Understanding the Sun and Solar System Plasmas

Future Directions in Solar and Space Physics

Solar and Space Physics Survey Committee

Committee on Solar and Space Physics

Space Studies Board

Division on Engineering and Physical Sciences

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The project was supported by the National Aeronautics and Space Administration under Contracts NASW 96013 and NASW 01001, the National Oceanic and Atmospheric Administration under Purchase Order No. 40-AA-NR-111308, the National Science Foundation under Grant No. ATM-0109283, the Office of Naval Research under Grant No. N00014-01-1-0753, and the Air Force Office of Scientific Research under Purchase Order No. FQ8671-0101168.

Support for this publication was provided by The Presidents' Circle Communication Initiative of the National Academies.

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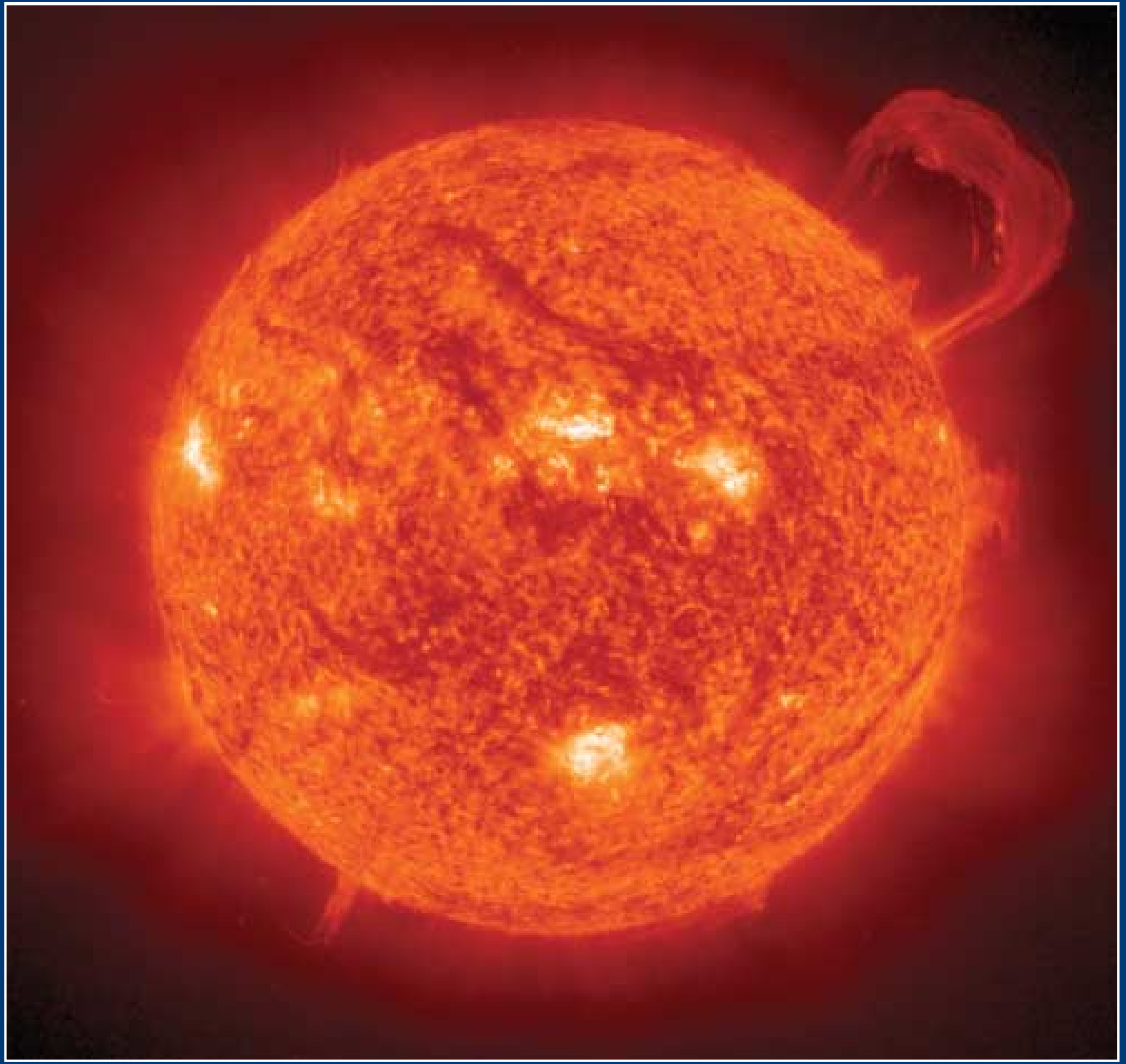

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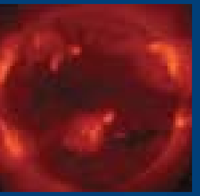


THE HELIOSPHERE

THE DOMAIN OF SOLAR AND SPACE PHYSICS

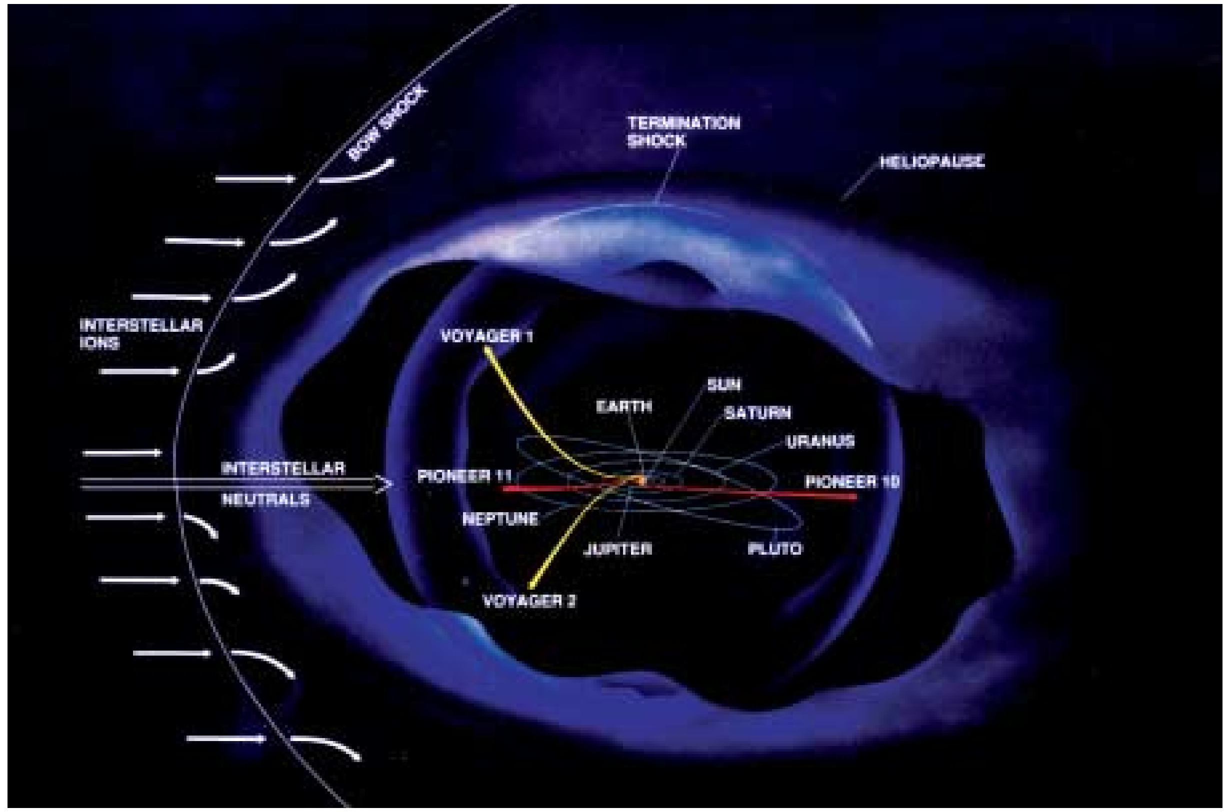
The Sun is the source of the heat and light that maintain Earth's habitable environment, and the ultimate source of energy for life itself. It is also the origin of an invisible influence—in the form of a continual outflow of ionized gas, the **solar wind**—that affects not only Earth but also the other planets, moons, asteroids, and comets of our solar system. The region within which the Sun exerts this unseen influence is called the **heliosphere,** after "helios," the Greek word for the Sun. The heliosphere can be thought of as a giant bubble inflated by the solar wind within the mixture of electrically neutral gas, ionized gas, and interstellar dust that form our solar system's local galactic environment. Its boundaries are still uncharted but are thought to lie some 9 billion to 10 billion miles from the Sun, well beyond the orbit of Pluto, the outermost planet.

As the solar wind flows away from the Sun and fills the heliosphere, it interacts in various ways with the planets and other solar system bodies that it encounters. The nature of this complex interaction depends critically on whether the object has an internally generated magnetic field (Mercury, Earth, the giant outer planets) or not (Venus, Mars, comets, the Moon). Mars today, for example, has no strong global magnetic field, and so the solar wind impinges directly on a significant fraction of its thin carbon dioxide atmosphere. The erosion of the atmosphere resulting from this interaction over the last 3 billion years may have played an important role in the evolution of Mars's atmosphere and climate. In contrast, Earth's atmosphere is protected from direct exposure to the solar wind by the terrestrial magnetic field, which forms a complex and dynamic structure—the **magnetosphere**—around which most of the solar wind is diverted. The interaction with the solar wind drives a flow of extremely dilute ionized gases within the magnetosphere, powers the northern and southern lights, and is responsible for sporadic but sometimes quite severe disturbances in Earth's space environment. Such **space weather** disturbances can interfere with communications and navigation systems, disrupt power systems, and pose a health and safety threat to astronauts.

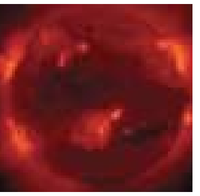
Solar and space physics is the scientific discipline that seeks to understand the inner workings of the Sun, the acceleration of its outer atmosphere into a supersonic wind, and the interaction of the solar wind with planetary upper atmospheres and magnetospheres, comets and other small bodies, and the local interstellar medium.

Solar and space physics is a branch of **plasma physics**. Everyone is familiar with the three most common states of matter—solid, liquid, and gas. But there is also a less well known fourth state, **plasma**, which occurs when a gas becomes so hot that electrons separate from the atoms that make up the gas, resulting in a mix of negatively charged electrons and positively charged ions. Unlike ordinary gases (the air we breathe, for example), plasmas can carry electrical currents, and so their motion is subject to the influence of electrical and magnetic fields. Solar and space physics studies the behavior of plasmas in our solar system and their interactions with each other and with non-plasmas such as interstellar dust grains or the neutral gases of planetary atmospheres. It seeks to identify the composition of solar system plasmas and to understand the magnetic fields, electric fields, currents, and waves through and by which energy is transferred within them.

Astrophysics, too, is concerned with matter in the plasma state. However, the objects that it studies lie far outside the boundaries of our solar system and can be studied only remotely, through the detection of the electromagnetic radiation that they emit or that passes through them. Solar and space physics is unique among the space sciences in that, since the beginning of the space age, it has been able to sample solar system plasmas and their associated electric and magnetic fields directly, through in situ measurements from satellites. Such measurements have been an invaluable source of knowledge about the physics of plasmas. What scientists have learned about the behavior of plasma within our own solar system can help them understand similar processes in remote astrophysical environments, inaccessible to direct measurement.



Artist's rendering of the heliosphere, showing its structure and boundaries.



Solar and space physics is also unique among the space sciences in that what it learns about solar system plasmas can be of practical as well as purely scientific value. That is, the better scientists understand the workings of the Sun, the greater our capability will be to anticipate and protect against the adverse effects of space weather—whether in Earth's own magnetosphere or in the space environments of those planets on which we hope to live and work in the future.

Solar and space physics is a relatively mature discipline in which the question *what* is increasingly replaced by the questions *how* and *why*. Why does the Sun's magnetic activity exhibit an 11-year cycle? How is the solar atmosphere heated to a million or more degrees, while the temperature of the Sun's visible surface measures only around 6,000 degrees? How is the solar wind accelerated to supersonic velocities? How do magnetic fields interconnect, causing the rapid conversion of magnetic energy to charged-particle kinetic energy in solar flares and magnetospheric substorms? How do the heliosphere and our galaxy interact?

These are but a few of the major questions that solar and space physicists will seek to answer during the coming decade. These questions and the research initiatives needed to address them were the subject of an 18-month study organized by the National Research Council's Space Studies Board and its Committee on Solar and Space Physics and carried out in 2001 and 2002 by five ad hoc study panels under the oversight of the Solar and Space Physics Survey Committee. The Survey Committee's findings and recommendations with respect to scientific goals for solar and space physics and an integrated research strategy for the next decade are reported in *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics*. That 177-page report forms the basis for this booklet, which offers the general reader an overview of the field of solar and space physics, along with a summary of the key problems that solar and space physics research will target during the next decade and the principal research initiatives recommended by the Survey Committee.

SOLAR AND SPACE PHYSICS

The fundamental goal of solar and space physics research is to discover, to explore, and ultimately to understand the activity of a star—our Sun—and the often complex effects of that activity on the interplanetary environment, the planets and other solar system bodies, and the interstellar medium.

The lessons of solar and space physics are often relevant to our understanding of astrophysical objects lying beyond our solar system.

Solar and space physics, though "pure" science, also yields important practical benefits in the area of space weather.

