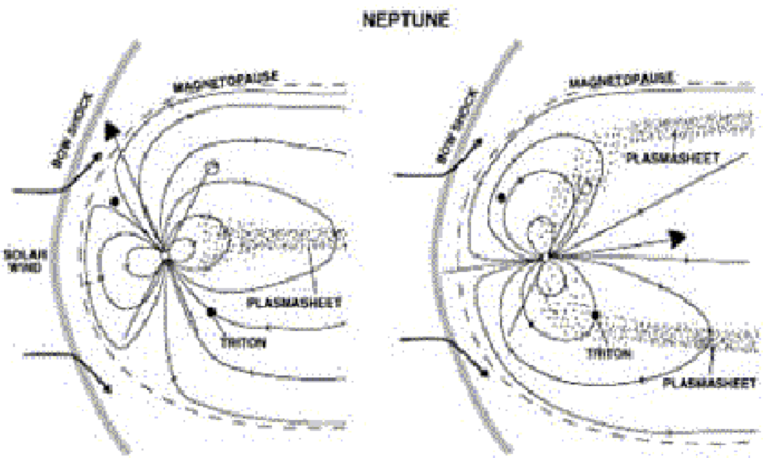
Mission Description

- Example Mission Design
  - Small Delta II
  - Elliptical Low-Altitude Polar Orbit
    - 100 km x 500 km
    - 1-year Flight Time, 2-year OPS
- Flight System Concept
  - Spin-Stabilized Platform
  - Solar Array Implementation

Measurement Strategy

- Neutral Species Escape Rates, Isotopic Ratios, Densities, Temperatures, Winds and Composition
- Thermal Plasmas (Ions and Electrons), Pick-up Ions, Energetic Particles and Magnetic and Electric Fields
- Integrated Theory and Data Analysis Program
- EUV/FUV spectra for remote sensing of escaping atoms

Neptune Orbiter



Science Objectives

- Map Neptune's highly asymmetric magnetic field
- Determine the magnetospheric structure as the highly oblique and offset magnetic field rotates with the planet
- Determine the densities, compositions, and temperatures of magnetospheric plasma populations, and their distributions throughout the magnetosphere
- Measure the plasma flows associated with the dynamics of the magnetosphere driven by the planet's rotation and by the solar wind
- Determine whether Triton has an intrinsic magnetic field, and characterize the plasma interaction with Triton and its atmosphere
- Compare the magnetosphere of Neptune with other planetary magnetospheres and compare the Triton-magnetosphere Interaction with the Galilean satellites of Jupiter and with the role of Titan in Saturn's magnetosphere

Mission Description

- Example Mission Design
  - Delta/Altas Launch (Jupiter Gravity Assist Trajectory)
  - 9-12 yrs to Neptune + 2 yrs in orbit
  - Aerocapture, Optical Com, µ-S/C Technology
  - Autonomous operation and navigation
  - Multiple flybys of Triton
- Flight System Concept
  - Fields & Particles Instrumentation (Plasma, Energetic Particle, Magnetic & Electric Fields)

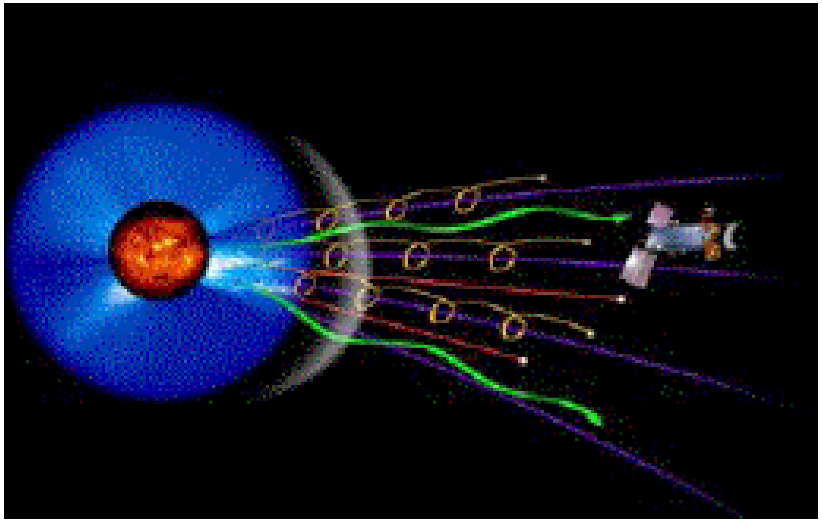
Measurement Strategy

- Thermal plasmas, energetic particles, magnetic and electric fields, plasma waves, and auroral measurements (including UV spectral imaging of Neptune and Triton)
- Integrated theory and data analysis program involving numerical simulations processes, and energetic-particle acceleration under a variety of planetary magnetic-dipole orientations

Enabling Technology Development

- Aerocapture (0.3 to 0.4 mass ratio)
- Advanced Telecom: Optical or large-diameter inflatable antenna
- Advanced Radioisotope Power
- Autonomous spacecraft operations

Particle Acceleration Solar Orbiter



Enabling Technology Development

- Solar Sail @ 9 g/m^2, 87 m Radius
- High Temperature Solar Arrays
- Solar Sail Navigation Tools
- Autonomous Thrust Vector Control
- Advanced Thermal Control

Science Objectives

- Understand particle acceleration mechanisms
- Distinguish between flare and shock accelerated particles
- Study location and nature of energy release and particle acceleration for the most energetic particles.
- Determine conditions for shock acceleration and evidence for post-eruption magnetic reconnection.
- Study active region evolution

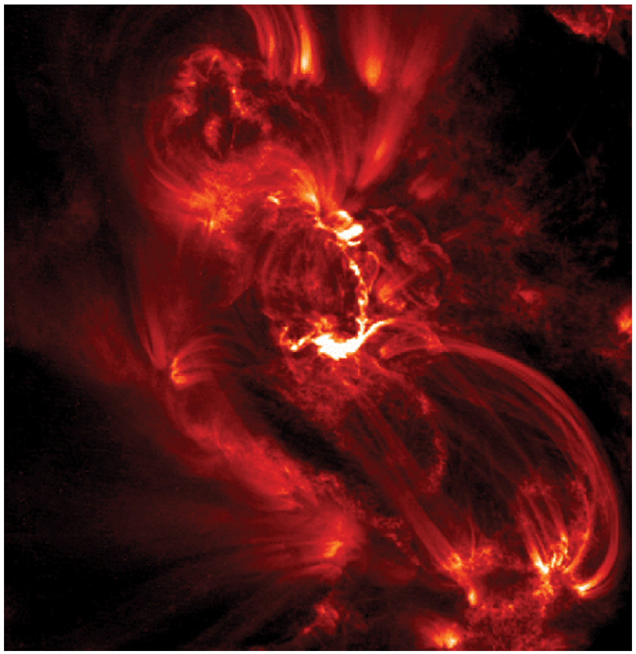
Mission Description

- Example Mission Design
  - Delta II Launch (C_3 = 0 km^2/s^2)
  - Solar Sail Trajectory
    - Transfer From 1 AU to a 0.169 AU Circular Solar Equatorial Orbit (Period: 25.4 days)
    - 3-Year Transition to Final Orbit
  - Continuous Viewing of Active/CME Source Region
    - 4-5 years In Final Orbit
- Flight System Concept
  - Spin-Stabilized Platform (500 kg [inc. 80 kg of Sci.])
  - Advanced Thermal Design for 0.16 AU Orbit