MAJOR THEMES IN SOLAR AND SPACE PHYSICS RESEARCH

In surveying the current state of ground-based and space-based research in solar and space physics and recommending directions for future research, the Solar and Space Physics Survey Committee organized the outstanding questions that will be the focus of solar and space physics investigations during the next decade in terms of the following five themes or challenges:

THE SUN'S DYNAMIC INTERIOR AND CORONA

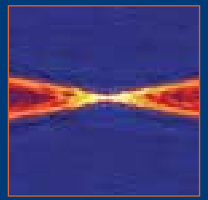
Understanding the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the causes of solar activity and the origin of the solar cycle, and the structure and dynamics of the corona

CHARTING THE HELIOSPHERE

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

SPACE ENVIRONMENTS OF EARTH AND OTHER SOLAR SYSTEM BODIES

Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences

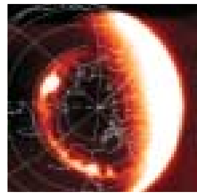


FUNDAMENTAL SPACE PLASMA PHYSICS

Understanding the basic physical principles manifest in processes observed in solar and space plasmas

SPACE WEATHER

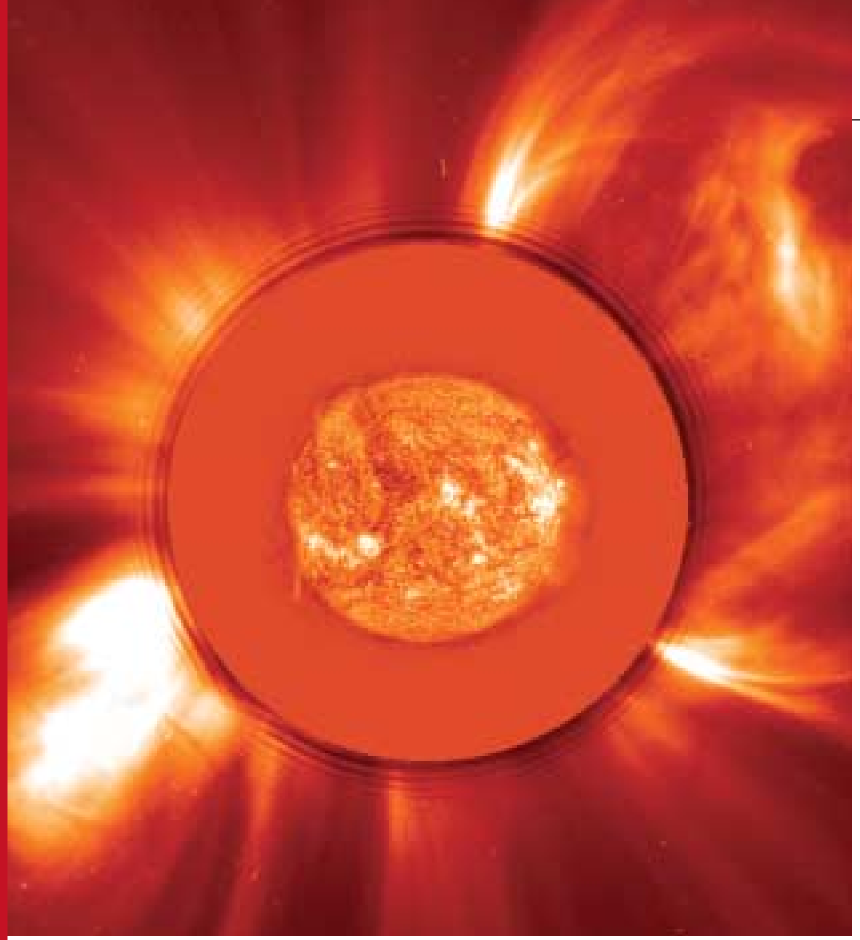
Developing near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earth's magnetosphere



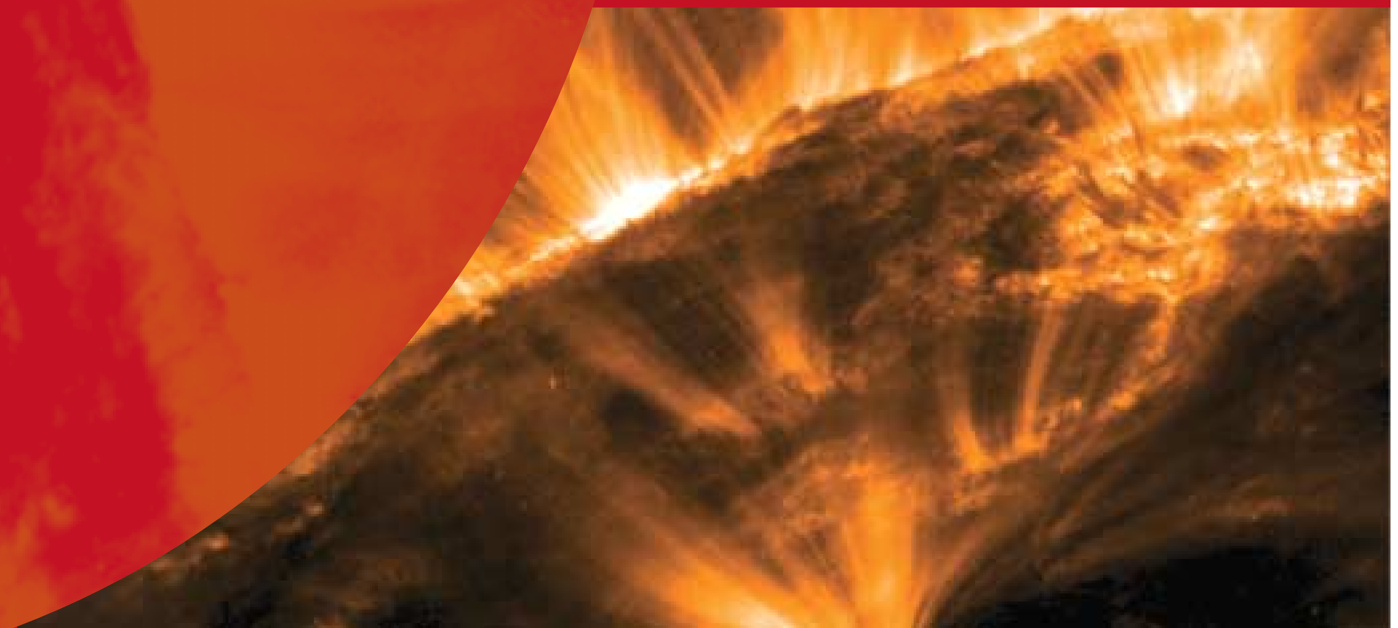
THE MAGNETIC SUN

The Sun is a magnetic star. The thermonuclear furnace in its 15-million-degree core heats and churns the electrically conducting plasma in the outer third of the Sun in much the same way as a stove heats and churns boiling water. This part of the Sun is called the **convective zone**. Plasma in motion drives a dynamo that generates a global magnetic field as well as smaller-scale local fields. As these magnetic fields emerge through the Sun's visible surface (the **photosphere**), they form sunspots and other **active regions** and create complex and dynamic plasma structures in the Sun's upper atmosphere (**corona**). The Sun's magnetic fields store enormous amounts of energy, which can be released gradually or explosively. Explosive energy release occurs in **flares** and **coronal mass ejections** (CMEs). Flares are intense releases of energy in the form of electromagnetic radiation and energetic particles; CMEs are transient events in which huge quantities of coronal plasma and magnetic fields are propelled into the heliosphere, sometimes at initial speeds in excess of 1,000 kilometers per second.

The Sun's magnetic activity increases and decreases in a nearly regular cycle, as is seen in the rise and fall of the number of sunspots every 11 years. (Shaped by intense, local magnetic activity, sunspots are somewhat cooler than the surrounding gases, and therefore appear darker.) With increasing magnetic activity, changes occur in the structure of the corona and the solar wind, while CMEs and flares become more frequent. Around the peak of the solar cycle, the Sun's global magnetic field "flips"—that is, the north magnetic pole becomes the south magnetic pole, and vice versa! Not surprisingly, the Sun's effect on the solar system ebbs and flows with its magnetic cycle. For example, solar-cycle-driven changes in the structure of the solar wind are thought to cause variations in the shape of the heliospheric "bubble." Of more immediate concern to us here on Earth is the increase in space weather disturbances during the periods of high solar activity. Such perturbations, and potential impacts on satellites, radio communications, and high-flying humans, are triggered by encounters of fast CMEs with Earth's magnetic field.



Coronal mass ejections, such as the two seen here heading in opposite directions from the Sun, are the primary drivers of heliospheric and geomagnetic disturbances.



Magnetic fields emerging from the solar interior organize the Sun's million-degree corona in a complex architecture of loops, arcades, and filaments.

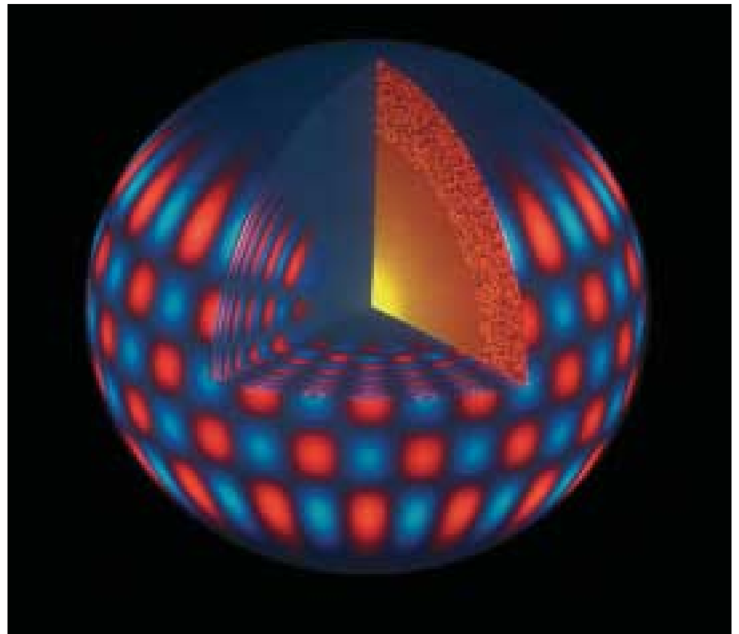
PROBING THE SUN'S INTERIOR

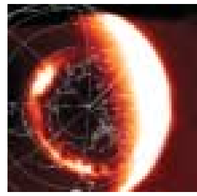
Although the Sun has no solid surface—it is a churning ball of gases—the intense brightness of its photosphere blinds us. So how do we know what is going on inside? The answer: through helioseismology, the study of "sunquakes." Helioseismology probes the structure and dynamics of the Sun's interior by observing oscillations on the photosphere. By analyzing the patterns of these oscillations, helioseismologists are able to infer the shape and motions of solar plasma deep in the interior. Helioseismic observations have revealed strong variations in the velocity of the plasma flows at both the base and the top of the convective zone. It is in such layers of differential flow that the Sun's large-scale magnetic field (lower layer) and small-scale magnetic field (upper layer) are likely to originate. A significant accomplishment of helioseismology, with important ramifications for other fields, is the validation of theoretical models of the Sun's interior.

THE CORONA AND SOLAR WIND

The wind that inflates the heliosphere, the solar wind, blows continuously. It originates in the several-million-degree solar

Artist's concept of the solar oscillations used in helioseismology to probe the Sun's interior.

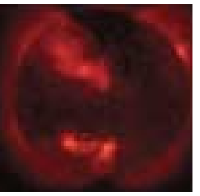


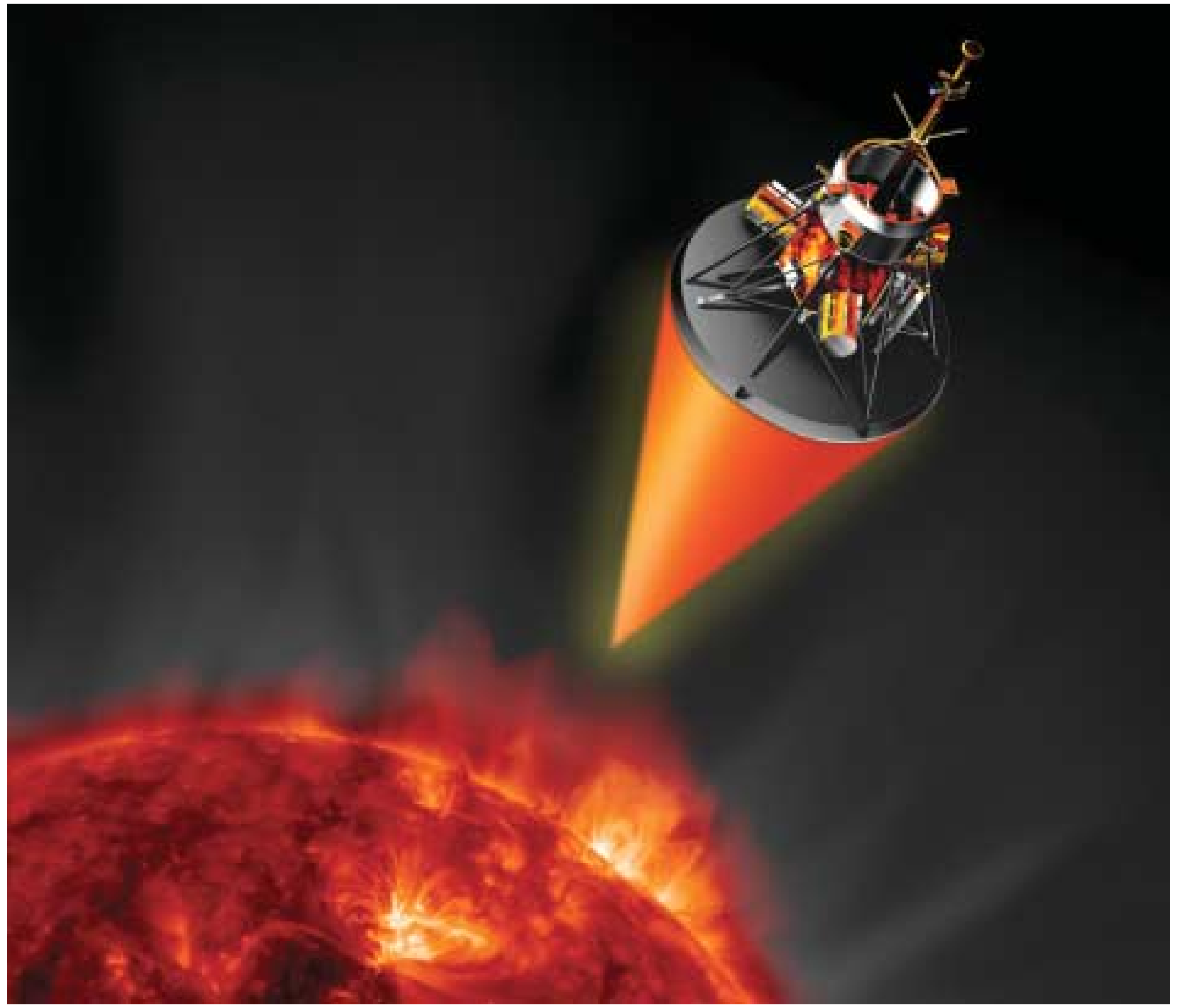


corona and is accelerated to supersonic speeds near the Sun by processes scientists still do not fully understand. As the solar wind blows through interplanetary space, it carries embedded in its flow a magnetic field, the **interplanetary magnetic field** (IMF). Like its coronal source, the solar wind is structured and variable. It changes in density, speed, and temperature, and in the strength and orientation of the IMF. At solar minimum, the heliosphere is dominated by a fast solar wind from the Sun's high latitudes, whereas during solar maximum it is dominated by a slow and variable wind from all latitudes. This change in the structure of the solar wind reflects the dramatic reconfiguration of the corona that takes place as the Sun's magnetic field reverses. At the peak of the Sun's activity cycle, the solar wind is also increasingly disturbed by the passage of CMEs, which occur over 10 times more often at solar maximum than at solar minimum.

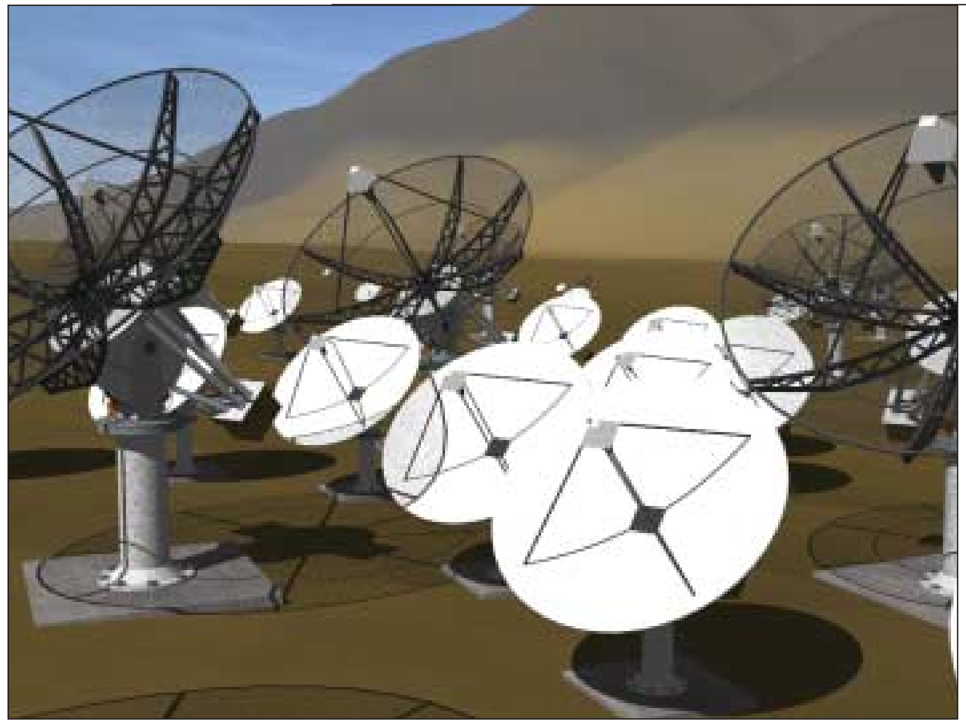
Like all solar activity, the solar wind's energy derives ultimately from the fusion of hydrogen nuclei in the Sun's core. But it is not known how the solar wind is accelerated to speeds ranging from 300 to 700 kilometers per second—and how its source, the Sun's corona, is heated to temperatures many hundreds of times hotter than those of the Sun's visible surface. Answers to these two fundamental questions will be provided by **Solar Probe**, a spacecraft that will sample the solar wind and corona in the near-Sun region, one of the last unexplored parts of the solar system and the source of the heliosphere itself. Such measurements will determine how energy flows upward in the solar atmosphere, heating the corona and accelerating the solar wind, and will also reveal how the wind evolves with distance in the inner heliosphere.

How energy stored in solar magnetic fields is explosively released in flares and CMEs is also poorly understood and is one of the key questions to be answered by the **Frequency-Agile Solar Radiotelescope** (FASR), the Survey Committee's top ground-based solar physics initiative. FASR is a revolutionary new observational tool that combines radio imaging and radio spectroscopy to study energy release in flares and CMEs, the three-dimensional structure of the solar atmosphere, and the magnetic fields that thread the corona.

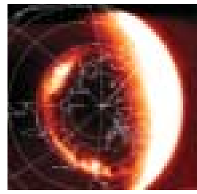




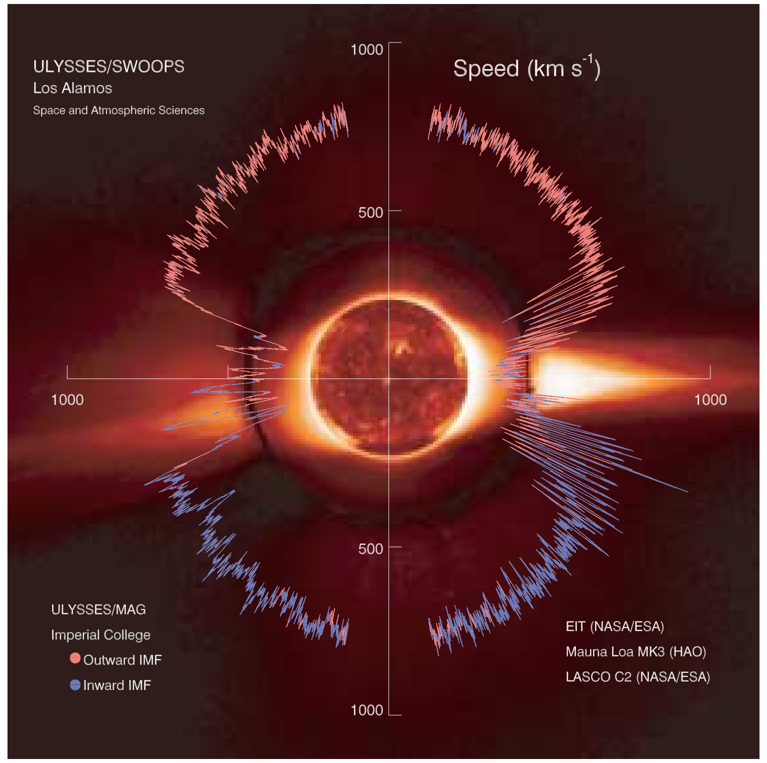
The first spacecraft to explore the near-Sun region, Solar Probe will revolutionize our basic understanding of the expanding solar atmosphere.

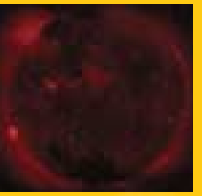


The 100-dish Frequency-Agile Solar Radiotelescope will combine radio imaging and radio spectroscopy to study the solar chromosphere and corona.



Ulysses measurements of solar wind speed, plotted as a function of latitude, clearly show the bimodal character of the solar wind around solar minimum: a fast wind from polar coronal holes and a slow wind from the low-latitude streamer belt.

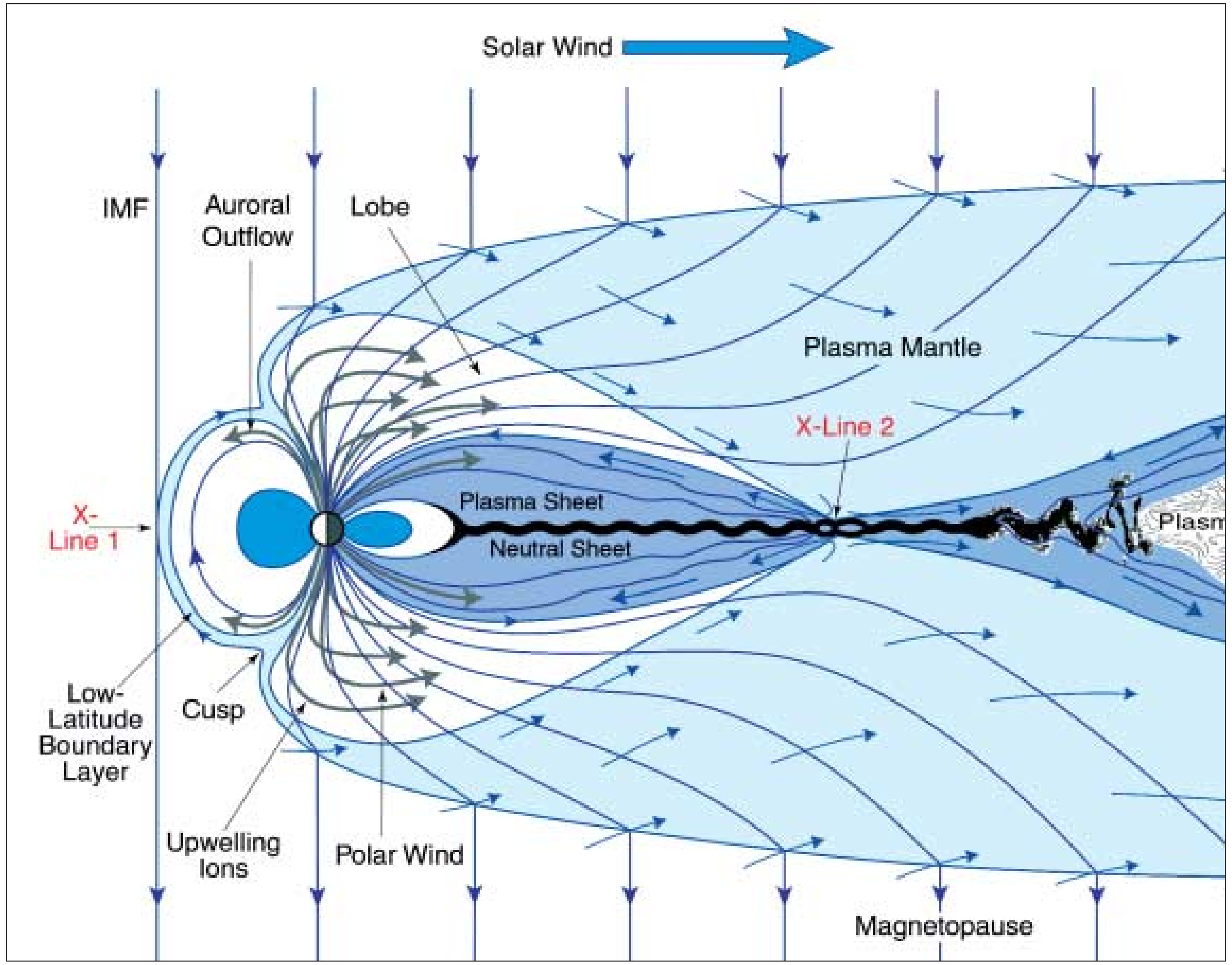




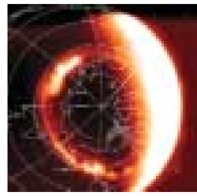
EARTH'S DYNAMIC MAGNETIC SHIELD

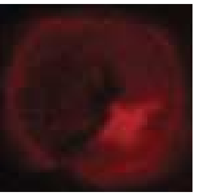
The solar wind does not impact Earth directly but is deflected—like a stream diverted around a boulder—by our planet's magnetic field, which forms a tear-drop-shaped cavity in the solar wind flow. This cavity—the **magnetosphere**—contains highly dilute plasmas whose behavior is controlled by Earth's magnetic field and its interaction with the solar wind. Its size depends on the velocity and density of the solar wind and on the IMF. The magnetosphere typically extends to around 10 times the radius of Earth in the sunward or "upstream" direction, and hundreds of Earth radii in the direction away from the Sun, or "downstream." (1 Earth radius = 6,378 kilometers.)