Measurement Strategy

- High energy solar flare imager (< 1 arcsec)
- 1-100 Mev/nuc, resolve composition up to Fe
- Neutron spectrometer, > 5MeV neutrons
- Gamma-ray spectrometer for nuclear lines
- Solar Wind and magnetic field instruments

Reconnection And Microscale (RAM)



Minimum Technology Design was Baselined

- Enabling technology required - Large array, small pixel calorimeters for soft x-ray spectroscopy
- New enhancing technology should reduce spacecraft cost by 10%

Science Objectives

- What are the mechanisms that lead to reconnection?
- What micro-scale instabilities lead to global effects?
- Where are the regions of particle acceleration?
- Where are the reconnection regions and what is their topology?

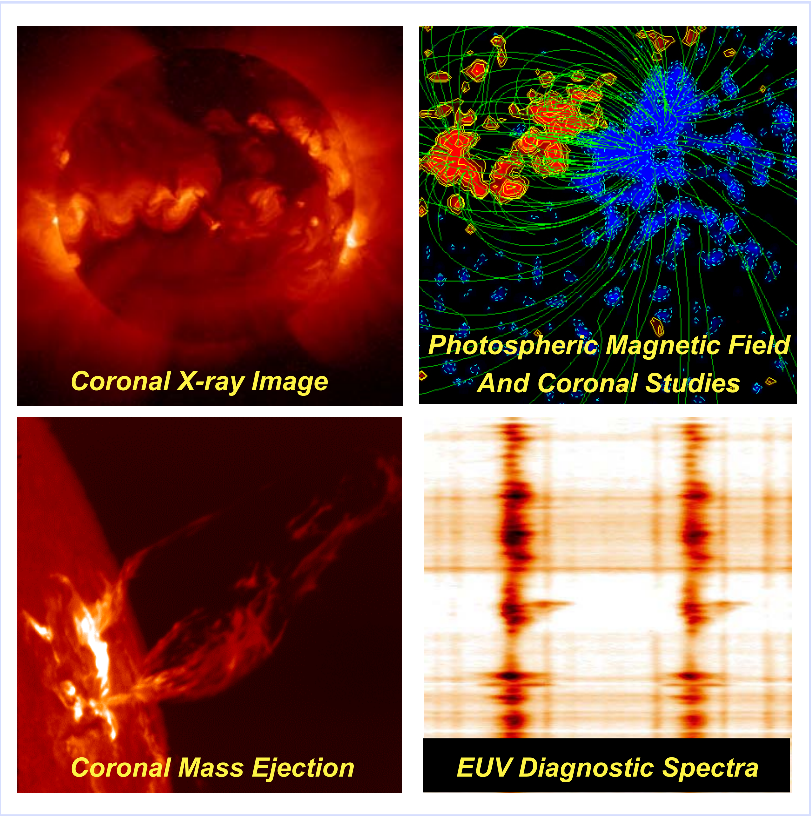
Mission Description

- Mission Design
  - Solar observations from single geosynchronous platform
  - Mission lifetime of 2 years
- Payload
  - High Resolution EUV Imaging instrument
  - EUV spectrograph
  - X-ray calorimeter
  - EUV Intermediate Scale Imager

Measurement Strategy

- Ultra-high resolution (0.02"/pixel) EUV coronal imaging
- High resolution (0.1"/pixel) EUV/UV spectroscopy
- X-ray Imaging Spectroscopy (1"/pixel; (E/DE) ~ 500 @ 1 keV) from 0.2 to 10 keV, with millisecond time resolution.
- Multi-wavelength EUV/UV intermediate scale imager (0.1"/pixel)
- High time resolution in all instruments

Solar-B



No “enabling” technology required.

Science Objectives

- To follow the flow of magnetic energy from the Sun’s photosphere to the corona in order to understand the steady state release of energy, which heats the corona and the transient release of energy that produces CMEs and solar flares.

Mission Description

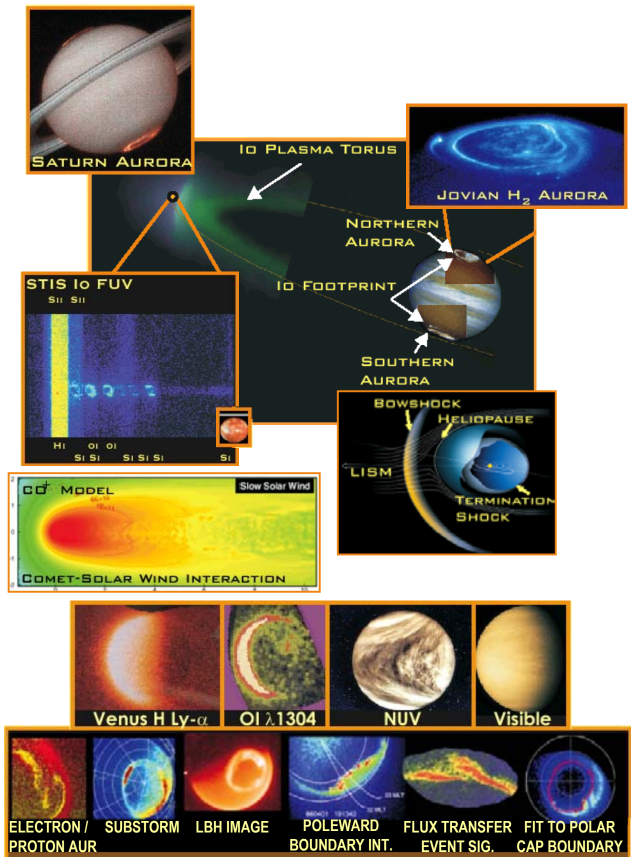
- Japanese mission with international partners.
- Single satellite in a Sun-synchronous, 600 km circular orbit, for continuous 24 hr coverage.
- Minimum mission lifetime 3 years with 8-year lifetime desirable.
- Three remote sensing telescopes observe the Sun in the optical (SOT/FPP), ultraviolet (EIS), and X-ray (XRT).
- Image motion compensation enables 0.25 arcsec angular resolution in the visible.

Measurement Strategy

- The three telescopes have overlapping fields of view and can observe the same features simultaneously.
- The FPP will measure photospheric vector magnetic fields and granulation dynamics.
- The XRT will measure the coronal response to changes in the photospheric magnetic field and provide coronal temperature and density diagnostics.
- EIS, an imaging spectrometer, will provide spatially resolved temperatures, densities, and velocities of the material in the chromosphere and corona.

Solar Connections Observatory for Planetary Environments

SCOPE



Technology Requirements

- Light-weight, metal-matrix-composite mirror design
- High- sensitivity/dynamic-range photon counting UV detectors

Science Objectives

- Compare the global effects of external and internal driving mechanisms on planet and comet near-space environments through observations of auroral, airglow, coronal, and/or internal plasma emissions
- Differentiate features of Jupiter's (and other giant planets') auroral emissions due to internal processes (rotation and internal plasma sources) from those due to the solar wind interaction
- Measure the response of ionosphere-solar wind coupling to changes in solar activity in planet systems without magnetospheres (Mars, Venus, Comets)
- Refine and expand our knowledge of Earth's global geospace response by extending auroral observations into new domains of spatial and spectral resolution
- Directly compare the terrestrial solar interaction with those of superior (Mars-Neptune) planets from opposition campaigns that monitor both systems along the same Sun-planet line
- Map the opacity and velocity structure of the interplanetary hydrogen
- Study the transition region between the heliosphere and LISM

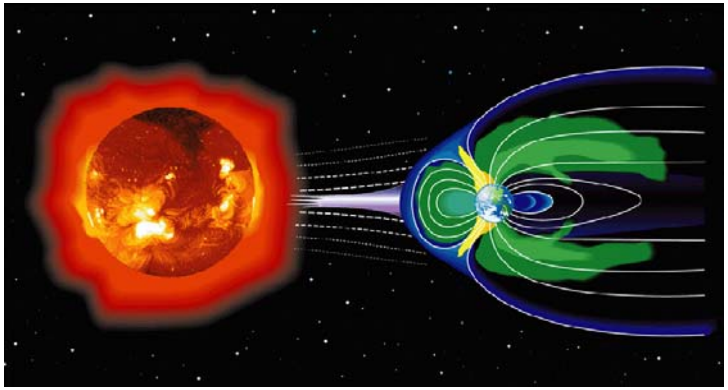
Mission Description

- Dual meter-class telescopes (EUV & UV) covering bandpasses from 55 - 310 nm
- Hubble Space Telescope (HST) - class performance for UV observations. Highest sensitivity and spatial resolution yet achieved below 120 nm
- High ($R<10^5$) spectral resolution measurements of diffuse emissions with 50 times the etendue of HST-STIS.
- Inner solar system observations of Venus, Mercury, and comets to within ~0.35 AU of the Sun
- L1-halo orbit for uninterrupted observations of the Earth's North or South polar regions and a remote perspective on planets giving full hemisphere studies up to rotational poles.
- 5+ years potential operational lifetime

Measurement Strategies

- Global imaging of auroral emissions, upper atmospheric circulation, exospheres and near-space plasma distributions
- Imaging spectroscopy of UV ion-neutral emissions and atmospheric absorption features
- Narrow-field spectroscopy of planetary (auroral-dayglow-coronal) H Ly-α profiles
- Wide-field line profile measurements of diffuse H Ly-α emission from the interplanetary medium (IPM), comets, geocorona,and the heliopause
- Pencil-beam measurement of heliopause and LISM dynamics from H Ly-α and H Ly-β line-of-sight absorption spectroscopy
- High speed photon counting detectors for precision time resolution
- Coordinated SCOPE observations of planetary targets, the IPM and heliopause with existing in situ space probes
- Cross-cutting techniques for characterizing auroral emissions in planetary magnetospheres, such as the development of auroral indices as a function of precipitating species at each of the planets (i.e., hemispheric power, auroral oval location, auroral oval size, etc.)

Solar Dynamics Observatory (SDO)



Enabling Technology Development

- C&DH Ethernet
- Ka-Band Telecommunications
- Active Pixel Star Tracker
- Radiation Hardened Field Programmable Gate Array (RHrFPGA)

Science Objectives

- Understand the nature and source of the solar variability that affects life and society
- Make accurate measurements of the solar parameters that are necessary to provide a deeper understanding of the mechanisms that underlie the Sun's variability on timescales ranging from seconds to centuries
- Through remote sensing, monitor and record those aspects of the Sun's variable radiative, particulate, and magnetic plasma outputs that have the greatest impact on the terrestrial environment and the surrounding heliosphere.

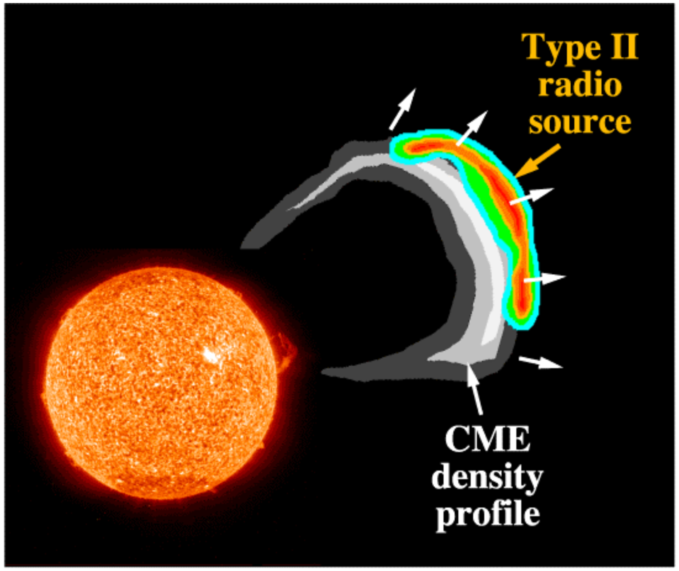
Mission Description

- NASA GSFC will manage the mission, build the S/C in-house, manage & integrate the instruments, develop/manage the Ground System & Mission Operations, & perform Observatory environmental testing at GSFC
- August 2007 Delta launch from KSC into GEO-Transfer Orbit (GTO), circularize to GEO-Sync Orbit, inclined 28.5 degrees
- Investigations responsible for development of their Instrument & Science Operations Center. SDO Investigations will be selected 09/02

Measurement Strategy

- <u>Helio/Magnetic Imager</u>: near- Diagnostic measurements of the near-surface dynamics of the solar interior
- <u>Atmospheric Imaging Assembly</u>: Characterization of the rapid evolution of the plasma in chromosphere and lower corona
- <u>Spectrometer for Irradiance in the Extreme-Ultraviolet</u>: Full disk observations of Solar EUV with 0.1 nm resolution
- <u>White-Light Coronagraphic Imager</u>: measure polarized intensity in white light to detect/characterize Coronal Mass Ejections (CME's)

Solar Imaging Radio Array



Two dimensional radio imaging of the CME-driven shock front and the CME density profile is critical for predicting the space weather effects of CMEs

Science Objectives

- Understand CME structure, propagation, and evolution from the Sun to 1 AU
- Apply solar radio burst images to mapping of solar wind density structures and magnetic field topology, providing a unique tool for solar wind analysis
- Enhance space weather prediction capabilities using radio images of CMEs
- Observe and analyze the global response of Earth's magnetosphere to CMEs and other space-weather-effective events from an external perspective
- Image the low-frequency (< 30 MHz) radio universe at high angular resolution and catalog and understand the objects found therein