How the magnetosphere responds to the continuous buffeting by the solar wind depends strongly on the direction and strength of the IMF. Put simply, like poles repel and opposites attract. When the magnetic orientation of the IMF is opposite that of Earth's magnetic field on the sunward face of the magnetosphere, the two magnetic fields slam together and can cancel each other out. This annihilation process is called **magnetic reconnection**. Reconnection is the primary process by which Earth's magnetic shield is breached and energy transferred from the solar wind to the magnetosphere. This transfer of energy in turn drives the flow of plasma within the magnetosphere and leads to the buildup of magnetic energy in the magnetotail—the downstream portion of the magnetosphere, which looks a little like the tail of a comet. The energy stored in the tail is then explosively released in events known as **magnetospheric substorms**. During substorms, the magnetic field lines in the magnetotail behave like elastic bands that are stretched and then abruptly released, snapping back to their original configuration. The reconnection of stretched and stressed magnetic field lines in the tail is an important element of this process. Some of the energy released in substorms drives powerful electrical currents that inject several billion watts of power into the upper atmosphere and produce spectacular displays of the **aurora borealis** and **aurora australis**—the northern and southern lights.



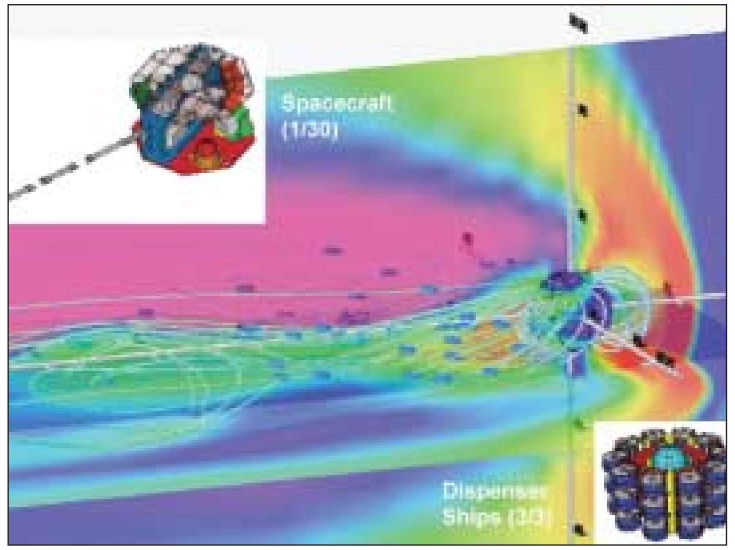
Drawing (not to scale) showing the structure of Earth's magnetosphere and illustrating the process of reconnection between the interplanetary and geomagnetic fields. Magnetic fields reconnect or annihilate where the fields point in opposite directions, at the sunward boundary of the magnetosphere and downstream of Earth in the magnetotail. At "X-Line 1," the interplanetary magnetic field (IMF) and the closed geomagnetic field cancel or annihilate, producing open field lines that have one end at Earth and the other in the solar wind. The open field lines are carried by the solar wind downstream of Earth, toward a second reconnection site (X-Line 2) in the magnetotail. The field lines above and below this site have opposite direction and reconnect, producing plasma outflows from the reconnection site both toward and away from Earth.





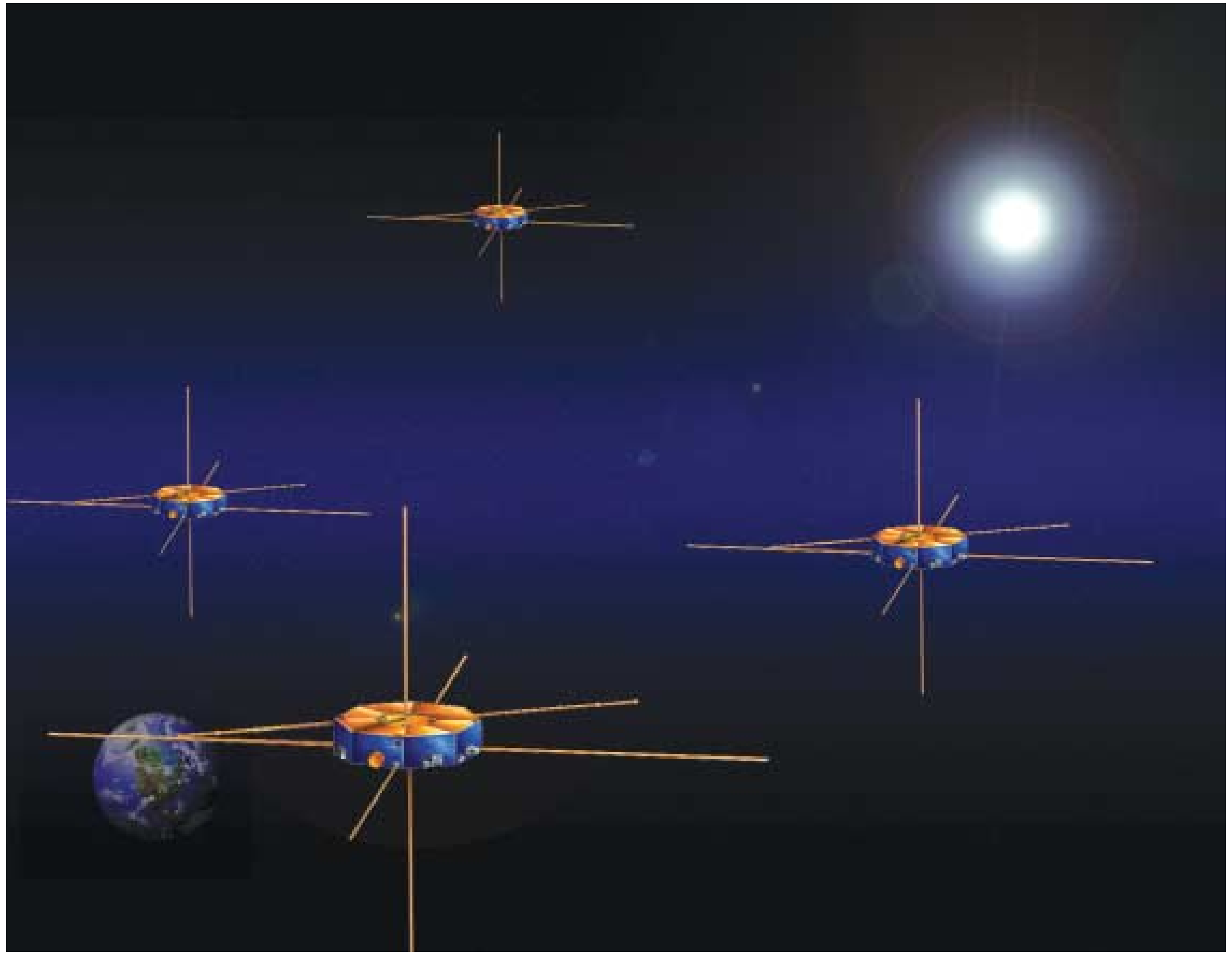
While the importance of reconnection is widely recognized and its effects well-known, scientists still do not fully understand how oppositely directed magnetic field lines cancel themselves out at reconnection sites. Achieving this understanding requires in situ measurement of charged particles, and of electric and magnetic fields at the reconnection site. Such measurements are challenging, owing to the small size of the sites, and must be made simultaneously from multiple vantage points. The exploration of these localized regions surrounding reconnection sites is one of the principal objectives of the **Magnetospheric Multiscale** (MMS) mission, a four-spacecraft Solar Terrestrial Probe designed to study microphysical processes in key boundary regions of Earth's magnetosphere, from the subsolar magnetopause to the high-latitude magnetopause, and from the near-Earth magnetotail to its most remote regions. In addition to reconnection, MMS will study the roles of particle acceleration and turbulence in the transfer of energy within and across magnetospheric boundaries. MMS is the Survey Committee's highest-priority initiative in the moderate-cost category.

The Magnetospheric Constellation mission's fleet of microsatellites will provide information about the large-scale structure and dynamics of the magnetosphere by acquiring data at multiple locations simultaneously.

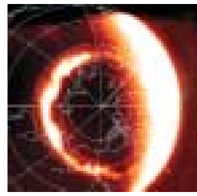


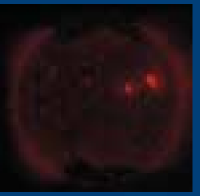
The northern and southern lights are dramatic visible manifestations of disturbances in the invisible plasmas of Earth's magnetosphere.

The circulation of energy through plasmas occurs throughout the universe, in solar flares, in planetary magnetospheres, and in protostars, as well as in Earth's magnetosphere. In Earth's magnetosphere, researchers can measure the flow of energy directly, but the system is so vast and dynamic that localized measurements from individual satellites are of little use in capturing the overall dynamic behavior and structure of the magnetosphere. The **Magnetospheric Constellation** (MagCon) mission will solve this problem by deploying dozens of small, autonomous microsatellites to perform continuous measurements of the magnetospheric plasma and magnetic fields. These measurements will provide the "pixels" from which the "big picture" of the entire magnetosphere can be composed. Computer modeling and theory will play a critical role in integrating the data pixels into a coherent depiction of magnetospheric dynamics.



Particles and fields measurements by the four identically instrumented Magnetospheric Multiscale spacecraft will allow space physicists to answer long-standing questions about the universal process of magnetic reconnection.



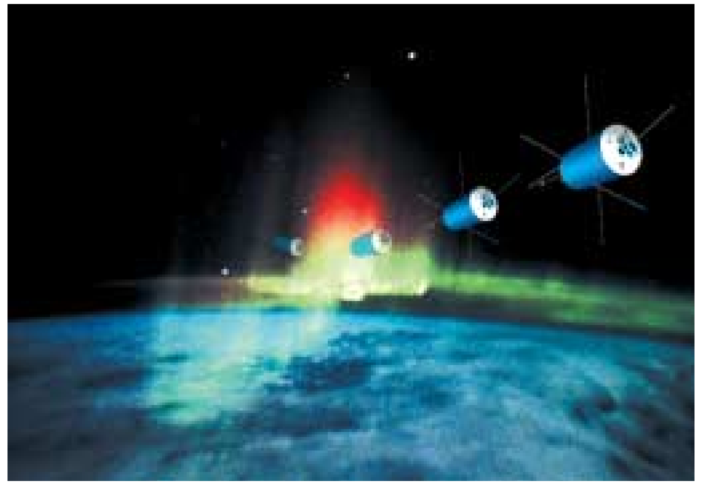


THE THRESHOLD OF SPACE

EARTH'S UPPER ATMOSPHERE

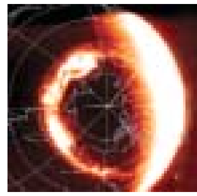
At an altitude of approximately 80 kilometers, some of the electrically neutral atoms and molecules of Earth's thin upper atmosphere are ionized by the Sun's ultraviolet and x-ray radiation, creating the **ionosphere**. This is not really a separate layer of the atmosphere, but rather a population of electrons and ions that are mixed in with the neutral gas of the **thermosphere**. It is the ionosphere that makes long-distance radio communication possible, since it acts as a kind of mirror in the sky, bouncing electromagnetic signals back down to Earth, over the horizon from their point of origin. At Earth's high northern and southern latitudes, intense current systems link this ionospheric plasma with the plasmas of the magnetosphere and channel energy from the magnetosphere into the upper atmosphere. What happens to this energy—whose source is ultimately the solar wind—once it is deposited in Earth's upper atmosphere? Some of it powers the northern and southern lights, some of it goes into heating the upper atmosphere, and some of it drives thermospheric winds with speeds as great as 1,000 meters per second. Disturbances in the ionosphere can result in disruption of radio communications; and navigation signals beamed to Earth from Global Positioning System (GPS) satellites, high above the ionosphere at an altitude of 35,500 kilometers, can be degraded as they pass through disturbed regions in the ionosphere. Sun-Earth interactions can distort the ionospheric mirror and garble communications. Earlier studies have taught scientists much about the structure, energetics, and dynamics of the upper atmosphere. However, the different spatial and temporal scales on which magnetospheric energy is deposited and redistributed in this region are poorly known, as is the complex and ever-changing relationship between small-, intermediate-, and large-scale phenomena.

The Survey Committee assigns high priority to two initiatives, one space-based and one ground-based, that will employ novel investigative strategies



During the 2-year multispacecraft Geospace Electrodynamic Connections mission, "deep dipping" maneuvers will be performed to allow in situ measurements down to altitudes as low as 130 kilometers.

Artist's concept of the portable Advanced Modular Incoherent Scatter Radar deployed at a high-latitude site to study the response of the upper atmosphere to auroral activity.



and techniques to study the transfer of energy between the magnetosphere and the upper atmosphere, and the processing of this energy within the upper atmosphere.

The **Geospace Electrodynamic Connections** (GEC) mission is a Solar Terrestrial Probe mission that will make simultaneous measurements from several spacecraft at different locations in the high-latitude ionosphere and thermosphere, a region not systematically sampled by spacecraft since the 1960s. Together with supporting ground-based observations, GEC will answer a number of outstanding questions about the coupling of the magnetosphere to the upper atmosphere and of the ionosphere to the thermosphere.