Mission Description

- Microsat constellation of 10 – 16 identical spacecraft
- Crossed dipole antennas and low frequency radio receivers
- Quasi-spherical constellation with <100 km diameter
- Nearly circular distant retrograde orbit (~10^6 km from Earth) or other terrestrial radio interference limiting orbit
- Individual microsat communication with ground stations

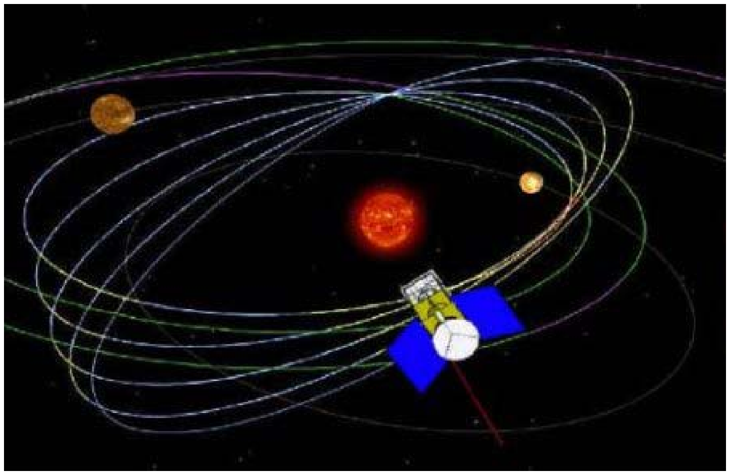
Technology Requirements

- Intermicrosat ranging (to ~3 m)
- "Full-sky" aperture synthesis mapping algorithm development
- Onboard data cross-correlation desirable (for space weather snapshots)

Measurement Strategies

- High spatial and temporal resolution
- Frequency range from ~30 MHz to ~30 kHz
- Frequency spacing and time resolution optimized for solar burst analysis
- Rapid data processing for space weather prediction

Solar Orbiter



Technology

- Solar Electric Propulsion to be validated on ESA SMART-1 mission in 2003
- High temperature thermal management to accommodate solar intensity 25x than seen at Earth

Science Objectives

Key science questions to be addressed are:

- What are the fundamental physical processes at work in the solar atmosphere and in the heliosphere?
- What are the links between the magnetic-field-dominated regime in the solar corona and the particle-dominated regime in the heliosphere?
- How does the Sun rule interplanetary space?
- What are the properties of plasma, fields and particles in the near-Sun heliosphere?
- What is the fine-scale structure and dynamics of the Sun's magnetized atmosphere?
- What is the structure and dynamics of the Sun's polar regions?

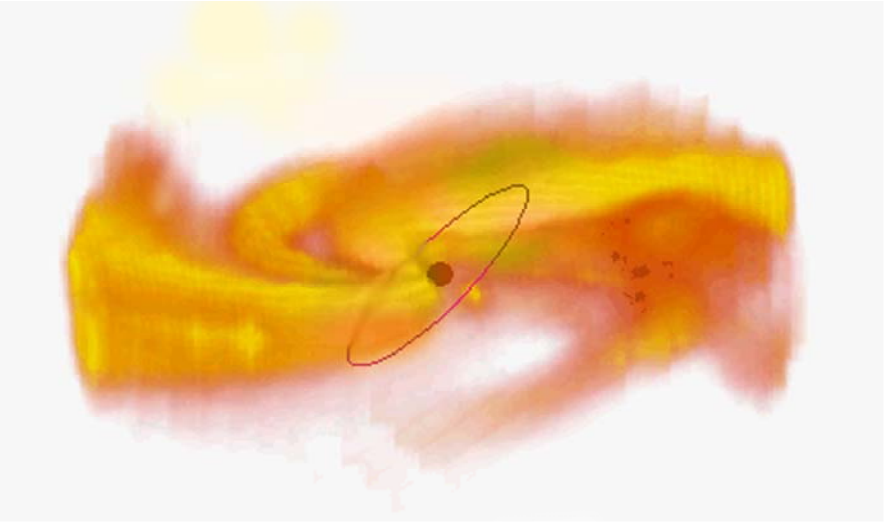
Mission Description

- ESA Mission
- 3 axis stabilized spacecraft will use solar electric propulsion and multiple planetary swing-by manoeuvres to reach a perihelion of 45 solar radii (0.2 AU) at an orbital period of 149 days.
- Multiple VGAs to increase inclination of orbital plane 30 degrees
- Perihelion "Hover" period during perihelion passes will allow imaging of solar storm buildup over several days.

Measurement Strategy

- Two instrument suites: in-situ + remote sensing
- Heliospheric in-situ: solar wind plasma analyser, radio and plasma wave analyser, magnetometer, energetic particle detectors, interplanetary dust and neutral particle detectors, neutron detector.
- Remote sensing: high resolution EUV imager and spectrometer, visible-light telescope and magnetograph, coronagraph, radiometer.
- Co-rotation during perihelion passes ⇒ steady magnetic linkage ⇒high resolution imaging + spectroscopy of solar atmosphere coupled with in-situ plasma measurements
- Out-of-ecliptic observations: magnetic fields, rotation and subsurface flows near poles, longitudinal extent of CMEs, global corona

Solar Polar Imager



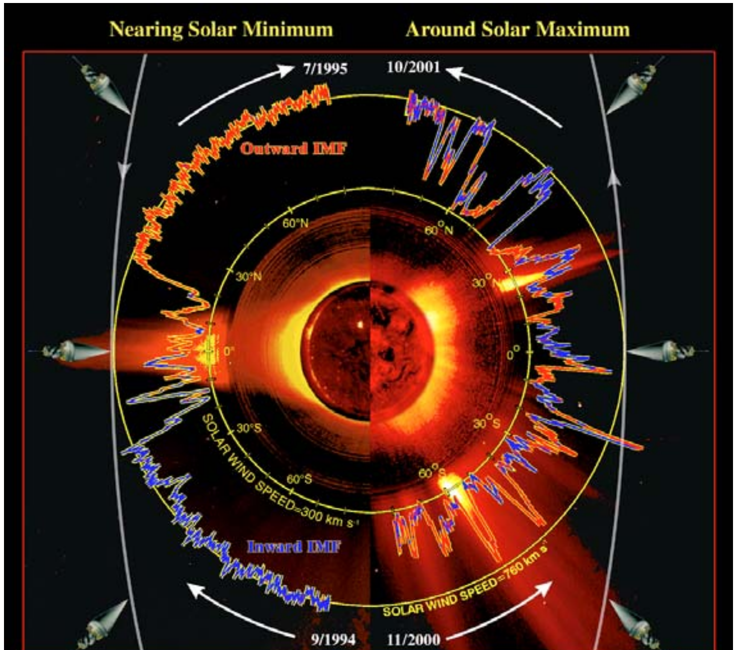
Science Objectives
- Measure near-surface meridional circulation
- Measure sub-surface jets and azimuthal and meridional circulation
- Measure the Sun's polar magnetic field and refine solar dynamo models
- Measure global oscillations on the far side of the Sun
- Image global effects of CMEs and evolution on the full 3-D corona
- Track the complete life cycle of active regions and coronal holes
- Link variations in the high-latitude heliosphere to surface conditions
- Measure angular momentum loss in the solar wind

Mission Description
- Example Mission Design
  - Launch: Delta II 2425, 769 kg @ $C_3 = 0.25\ km^2/s^2$
  - Solar Sail Trajectory
    - 4 - 5 Year Flight Time, 2 year OPS
  - Final Orbit: 0.48 AU Circular Solar Orbit with 60° Inclination
    - 3:1 Resonance with Earth
- Flight System Concept
  - 3-Axis Stabilized
  - Solar Array Implementation
  - Payload: 34 kg, 24.5 W, 15.6 kbps

Measurement Strategy
- Surface Velocity for Helioseismology Investigations
- High Latitude Magnetic Fields and Coronal Holes
- Image Corona and Inner Heliosphere from Over Poles
- Image Coronal Mass Ejections in the Ecliptic Plane
- In-situ Particles and Fields Measurements
- Solar Irradiance in Polar Regions

Enabling Technology Development
- Solar Sail @ 10-14 g/m^2, $\sqrt{A}$ = 100-141 m
- Micro-S/C Components and Subsystems
- Low Mass/Power Instrumentation
- Autonomous Thrust Vector Control
- Solar Sail Navigation Tools

Solar Probe



Dial plots courtesy of the Ulysses/SWOOPS team

Enabling Technology Development

- Thermal Protection System for 3000 Sun Environment
- Ka-Band Telecommunications
- Multi-Mission RTGs

Science Objectives

- Determine the acceleration processes and find the source regions of fast and slow solar wind at minimum and maximum solar activity
- Locate the source and trace the flow of energy that heats the corona
- Construct the 3-D coronal density configuration from pole to pole; determine the subsurface flow pattern and the structure of the polar magnetic field and its relationship with the overlying corona
- Identify the acceleration mechanisms and locate the source regions of energetic particles, and determine the role of plasma waves and turbulence in the production of solar wind and energetic particles

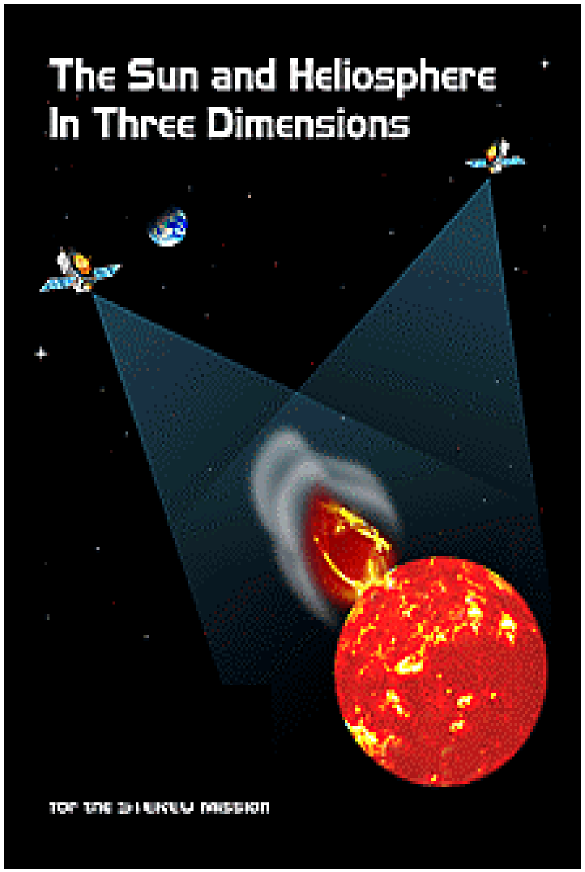
Mission Description

- Mission Design
  - Launch opportunity every 13 months (baseline is May 2010 launch)
  - Two solar passes (polar, 4 R_S) within 7.1 yr; three within 11.1 yr
  - Atlas 551/Star-48B launch vehicle; 713 kg @ C_3 = 128 km^2/s^2
  - JGA trajectory with post-perihelion ΔV for successive passes
  - 3.1-yr cruise; 0.02 × 5 AU final orbit with period of 4 yr
- Flight System Concept
  - 15° half-angle conical carbon-carbon heat shield
  - 3-axis stabilized with 0.2° pointing control and 0.05° knowledge
  - RTG power source (3 Multi-Mission RTGs supply 330 W BOL)
  - Ka-band downlink, X-band uplink using 34-m DSN dishes
  - Data rate: up to 40 kbps real-time with 200 kbps additional stored data
  - Payload: 50 kg, 47 W

Measurement Strategy

- In situ instruments (solar wind electrons & ion composition, magnetometer, energetic particle composition, plasma waves, & fast solar wind ion detector)
- Remote-sensing instruments (EUV imager, visible magnetograph-helioseismograph, & all-sky 3-D coronagraph)
- Characterize the solar wind within a high-speed stream
- Characterize the plasma in a closed coronal structure and probe the sub-sonic solar wind
- Image the longitudinal structure of the white-light corona from the poles
- Produce high-resolution images in each available wavelength
- Characterize plasma waves, turbulence, and/or shocks that cause coronal heating
- Determine the differences in sw characteristics during solar max and min

Solar Terrestrial Relations Observatory (STEREO)



Technology Development

- No enabling technologies required.

Science Objectives

- Understand the causes and mechanisms of CME initiation
- Characterize the propagation of CMEs through the heliosphere
- Discover the mechanisms and sites of energetic particle acceleration in the low corona and the interplanetary medium
- Develop a 3D time-dependent model of the magnetic topology, temperature, density, and velocity structure of the ambient solar wind