For ground-based geospace research, the **Advanced Modular Incoherent Scatter Radar** (AMISR) is the Survey Committee's top-ranked small initiative. It will combine a powerful state-of-the-art incoherent scatter radar with supporting optical and radio instrumentation. To maximize return on investment, and taking advantage of progress in the miniaturization of instruments, AMISR will be designed to be modular and mobile. AMISR can be deployed to different geographical locations and reconfigured to probe the upper atmospheric phenomena specific to each location. This unique capability will allow AMISR to investigate a wide range of ionospheric phenomena at polar, auroral, equatorial, and mid-latitudes, and to operate in close conjunction with other ground-based, suborbital, and satellite investigations of the geospace environment. Initially, AMISR will focus on the coupling between the neutral atmosphere and the ionospheric plasma in the auroral oval.

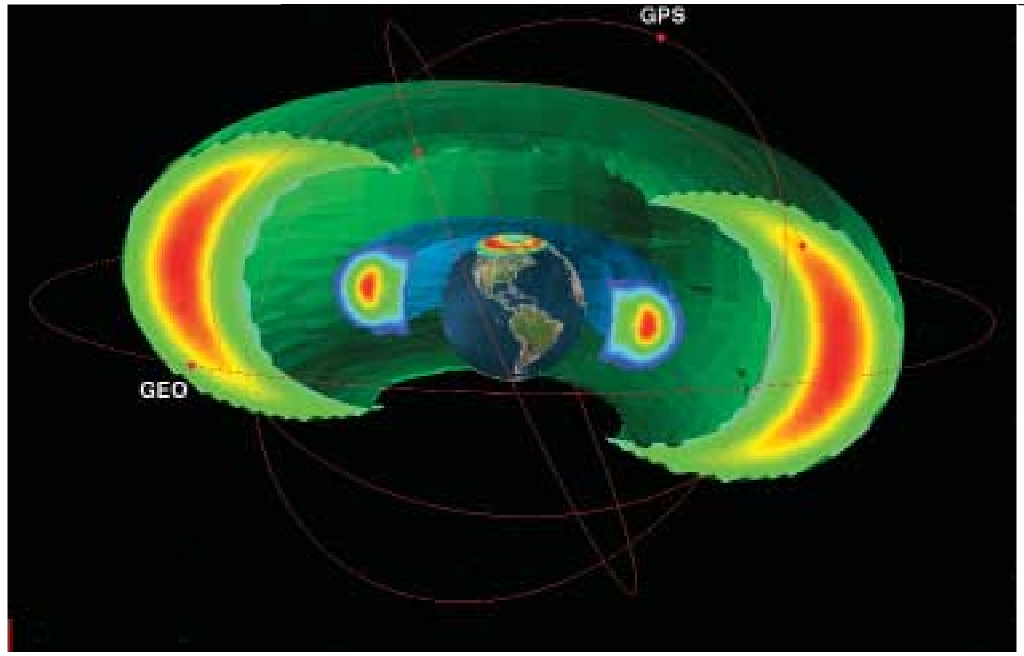
STORMS IN SPACE

SPACE WEATHER

Although Earth's magnetic shield protects our planet from direct exposure to the solar wind, strong variations in the solar wind drive major changes in Earth's space environment. The largest, most powerful disturbances in the geospace environment are known as **magnetic storms**, which are triggered by fast CMEs and, during the declining phase of the solar cycle, by high-speed solar wind streams. Magnetic storms are accompanied by dramatic auroral displays, increases in the flux of energetic particles surrounding Earth, and ionospheric disturbances. Like severe weather in Earth's lower atmosphere, severe magnetic storms can adversely affect human activities. Indeed, as society becomes increasingly dependent on space-based technologies, our vulnerability to space weather becomes more obvious, and the need to understand it and mitigate its effects becomes more urgent.

As magnetic storms rage through the magnetosphere, charged particles can be trapped and dramatically accelerated in Earth's magnetic field, enhancing the intense belts of extremely energetic radiation encircling Earth. These are the Van Allen radiation belts, whose discovery in 1958 was one of the first great accomplishments of the space age. The radiation belts show fascinating and puzzling variations over a tremendous range of time scales, from microseconds to years. Electrons in the radiation belts, accelerated to velocities approaching the speed of light, are of special interest because these particles can damage spacecraft electronics and present a serious radiation hazard to astronauts on board the International Space Station.

Because the magnetosphere and the ionosphere are electrically coupled, disturbances in the magnetosphere also affect Earth's upper atmosphere. As noted in the preceding section, storm-time disturbances in the ionosphere can interfere with high-frequency radio communication and navigation signals from GPS satellites. Electrical currents flowing high up in the ionosphere can generate induced currents in power transmission lines and transformers on the ground, potentially causing serious disruption

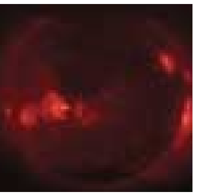


Model-generated image of Earth's radiation belts, showing the inner proton belt and the outer electron belt, along with representative orbits for Global Positioning System (GPS) and geosynchronous (GEO) satellites.

of power service as happened in Quebec during the major magnetic storm of March 1989. Even the neutral atmosphere is affected by space storms. Magnetic-storm-induced heating of the thermosphere changes its density and perturbs the orbits of satellites and space debris in low Earth orbit by increasing drag, thereby interfering with orbital tracking and prediction by ground stations.

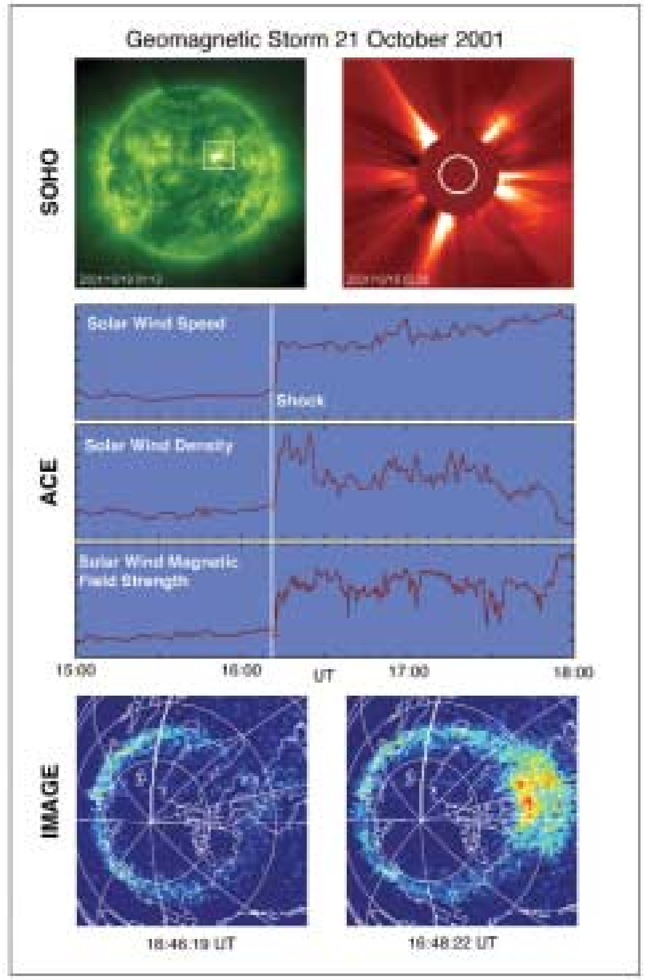
NASA's new Exploration Initiative envisions sending astronauts to a Moon base and on extended journeys through space and perhaps to Mars. Astronauts on future lunar and planetary missions will face a serious hazard in the form of episodic energetic solar particle events and ongoing galactic cosmic-ray fluxes, which may impose limitations on what astronauts can undertake. Solar flares spit out particles, sometimes with velocities approaching the speed of light. Fast CMEs drive powerful shock waves in front of them, which accelerate solar wind ions to energies high enough to penetrate a space suit or the hull of a spacecraft. All these fast particles rush outward along the magnetic fields in interplanetary space, engulfing Earth, the Moon, and Mars in a matter of minutes. They can provide a lethal dose of radiation. An astronaut needs to know when such bursts of fast particles are expected so as not to venture too far from the shelter provided in the center of a spacecraft or in a lunar or martian base. In addition to this transient hazard, there is the continuing exposure to galactic cosmic rays, month after month, which can accumulate to levels damaging to long-term health. The astronaut can be shielded from galactic cosmic rays only in a deep underground bunker on the Moon or Mars.

Protecting technological systems and astronauts against space weather requires both timely knowledge of current conditions in space and the ability to forecast space weather disturbances with adequate advance notice. Successful forecasting, in turn, requires an understanding of the basic physical processes at work in space weather. A framework for developing this understanding and the desired "now casting" and forecasting capabilities is provided by the **U.S. National Space Weather Program**, a multiagency program



formed in 1995 to coordinate the space weather activities of the various government agencies. The Survey Committee strongly recommends continued support for this important national program.

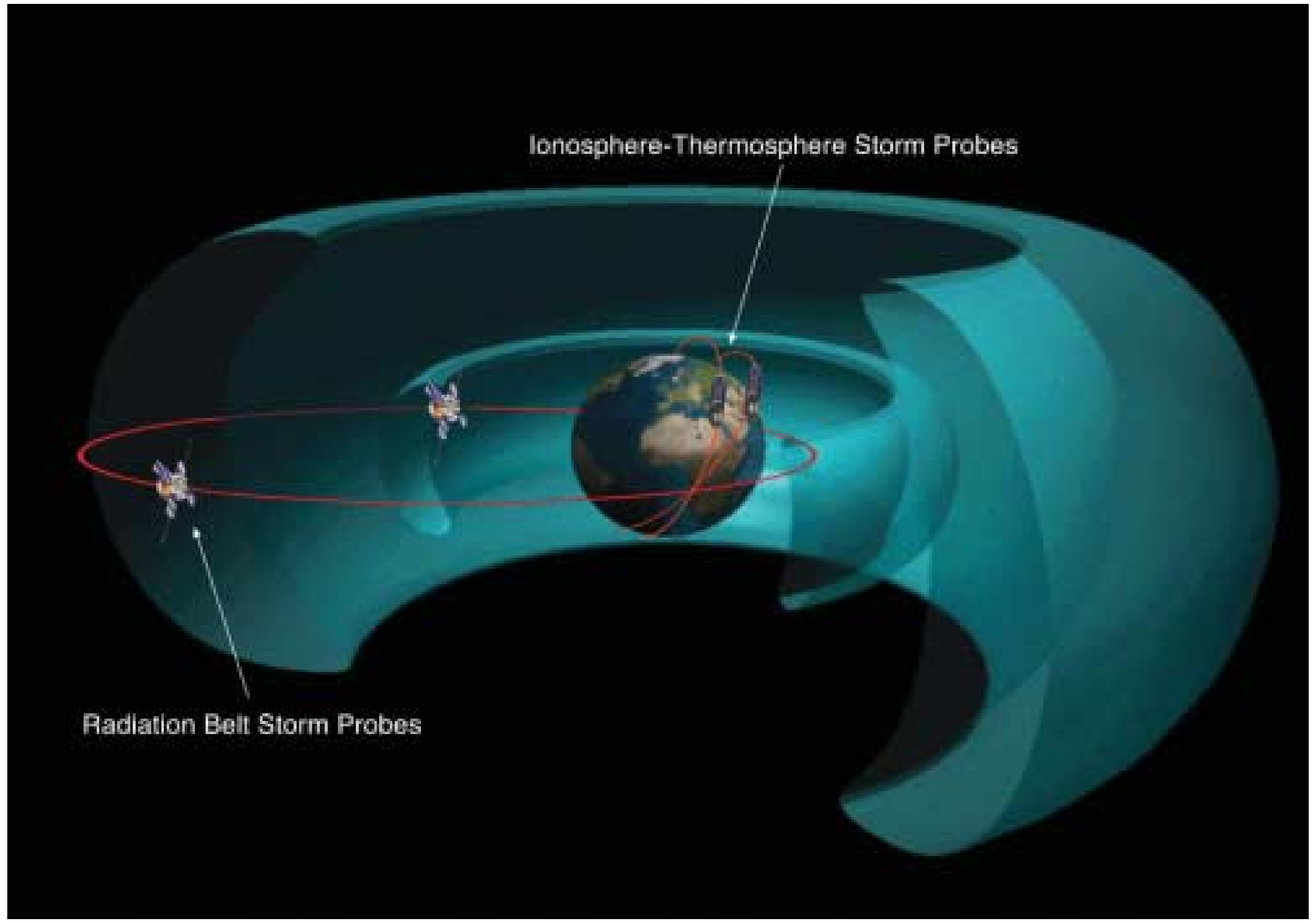
It also recommends deployment of a **Solar Wind Monitor** upstream of Earth and, as the second-highest priority in the "moderate missions" category, development of the radiation belt and ionosphere-thermosphere probes envisioned as part of the **Geospace Missions Network** of NASA's Living With a Star (LWS) program. The LWS program sponsors basic research targeted at the specific regions of space and the physical processes most relevant to our understanding of space weather.



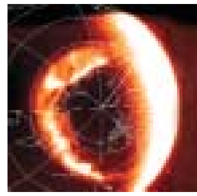
The genesis of a geomagnetic storm. An X-class flare (upper left) and associated coronal mass ejection (CME) were observed by the SOHO spacecraft early on October 19, 2001. The ACE spacecraft, stationed 1.5 million kilometers upstream from Earth, detected the interplanetary shock driven by the CME 2.5 days later, at 16:15 UT on October 21. (The sharp rise in the solar wind speed, density, and magnetic field strength seen in the middle panels indicates the shock's passage.) About half an hour later, the shock slammed into Earth's magnetic field, triggering the bright proton auroral flash over northern Canada observed by the IMAGE spacecraft (bottom right) and initiating a geomagnetic storm, which reached its most intense levels on October 21 and 22.