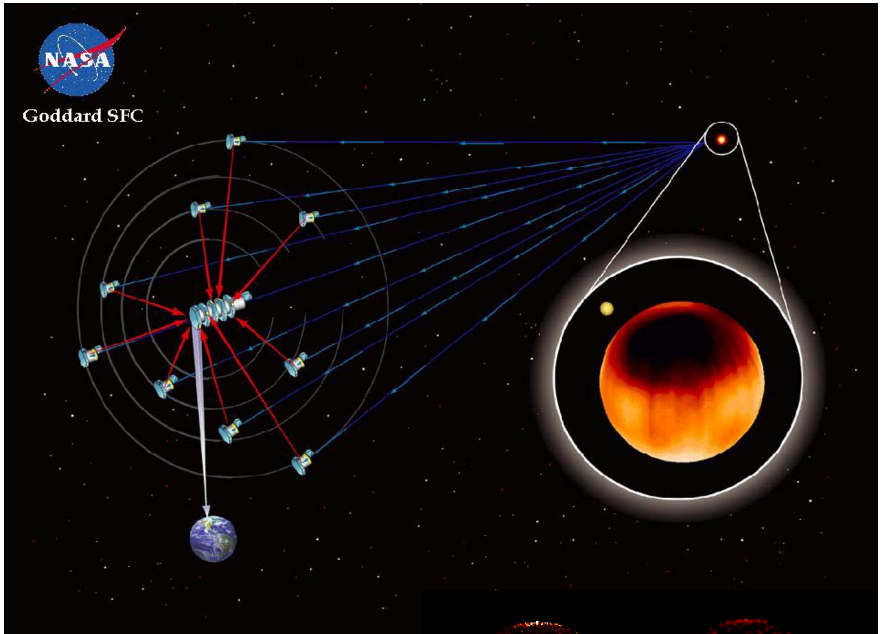
Mission Description

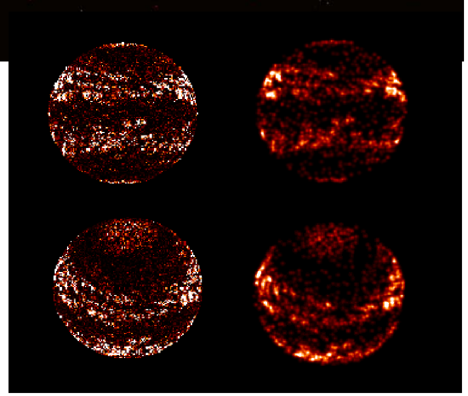
- Two Functionally Identical Spacecraft in Heliocentric Orbits at 1 AU (22°/yr Drift From Earth Orbit Leading/ Lagging Configuration).
- The 3 year STEREO mission is a multilateral international collaboration involving participants from France, Germany, the United States and the United Kingdom
- The investigations include a Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI), a STEREO/WAVES (SWAVES) interplanetary radio burst tracker, an In Situ Measurements of Particles and CME Transients (IMPACT), and a PLAsma and Suprathermal Ion and Composition experiment (PLASTIC).

Measurement Strategy

- SECCHI will track Coronal Mass Ejections (CMEs) from the Sun to the Earth utilizing
- Two White Light Coronagraphs, an Extreme Ultraviolet Imager, and a Heliospheric Imager with overlapping fields of view to observe the same features simultaneously
- IMPACT will sample the 3-D distribution of solar wind plasma electrons, the characteristics of the energetic particle ions and electrons, and the local magnetic field utilizing a Solar Wind Experiment, a Suprathermal Electron Telescope, a Magnetometer Experiment, and a Solar Energetic Particle Experiment Suite
- PLASTIC will provide the plasma characteristics of electrons (1-1000 eV) protons, alpha particles, and heavy ion (300-8000 eV) that characterize the CME plasma
- SWAVES utilizes in-situ as well as remote sensing mesurements to tracks CME Driven Shocks from the Corona to the Earth

Stellar Imager





Science Objectives

- Explore the patterns in surface magnetic fields throughout activity cycles on a substantial sample of stars like the Sun in order to develop and test a predictive dynamo model for the Sun.
- Image the evolving dynamo patterns on nearby stars by repeatedly observing them with ~1,000 resolution elements on their surface using UV emission as a proxy for magnetic field.
- Image the structure and differential rotation of stellar interiors by the asteroseismic technique of acoustic imaging, achieving 30 resolution elements on stellar disks with 1-min. time resolution in one or more broad optical pass bands.

Mission Description

- Days to weeks of uninterrupted observing from a very stable environment, such as L2
- Strategic mission, with 9 or more coordinated spacecraft
- Mission lifetime: 5-10 years

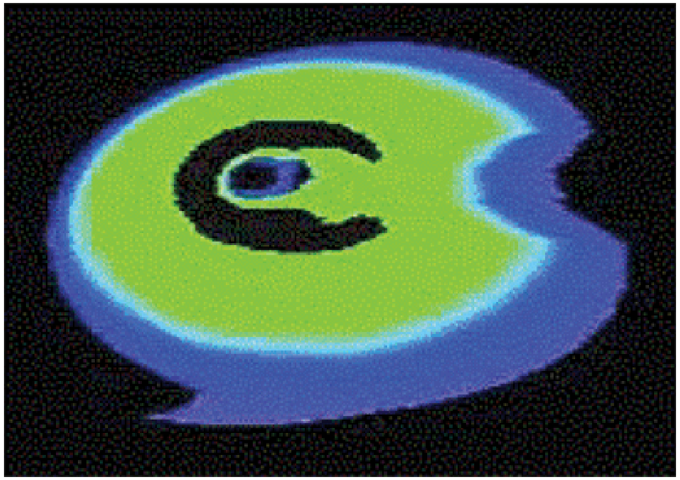
Measurement Strategy

- Angular resolution of images better than 0.1 milli-arcsec
- Reconfigure the imaging array fast enough to obtain images of stars within 1% of their rotation period
- Compile at least ~20 images within a stellar rotation period to measure surface differential rotation and field evolution
- Revisit targets repeatedly during 3-6 month intervals over a period of 5-10 years.
- Determine the interval structure and rotation with adequate resolution in layers where the dynamo operates

Key Technology Requirements

- Precise formation flying with low-mass, efficient propulsion
- Interferometric beam combining with ~5nm precision

Sun-Earth Energy Connector (SEEC)



Studying the plasmasphere is one aspect of tracing the flow of radiant EUV energy from the Sun to determine its effect on the Earth.

Technology Requirements

- Ionospheric 911Å imaging system
- Simultaneous Sun and Earth viewing at >3RE
- Optics-free photoelectron spectrometer

Science Objectives

- Quantify the relationships between solar radiation and space weather on local and planetary scales by:
  - Specifying solar EUV radiation variability and its source mechanisms
  - Simultaneously mapping the neutral and plasma near-Earth space environments
  - Establishing instantaneous relationships among solar radiation, precipitating energetic particles, and the space environment

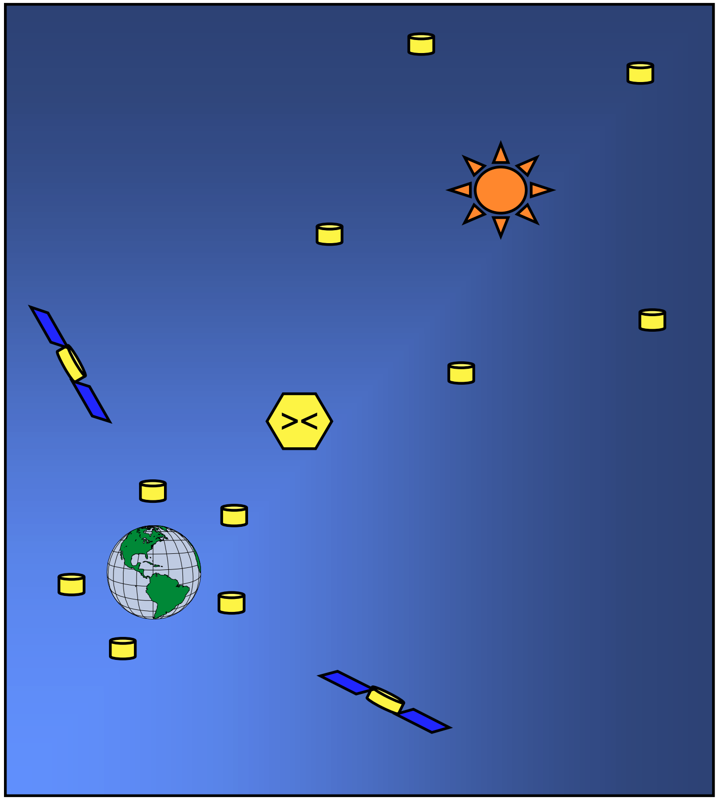
Mission Description

- MIDEX or STP class mission
- Orbit at >3RE, ~50° inclination
- Simultaneous imaging of the Sun's outer atmosphere and Earth's neutral atmosphere, day-night ionosphere, and plasmasphere