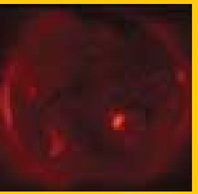
MONITORING THE SOLAR WIND

Knowing solar wind conditions upstream from Earth is important both for scientific research and for space weather forecasting. At present, this vital information is provided by the Advanced Composition Explorer (ACE) and the Wind spacecraft. However, both spacecraft are now operating considerably beyond their planned lifetimes. The Survey Committee stresses the importance of continued solar wind monitoring after these missions are no longer operating, and it recommends that the National Oceanic and Atmospheric Administration (NOAA) assume responsibility for the deployment and operation of a new Solar Wind Monitor. Positioned 1.5 million kilometers upstream from Earth, at the Lagrangian point L1 (the point where the Sun's gravity is balanced by Earth's), the Solar Wind Monitor could provide roughly an hour's advance warning of changes in the solar wind.



The LWS Radiation Belt Storm Probes and Ionosphere-Thermosphere Storm Probes will study the effects of space storms on regions of geospace that can affect the operation of important technological systems.

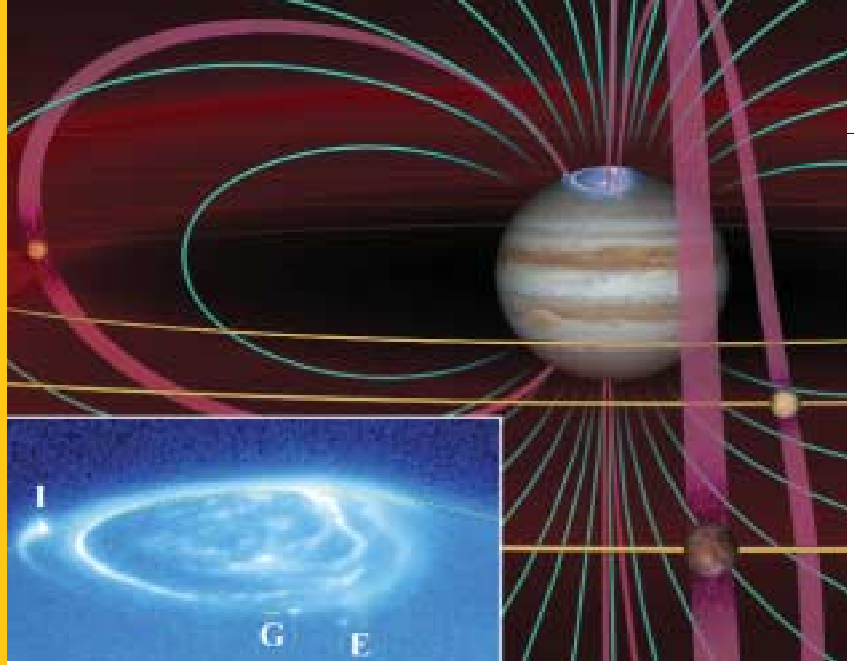




NO TWO MAGNETOSPHERES ARE ALIKE

Earth's is one of seven known magnetospheres in the solar system, all of which are nestled within the magnetosphere of the Sun, the heliosphere. The smallest planetary magnetosphere is Mercury's. The largest is Jupiter's. In fact, by volume Jupiter's magnetosphere is the largest object in the solar system, large enough to accommodate a thousand Suns within its confines. (The Sun itself is large enough to hold a million Earths.) Inside Jupiter's huge magnetosphere lurks another—the tiny magnetosphere of its moon, Ganymede; this mini-magnetosphere within a magnetosphere was a surprising and fascinating discovery made by the Galileo spacecraft during its 8-year tour of Jupiter's magnetosphere. Jupiter's magnetosphere is quite different from Earth's, not just in size, but also in two fundamental ways. First, a major source of the plasma that it contains is the moon Io, whose volcanos spew sulfur dioxide gas into the magnetosphere where it is transformed into sulfur and oxygen ions. Second, the two magnetospheres have quite different energy sources. While the dynamic variability of Earth's magnetosphere is generated by the solar wind, Jupiter's magnetosphere is powered by energy extracted from the gas giant's rapid rotation. (Jupiter completes one rotation roughly every 10 hours.) Jupiter's rotational energy is transferred to the magnetosphere by electrical currents that couple the co-rotating ionosphere to the magnetospheric plasma supplied by Io. Although the jovian magnetosphere is rotationally driven, the solar wind also exercises some degree of influence on magnetospheric processes. The extent of this influence is not known.

Auroras are observed at Jupiter and Saturn as well as at Earth (left, viewed from above the north pole). Jupiter's ultraviolet aurora is the most powerful in the solar system, radiating several terawatts of power.



Powerful electrical currents couple the moons Io, Ganymede, and Europa with Jupiter's ionosphere, producing auroral emissions at the footpoints of the magnetic field lines linking the moons to the ionosphere.

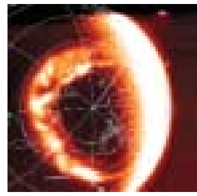
The Galileo orbiter has provided a wealth of new information about the structure and dynamics of Jupiter's magnetosphere. However, because the spacecraft was in an equatorial orbit, it was unable to make measurements in the polar magnetosphere, the region where the electrical currents that couple the ionosphere and magnetosphere flow, producing Jupiter's spectacular aurora. The Survey Committee considers observations in this region to be of such importance that it recommends a dedicated space physics mission to Jupiter's polar magnetosphere as its third-highest-priority moderate mission, after the MMS and the LWS geospace probes.

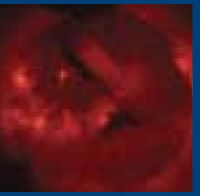
The **Jupiter Polar Mission** (JPM) will place a spacecraft in an elliptical polar orbit about Jupiter to study the processes that couple the ionosphere and magnetosphere, and transfer rotational energy to the magnetosphere. JPM will determine the relative contributions of planetary rotation and the solar wind as sources of magnetospheric energy, and will assess the role of Io's volcanism in providing the mass that drives the flow of plasma within the jovian magnetosphere. JPM will also identify the charged particles responsible for Jupiter's powerful aurora and determine how those particles are energized.

Why are such measurements so important? First, because of what they will reveal about the workings of a magnetosphere that is profoundly different from our own. And, second, because of what we may learn from them about the physics of magnetospheres belonging to other rapidly rotating astrophysical bodies, such as pulsars and protostellar disks.

PLANETARY MAGNETOSPHERES

The seven magnetospheres are Mercury's, Earth's, Jupiter's, Ganymede's, Saturn's, Uranus's, and Neptune's. The magnetospheres of Uranus and Neptune were briefly sampled during the Voyager flybys in 1986 and 1989; Galileo has just completed an extensive survey of the Jupiter system. Saturn's is the next magnetosphere to be explored. The Cassini spacecraft, which began its orbital tour of the Saturn system in July 2004, carries instruments to study the sources and sinks of Saturn's magnetospheric plasma and its interaction with the rings and with Saturn's moons, in particular with Titan. Characterization of Mercury's tiny magnetosphere will be one of the objectives of the MESSENGER mission. MESSENGER, the first spacecraft to visit Mercury since the Mariner flybys in the mid-1970s, will enter orbit around Mercury in 2009 following two flybys in 2007 and 2008.





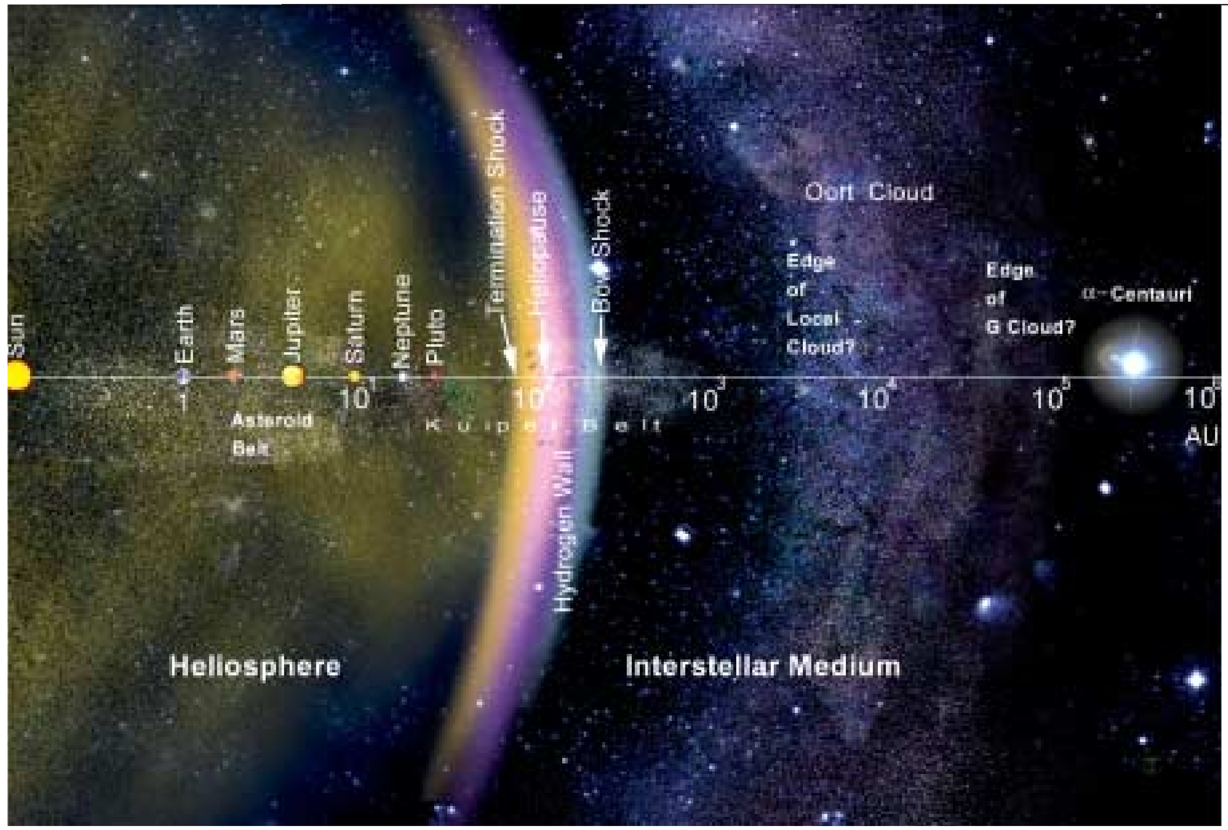
THE SUN'S GALACTIC ENVIRONMENT

THE OUTER LIMITS AND BEYOND

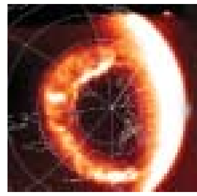
Where does the heliosphere end and the Sun's galactic environment—the **local interstellar medium** (LISM)—begin? The inner boundary of the heliosphere is a shock wave, the so-called **termination shock**, that forms where the supersonic solar wind is slowed to subsonic speeds by its encounter with the LISM. The heliosphere's outer boundary is the **heliopause**. Between it and the termination shock is the **heliosheath**—a region of solar wind that has been slowed and heated by its passage through the shock. The thickness of the heliosheath and the location of the heliopause are not known. However, recently published data suggest that the Voyager 1 deep-space probe may have encountered the termination shock at a distance of some 86 AU—more than 12.5 billion kilometers—from the Sun.

The heliosphere's boundaries are not static, but instead move with changes in the solar wind's density and speed, and vary in location with the solar cycle. The size and structure of the heliosphere depend not only on the properties of the solar wind but also on those of the LISM, and these change during the course of the Sun's journey around our galaxy. (The Sun orbits the galactic center at a speed of some 250 kilometers per second.) For the past few thousand years, for example, the Sun has been immersed in a low-density (0.2 protons per cubic centimeter) bubble within the local interstellar cloud with a temperature of about 7,000 K. At some point in the future, however, it will enter a different region of our galaxy, perhaps one of greater density. Recent computer simulations suggest that an encounter with an interstellar cloud whose density is 10 protons per cubic centimeter could push the termination shock as close to the Sun as 10 to 14 AU, well inside the orbit of Uranus. Such a dramatic change would increase the number of cosmic rays reaching Earth and could alter the interaction of our planet's magnetosphere with the solar wind.

The boundaries of the heliosphere are not completely impermeable to the LISM. Interstellar plasmas and magnetic fields are excluded from the heliosphere,



Artist's concept showing the heliosphere and its immediate galactic environment. Distances are indicated on a logarithmic scale. Earth's nearest stellar neighbor, α Centauri, is 4 light-years away.



but the electrically neutral, unmagnetized gases and large dust grains of the interstellar medium are not, and flow unimpeded across the heliopause and into the heliosphere, where they interact with the solar wind. A fascinating aspect of this interaction is the creation of **anomalous cosmic rays** (ACRs), a population of cosmic rays different in origin and composition from galactic cosmic rays. ACRs are produced from interstellar neutral atoms that are turned into ions by solar ultraviolet radiation, or by loss of an electron to a solar wind ion. These newly created ions are then "picked up" by the solar wind plasma and swept along in its outward flow to the termination shock, where they are accelerated to extremely high energies.