Measurement Strategies

- Simultaneous global images of the Sun and Earth
- High-angular-resolution images to observe local thermosphere, ionosphere, and plasmasphere weather
- Simultaneous high-accuracy solar EUV irradiance spectrum made with order-free spectrometer
- Development of new versions of neutral density and plasmaspheric-ionospheric models

Sun, Heliosphere, Earth Constellation



Science Objectives

- Provide long-term relevant information on the Earth, Sun and its interconnecting medium as a system
- Understand, monitor and track the Sun, Earth and Heliosphere as a dynamic and evolving system
- Provide timely reports and predictions on the status and possible major disturbances in the Earth, Sun System

Mission Description

- Establish an operational constellation of sensor suite(s) that satisfies the mission objectives
- Deploy sufficient sensors to measure the relevant data with adequate spatial and temporal and resolution
- Implement a data processing capability and information network to provide the required products and services
- Refresh, replace and enhance space borne constellation elements over time
- Improve modeling and algorithms as understanding and assets increase

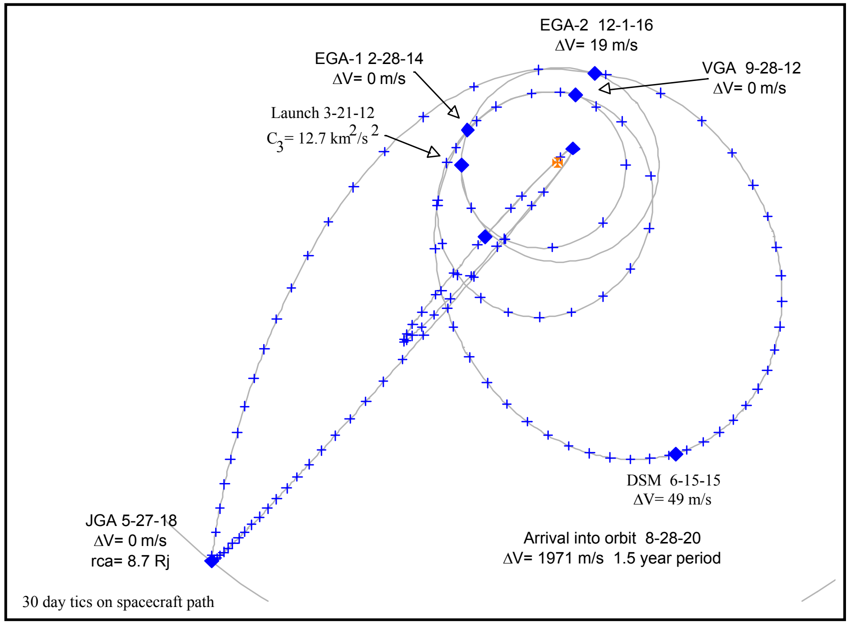
Technology Requirements

- Constellation suite(s) of sensors will all be developed and verified as roadmap missions are accomplished
- Technology to integrate multiple data streams from multiple sources to provide timely operational results may be needed

Measurement Strategy

- Remote sensing of the Sun from locations needed to provide data for proven predictive models
- In-situ sensors to measure key parameters in the Earth Sun interconnecting medium.
- Near Earth remote and in-situ measurements to complete and verify the monitoring and modeling of the Earth Sun System

Telemachus



Enabling Technology Development

- High Temperature Solar Arrays
- Dual Mode ACS (high precision 3-axis and F&P spin mode)

Science Objectives

- Understanding our changing Sun and its effects throughout the Solar System (Space Science Enterprise Strategic Plan, November 2000)
- Reveal through helioseismology how convection and rotation coupleand magnetic flux accumulates in the polar regions (solar dynamo)
- Uncover the mechanism(s) in the polar regions of the Sun that accelerate the solar wind and energetic particles and expel plasma and magnetic fields (CMEs)
- Exploit the polar viewpoint to examine the distribution of radio and x-ray emission simultaneously from all solar longitudes
- Determine the physics of the strongest stream/stream plasma interactions and transient shocks where they are first formed in the heliosphere