Scientists have long dreamed of sending a spacecraft to the boundaries of the heliosphere and into the interstellar medium beyond, of setting sail into the cosmic ocean. The twin Voyager spacecraft may provide a tantalizing first glimpse of this exotic environment; however, they are more than 25 years old, some of their instruments are no longer functioning, and the veteran explorers may run out of power before crossing the heliopause. What is needed is an **Interstellar Probe**, a mission specifically designed for the comprehensive investigation of the boundaries of the heliosphere and for the exploration of our local galactic environment. To reach its destination within a reasonable time (~15 years), an Interstellar Probe will have to travel much faster than any existing spacecraft. The Survey Committee urges that development of the needed advanced propulsion technology be given high priority. Although the LISM remains beyond reach for the present, interstellar material that finds its way into the inner heliosphere provides scientists with tantalizing samples of the stuff of our galactic environment. The Survey Committee endorses the concept of an **Interstellar Sampler** mission, which will measure interstellar neutrals and associated pickup ions (extra-solar ions picked up and carried along by the solar wind) in the inner heliosphere (1 to 4 AU) and provide energetic neutral atom and extreme-ultraviolet images of the heliospheric boundaries.

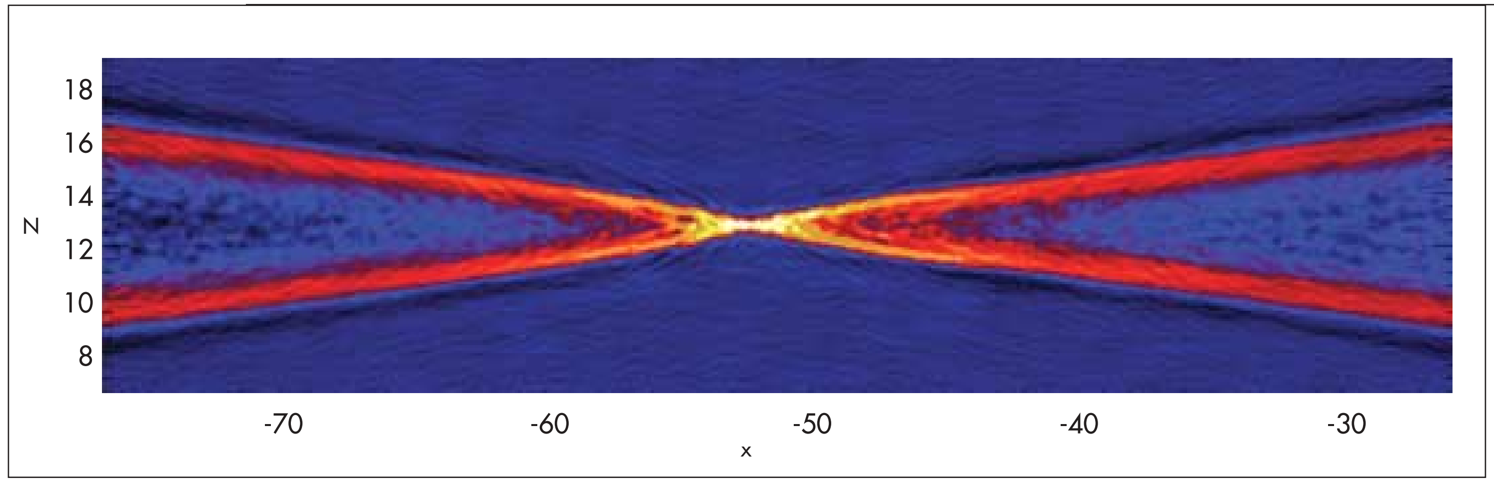
AN ASTROPHYSICAL LABORATORY IN OUR OWN BACKYARD

Plasmas exist everywhere in the universe—in the interiors of stars, in stellar winds, in the bizarre and highly energetic phenomena of stellar and galactic jets, and in the magnetospheres and ionospheres expected to surround extrasolar planets. It is only in our solar system, however, that the fundamental physical processes that occur in plasmas can be studied directly and in detail, through in situ measurements from spacecraft and sustained, high-resolution imaging from both space-based and ground-based observatories. The solar system thus serves as a "laboratory" for the investigation of processes common to all astrophysical plasmas.

At the center of this laboratory sits our Sun, a "cool" (6,000 K) main-sequence star with a hot (1,000,000 K) corona. The detailed knowledge that scientists obtain from helioseismic studies of the Sun's interior, high-resolution imaging of the solar surface and corona, and in situ measurements of the solar wind and the IMF is being applied to the study of other magnetically active stars, with their hot x-ray-emitting coronas, stellar winds, and enveloping "asterospheres." **Solar Probe** (originally known as Starprobe) is thus in a very real sense an astrophysics as well as a solar physics mission. By uncovering the mechanisms by which the Sun's corona is heated and the solar wind is accelerated, Solar Probe will yield insights into coronal heating and stellar wind acceleration at other low-mass main-sequence stars in our galaxy.

Earth's magnetosphere affords a unique laboratory for the investigation of magnetic reconnection, a process that has been invoked to explain a number of astrophysical phenomena, from solar flares and CMEs, to accretion disk flares, to the acceleration of electrons at velocities close to the speed of light in the lobes of giant radio galaxies. The **Magnetospheric Multiscale** (MMS) mission is specifically designed to probe reconnection sites in the magnetosphere in order to unravel the poorly understood microphysics involved in the rapid conversion of magnetic energy to particle kinetic energy. The improved understanding of this fundamental plasma process which the MMS mission is expected to yield will be of invaluable benefit to scientists seeking to understand the role of reconnection in other plasma environments, both within the solar system and in remote astrophysical settings.

Magnetic reconnection may be responsible for accelerating cosmic rays in the lobes of giant radio galaxies such as NVSS 2146+82, a hypothesis supported by theoretical studies of reconnection in solar system plasmas.



This computer simulation shows the intense currents generated by electrons where oppositely directed magnetic fields reconnect or annihilate. Magnetospheric multiscale will provide observational tests of our models and theories of reconnection.

FUNDAMENTAL PROCESSES IN ASTROPHYSICAL PLASMAS

The study of solar system plasmas has made substantial contributions to our understanding of such universal plasma processes as magnetic reconnection, magnetohydrodynamic turbulence, energetic particle acceleration, and the formation of collisionless shocks. With the appropriate scaling, lessons learned in our solar system can be applied to distant astrophysical plasmas that can only be studied remotely.

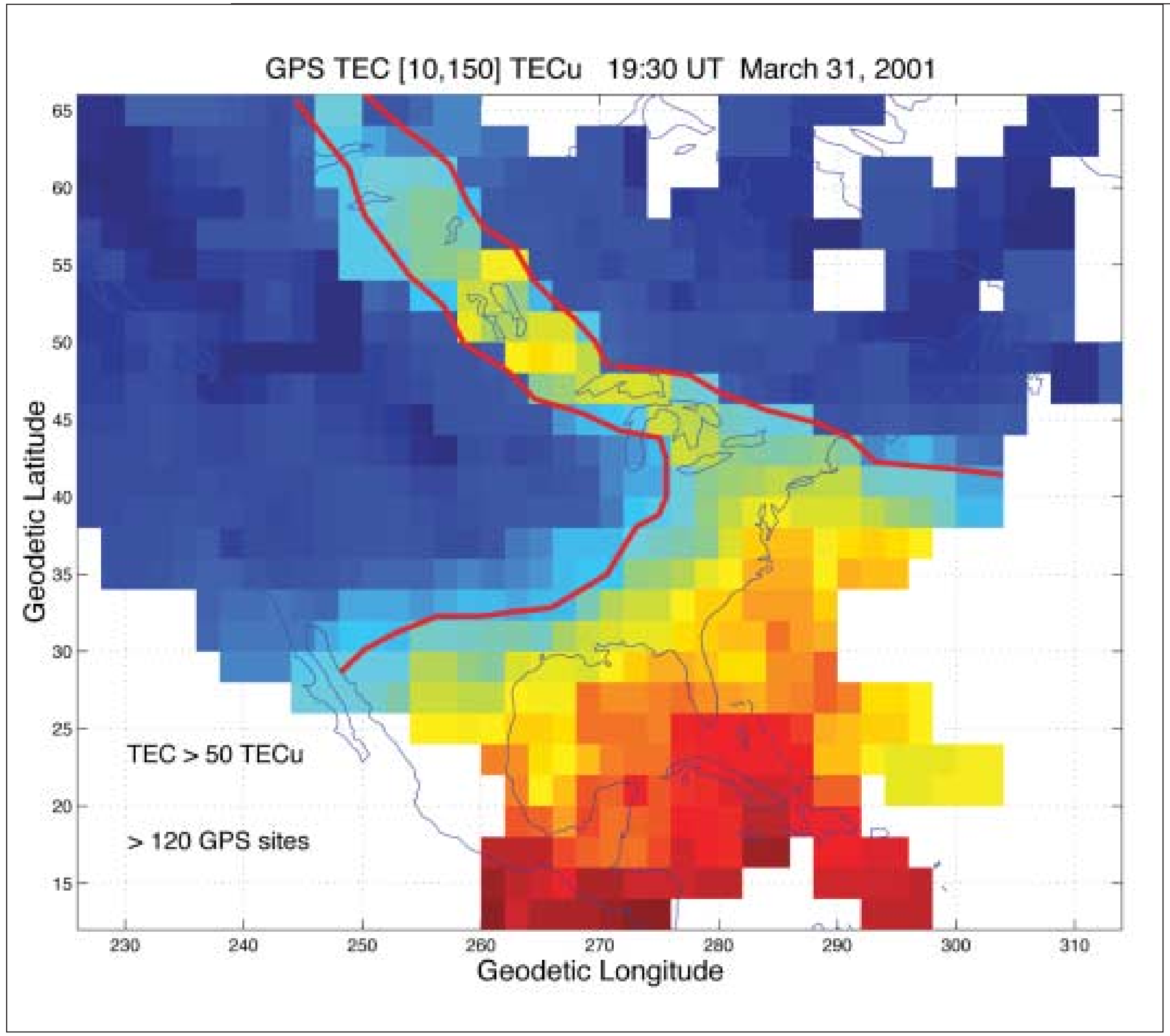
THEORY, COMPUTER MODELING, DATA EXPLORATION, AND DATA MINING

Solar and space physics has evolved from a strongly exploratory and discovery-driven discipline to a more mature, explanatory science. Moreover, the societal and economic importance of a capability for forecasting space weather has become increasingly apparent. Its character as a mature science and its role in space weather prediction present solar and space physicists with significant new challenges and opportunities in the areas of theory, computer modeling, and data exploration and mining.

CAPTURING COMPLEXITY

Solar system plasmas are complex systems, and their behavior is characterized by multiple interactions or "couplings" between different plasma regions and energy regimes, between different populations of particles, between different processes, and across different spatial and temporal scales. For example, the heliosphere contains cosmic rays, solar wind plasma, neutral atoms, and pickup ions, each of which interacts with the other but is described by its own set of equations. Similarly, the ionosphere-thermosphere and magnetosphere are different but interacting regions governed by distinct and different physical processes. The challenge to theoreticians and modelers is to develop the theoretical and computational tools needed to understand and describe solar system plasmas as dynamic, coupled systems.

To address this challenge, the Survey Committee proposes two new research initiatives. The **Coupling Complexity Research Initiative** will address multiprocess coupling, multiscale coupling, and multiregional feedback in solar system plasmas. The program advocates both the development of coupled global models of the different regions of the heliosphere and the synergistic investigation of important unresolved theoretical problems. The **Virtual Sun** initiative will incorporate a systems-oriented approach to theory, modeling, and simulations that will provide continuous models from the solar interior to the outer heliosphere. The relevant models will be developed in a modular fashion so that future improvements to models of

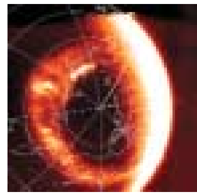


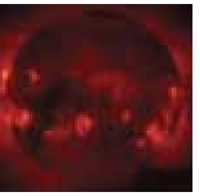
Total electron content (TEC) data derived from GPS navigation signals can be used to map ionospheric weather and will be incorporated in data assimilation models for space weather "nowcasting" and forecasting.

specific domains can be easily integrated. Initial efforts would focus on development of the modules pertaining to the solar dynamo (the source of solar magnetism) and magnetic reconnection (the prime mechanism for releasing stored magnetic energy).

DATA ASSIMILATION

The coming decade will see the availability of enormous quantities of space physics data that will have to be integrated or assimilated into physical models of Earth's space environment. Meteorologists were the first to use data





assimilation to improve terrestrial weather prediction. Data obtained at various times and places are used in combination with physics-based (numerical) models to provide, in real time, an essentially continuous "movie" of the behavior of the lower atmosphere. Data assimilation models can be used for "nowcasting"—that is, for describing the current weather conditions at any given time—and can also be run into the future, providing the weather forecasts that are seen on television. During the last 40 years, meteorologists have dramatically improved their ability to predict the weather, both because of the availability of faster computers, and hence better numerical models, and because of a large infusion of satellite and ground-based data.

In comparison, the space physics community has been slow to implement data assimilation techniques, primarily because there have been insufficient measurements for a meaningful assimilation. However, this situation is rapidly changing, and within the next decade several million measurements per day will be available for assimilation into specification and forecast models relevant to space physics. The data will be acquired from operational satellites of NOAA and the Department of Defense, the constellation of GPS satellites, and worldwide networks of ground-based instruments, such as the **Distributed Array of Small Instruments** (DASI; previously called the Small Instrument Distributed Ground-Based Network) recommended by the Survey Committee as a new initiative. Data assimilation models will play a particularly important role in space weather prediction, but will also contribute usefully to purely scientific investigations of Earth's space environment.