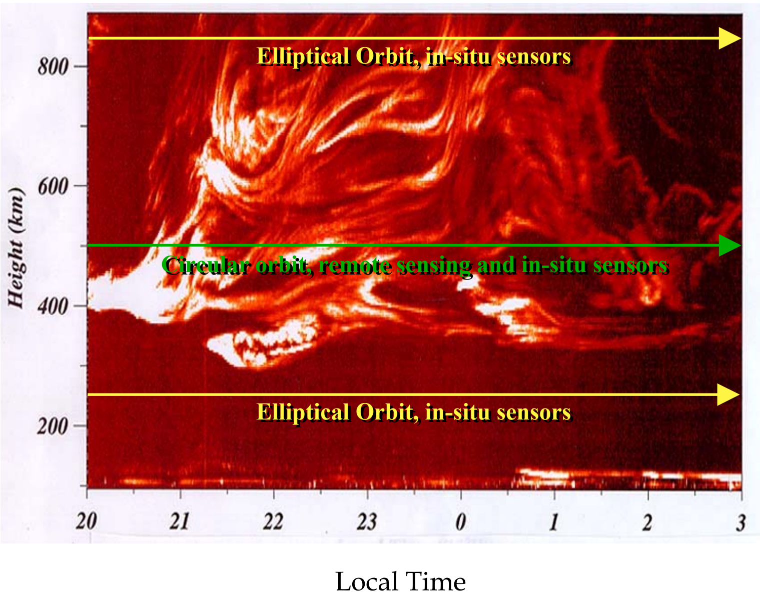
Mission Description

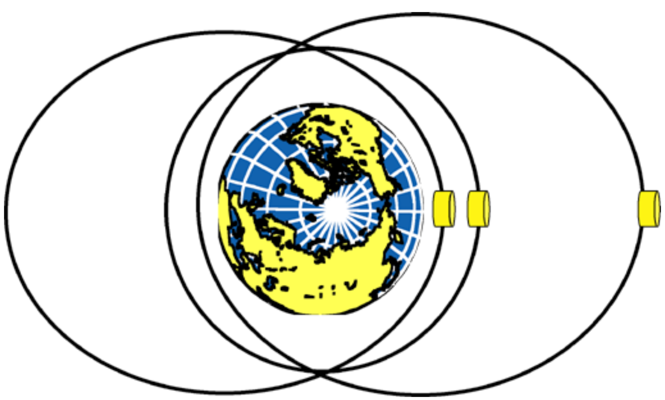
- Example Mission Design
  - Delta III Launch, 1765 kg @ C_3 = 17 km^2/s^2 (12.7 min)
  - VEEJGA Trajectory with Perihelion ΔV
    - 8.4 yr cruise, 3 yr science ops
    - 0.2 x 2.5 AU Final Orbit, Period: 1.5 years
  - 90° Heliographic Inclination
    - 1st 4.5 years ecliptic (VEEJGA); 3 years In Final Orbit (polar)
- Flight System Concept
  - 3-Axis and Spin-Stabilized Platform
  - Solar Arrays (Ultraflex, High Efficiency Silicon, High Temp Cells)
  - Payload: 33 kg, 42 W, 8 kbps
  - 2239 m/s ΔV
  - 30 arcsec (control), 10 arcsec (knowledge)

Measurement Strategy

- Continuous science except for 2 years beyond 3 AU (JGA)
- Optimized Solar and heliospheric imagers (Doppler magnetograph, two white light)
- Basic, proven fast plasma, magnetic field and energetic particles in situ detectors
- Improved plasma elemental and isotopic composition for coronal diagnostics and interstellar/cometary/”inner source” pickup ions
- Sensitive radio directional spectrograph and x-ray spectrometer

Tropical ITM Coupler





Minimum Technology Design was Baselined

- No "enabling" technology required
- New enhancing technology should reduce spacecraft cost by 10%

Science Objectives

- Measurement of neutral and plasma electro- dynamics at different altitudes simultaneously.
- Determine the coupling between the Earth's low latitude mesosphere, thermosphere, ionosphere, and inner plasmasphere.

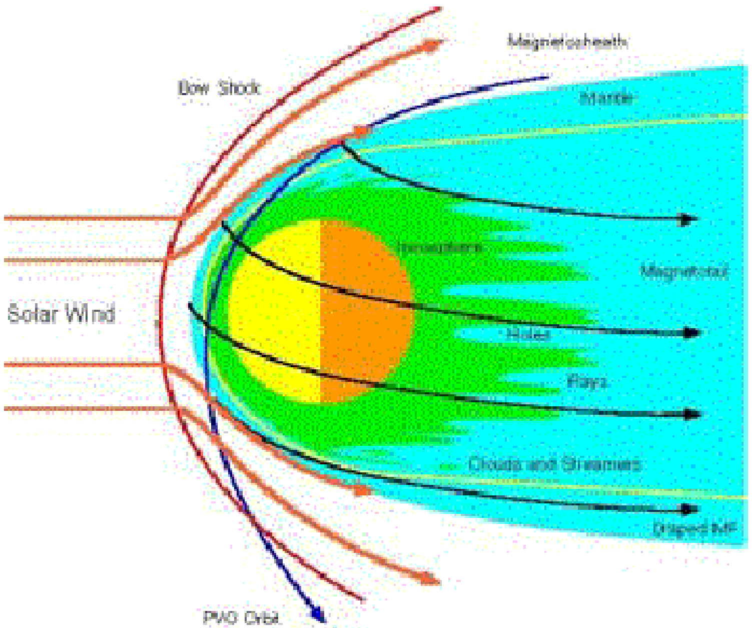
Mission Description

- 3 satellites with identical orbit periods and the same low inclination (<20°)
  - 2 with elliptical orbits (250 x 1500 km)
    - Apogees: 180 degrees apart
    - Dipping to 150 km perigee
  - 1 with a circular orbit of 600 km
- Payload (ram and nadir pointing)
  - 8 in-situ instruments on all 3
  - 4 remote sensing on circular spacecraft

Measurement Strategy

- Remote sensing: gravity waves, airglow, neutral winds, plasma density profiles;
- In-situ: electric, magnetic fields, thermal, energetic plasma, neutral properties, winds, lightning;
- Coverage (continuous in each orbit):
  - Conjunctions of the two elliptical satellites with each other and the circular satellite provide investigations of vertical coupling

Venus Aeronomy Probe



Science Objectives

- Determine Mechanisms for Energy Transfer From the Solar Wind to the Ionosphere and Upper Atmosphere
- Measure the Charged Particles Responsible for Auroral-Type Emissions and Infer their Acceleration Mechanisms
- Determine Formation Processes for Ionospheric Magnetic Flux Ropes, Ionospheric "Holes" on the Nightside and the Loss of Ionospheric Plasma in the Form of Streamers, Ray and Clouds

Mission Description

- Example Mission Design
  - Small Delta II
  - 1-Year Flight Time, 1year OPS
  - High Inclination Elliptical Orbit
    - 150 km x 12,000 km
- Flight System Concept
  - Spin-Stabilized Platform
  - Floating Potential Neutralization
  - Solar Array Implementation

Technology Development

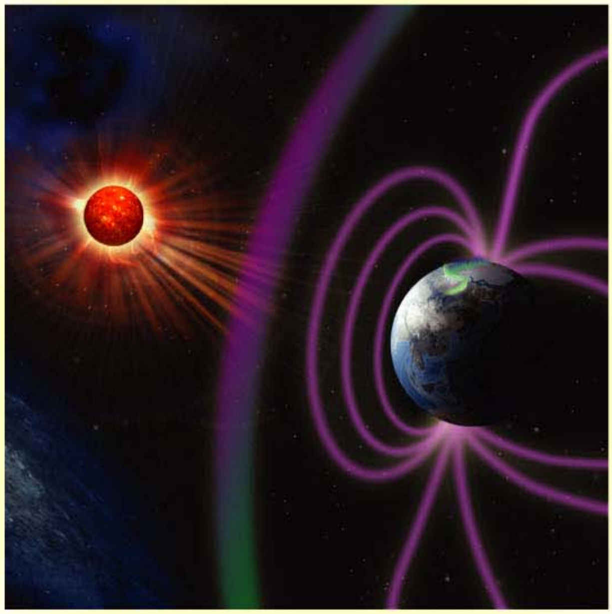
- Low Mass/Power Instrumentation
- Intelligent Instruments
- Non-Disruptive Floating Potential Neutralization

Measurement Strategy

- In-situ Plasma, Magnetic and Electric Fields and Plasma and Radio Wave Measurements
- In-situ Neutral Gas Composition, Density, Temperature, and Winds Measurements
- Remote Observations using a UV Spectral Imager, Fabry-Perot Interferometer, Energetic Neutral Atom Imager, Ionospheric Sounder

Sun-Earth Connection

ROADMAP 2003-2028



Understand the Sun,

Heliosphere, and Planetary

Environments as a Single

Connected System

http://sec.gsfc.nasa.gov

National Aeronautics and
Space Administration

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