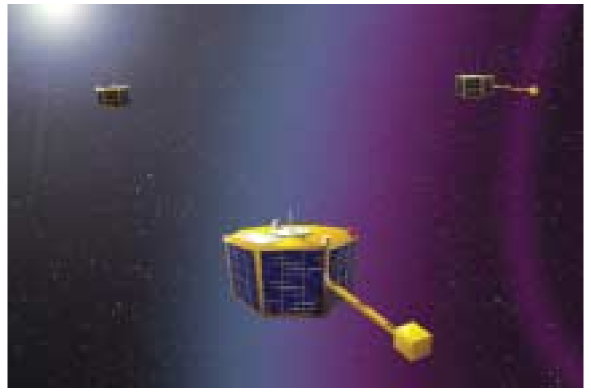
DISTRIBUTED ARRAY OF SMALL INSTRUMENTS

The Distributed Array of Small Instruments (DASI) is an initiative recommended by the Survey Committee for implementation by the National Science Foundation. Geographically distributed instrument arrays will provide the global coverage and high-resolution observations needed to characterize the dynamic behavior of the ionosphere and thermosphere. Instrumentation will include Global Positioning System (GPS) receivers, all-sky imagers, passive radars, Fabry-Perot interferometers, very low frequency (VLF) receivers, magnetometers, and ionosondes. Data will be available via the Internet in real time and will provide necessary inputs for data assimilation models. Instrument clusters located at universities and high schools will provide students with hands-on training in instrumentation and data analysis.

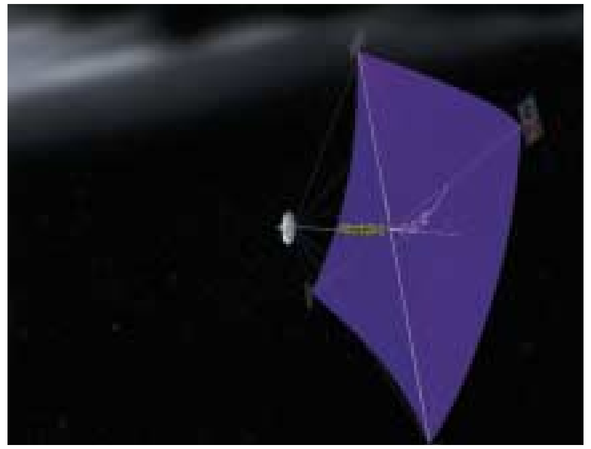
TECHNOLOGY

ENABLING THE FUTURE

Advances in solar and space physics result either from visiting new places, or from revisiting old places with new, improved observational capabilities. To these should be added revisiting old problems with new computational techniques and improved computational resources. Examples of missions that will advance our knowledge by visiting "new places" are **Solar Probe** and **Interstellar Probe**, which will visit the innermost and outermost unexplored regions of the heliosphere. Examples of missions that will bring new observational capabilities to bear on previously surveyed regions are the **MMS** mission, which will make measurements of unprecedently high time resolution from multiple spacecraft, and **MagCon**, which will deploy some 50 to 100 nanosatellites to capture the large-scale dynamics of the magnetosphere.



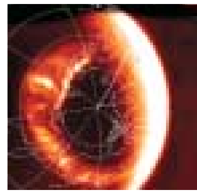
The New Millennium Program's Space Technology 5 mission (launch in 2005) will test advanced spacecraft technologies required for future space physics missions involving constellations of miniaturized satellites.



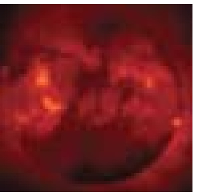
Artist's concept of a solar-sail-powered spacecraft. Solar sails are being considered for an Interstellar Probe and for a multispacecraft "sentinel" mission to study the propagation of heliospheric disturbances from the Sun to Earth.

Whether it is exploring new regions, revisiting previously explored regions with enhanced observational capabilities, or addressing old problems with new computing resources—in each case improvements in technology are required. The Survey Committee identifies seven main areas in which focused technology development, based on both the immediate and the projected needs of solar and space physics research, is required to support future advances in our knowledge and understanding of solar system plasmas:

- Developing new propulsion technologies to send spacecraft to the planets and beyond as efficiently as possible
- Developing highly miniaturized sensors of charged and neutral particles and photons
- Developing highly miniaturized spacecraft and advanced spacecraft subsystems for missions involving constellations of multiple spacecraft
- Gathering and assimilating the data from multiple platforms
- Integrating large space-physics databases into physics-based numerical models
- Deploying reliable, unmanned, ground-based ionospheric and geomagnetic measurement stations
- Developing a high-resolution, ground-based solar imager



STRENGTHENING THE NATION'S SOLAR AND SPACE PHYSICS ENTERPRISE

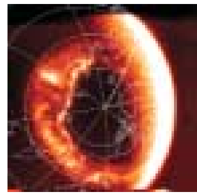


In addition to setting forth a national research strategy for solar and space physics for the coming decade, the Survey Committee's report proposes several measures to strengthen the national infrastructure for solar and space physics research and to ensure the availability of a sufficient number of scientists and technicians with the training and skills needed to carry out the recommended research initiatives. Among the issues addressed by the Survey Committee's proposals:

- Solar and space physics education at colleges and universities, especially on the undergraduate level
- The contribution of solar and space physics to K-12 education and public outreach
- University involvement in NASA's spaceflight program
- Cost-effective, reliable, and ready access to space
- Coordination among the research (NASA, NSF) and operational (NOAA, DOD) agencies engaged in solar and space physics research
- Controlling spaceflight mission cost growth
- International collaboration and cooperation in space research

Sounding rockets have proven to be a valuable asset for training students as well as an important tool for solar and space physics research.

FURTHER AND MORE ABUNDANT KNOWLEDGE



Albert Einstein once paraphrased an old Chinese proverb and wrote, "What does a fish know about the water in which he swims all his life?" For most of human history, the sea of space, through which our home planet and other solar system bodies travel as they orbit about the Sun, was a mystery, the subject of myth and of philosophical as well scientific speculation. It was just 40 years ago that the true nature of this realm finally became known, when measurements by the Mariner II spacecraft confirmed Eugene Parker's 1958 theory that the Sun's outer atmosphere expands supersonically to form the solar wind. Since then, numerous satellites have measured the properties of the solar wind and the near-Earth space environment; probes have visited all the planets except Pluto; and solar observatories in space and on the ground have provided detailed images of the Sun's corona and probed the solar interior.

Solar and space physicists have learned much during the past four decades about the Sun and the heliosphere, Earth's magnetosphere and space weather, and the space environments of other planets. But many important questions remain unanswered. As the famous 19th-century physicist Michael Faraday wrote, "It is the great beauty of our science that advancement in it, whether in a degree great or small, instead of exhausting the subject of research, opens the doors to further and more abundant knowledge, overflowing with beauty and utility." Answers to the outstanding questions in solar and space physics have so far eluded our grasp owing to the lack of observations in critical regions of the solar system, limitations on the capability of our observational techniques and strategies to resolve critical processes, and constraints on computational resources and techniques. The research initiatives recommended by the Solar and Space Physics Survey Committee and described in this booklet are designed to overcome these obstacles and to allow us to answer some of the outstanding questions about the activity of the Sun and the objects immersed in and interacting with its atmosphere. These questions focus increasingly on *how* and *why* rather than *what*. They are the "doors to further and more abundant knowledge," and to answer them will be to achieve a fundamental understanding of the physical processes that underlie the exotic and puzzling phenomena that occur in the fourth state of matter—an understanding that is not just of intrinsic intellectual importance but that also has practical benefits for humankind as it continues its evolution into a space-faring species.

> It is the great beauty of our science that advancement in it, whether in a degree great or small, instead of exhausting the subject of research, opens the doors to further and more abundant knowledge, overflowing with beauty and utility.
>
> **—Michael Faraday**

CREDITS FOR ILLUSTRATIONS

Cover	The background photo is of the aurora borealis as viewed from the vicinity of Fairbanks, Alaska. The three figures in the inset show the magnetically structured plasma of the Sun's million-degree corona (left); the plasmasphere, a cloud of low-energy plasma that surrounds Earth and co-rotates with it (top right); and an artist's conception of Jupiter's inner magnetosphere, with the Io plasma torus and the magnetic flux tubes that couple the planet's upper atmosphere with the magnetosphere. Ground-based aurora photo courtesy of Jan Curtis; coronal image courtesy of the Stanford-Lockheed Institute for Space Research and NASA; plasmasphere image courtesy of the IMAGE EUV team and NASA; rendering of the jovian magnetosphere courtesy of J.R. Spencer (Lowell Observatory).
Page 6	Image of a prominence extending from the Sun's northwest limb viewed at 304 Å with the Extreme-ultraviolet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory (SOHO). Courtesy of SOHO (ESA and NASA).
Page 9	Courtesy of R. Mewaldt (California Institute of Technology) and the NASA/Jet Propulsion Laboratory.
Page 12	Image of the solar corona viewed in the extreme ultraviolet (171 Å) with the telescope on board the Transition Region and Corona Explorer (TRACE) spacecraft. Courtesy of NASA and the Stanford-Lockheed Institute for Space Research.
Page 13 (top)	Courtesy of SOHO (ESA and NASA).
Page 13 (bottom)	Courtesy of J.W. Harvey and the GONG Project (National Solar Observatory/AURA/NSF).
Page 14	Courtesy of the Johns Hopkins University Applied Physics Laboratory.
Page 15 (top)	Courtesy of D.E. Gary (New Jersey Institute of Technology).
Page 15 (bottom)	Courtesy of D.J. McComas (Southwest Research Institute) and Ulysses (ESA and NASA).
Page 17	Courtesy of R. Treumann (Max-Planck-Institut für extraterrestrische Physik).
Page 18 (top)	Courtesy of J. Curtis.
Page 18 (bottom)	Courtesy of NASA/Goddard Space Flight Center.
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Page 23	Courtesy of R.V. Hilmer (Air Force Research Laboratory/Hanscom AFB).
Page 25	Courtesy of NASA/Living With a Star Program.
Page 26	The image of Earth's aurora courtesy of the IMAGE FUV imaging team and NASA. The images of Jupiter and Saturn were obtained with the Hubble Space Telescope and are used courtesy of NASA/STScI/AURA.
Page 27	Hubble Space Telescope image courtesy of J.T. Clarke (Boston University) and NASA/STScI. Artist's rendering of the jovian inner magnetosphere courtesy of J.R. Spencer (Lowell Observatory). Reprinted by permission from Nature 415, 997-999 and cover, copyright 2002, Macmillan Publishers Ltd.; http://www.nature.com.
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Page 30	Very Large Array image adapted from C. Palma et al., Multiwavelength observations of the second-largest known Fanroff-Riley type II radio galaxy, NVSS 2146+82, Astronomical Journal 119(5), 2068-2084, copyright 2000, American Astronomical Society. Courtesy of A. Bridle and W. Cotton (NRAO/NSF/AUI) and C. Palma (Pennsylvania State University).
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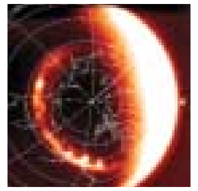
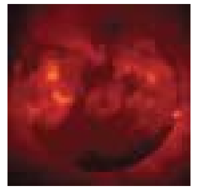
Page 33	Courtesy of J.C. Foster (MIT Haystack Observatory).
Page 35 (top)	Courtesy of NASA/Goddard Space Flight Center.
Page 35 (bottom)	Courtesy of NASA/Marshall Space Flight Center.
Page 36	Courtesy of P.J. Eberspeaker (NASA/Wallops Flight Facility).
Page 40	The northern and southern lights—the aurora borealis and aurora australis—are produced when energetic electrons and protons from the magnetosphere spiral downward along geomagnetic field lines into Earth's upper atmosphere and excite the atoms and molecules there, causing them to emit light at various wavelengths. Photo of the aurora borealis courtesy of Jan Curtis.

By quickly flipping the pages of this booklet from front to back, you can watch the development of an auroral storm as viewed from an Earth-orbiting satellite. By flipping from back to front, you can track the changes in the Sun's activity during the declining phase of one solar cycle and the rising phase of another.



Images from the Wideband Imaging Camera (WIC) on NASA's IMAGE spacecraft show the development of a typical auroral storm on October 22, 2001. The spacecraft is looking down onto the north pole from an initial altitude of 34,000 kilometers. Earth's daylit face is to the right. The auroral sequence, which spans an interval of roughly one hour, begins with a localized brightening over northern Russia. Within minutes the nightside oval has become active and expanded poleward, with bright, highly structured emissions embedded in a broad region of more diffuse emissions. WIC is a part of the IMAGE far-ultraviolet (FUV) imaging system and detects ultraviolet emissions produced by nitrogen molecules as they are bombarded by electrons from Earth's magnetosphere. Courtesy of the IMAGE FUV imaging team and NASA.



Images of x-ray emissions from the Sun's million-degree corona capture the change in solar activity during the declining phase of sunspot cycle 22 (September 1986 to May 1996) and the rising phase of sunspot cycle 23 (May 1996 to 2007). The images cover the interval from March 1992 to September 1999 and were acquired with the soft x-ray telescope (SXT) on board the Earth-orbiting Yohkoh solar observatory. Yohkoh (1991-2001) was a Japanese mission with collaboration from researchers in the United States and United Kingdom. Courtesy of the Lockheed Martin Solar and Astrophysics Laboratory.