Solar and Space Physics: A Science for a Technological Society: An Overview

ISBN
978-0-309-31392-6

32 pages
10 x 10
PAPERBACK (2014)

Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics); Space Studies Board; Division on Engineering and Physical Sciences; National Research Council

SOLAR AND SPACE PHYSICS

A SCIENCE FOR A TECHNOLOGICAL SOCIETY

AN OVERVIEW






NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

This booklet provides an overview of the most recent National Research Council decadal survey of solar and space physics, *Solar and Space Physics: A Science for a Technological Society* (The National Academies Press, Washington, D.C., 2013), authored by the Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics). Details about obtaining copies of the full report can be found at <http://sites.nationalacademies.org/SSB/index.htm>.

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Support for this publication was provided by the National Aeronautics and Space Administration (Contract NNH11CD57B, task number NNH14CL39D). Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the agency that provided support for the project.

The Space Studies Board acknowledges Arthur Charo, the decadal survey committee, and its Committee on Solar and Space Physics for drafting the text of this booklet.

Printed in the United States of America.

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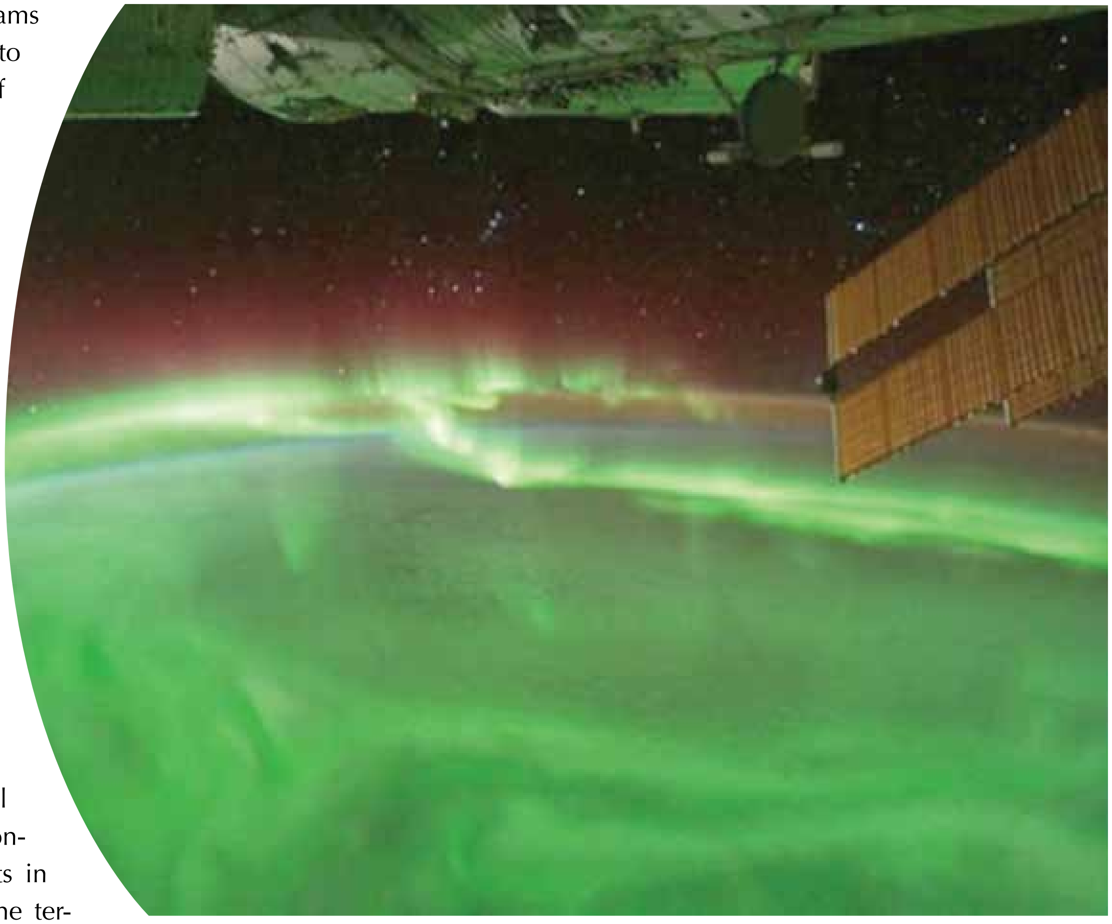
SOLAR AND SPACE PHYSICS

A Science for a Technological Society

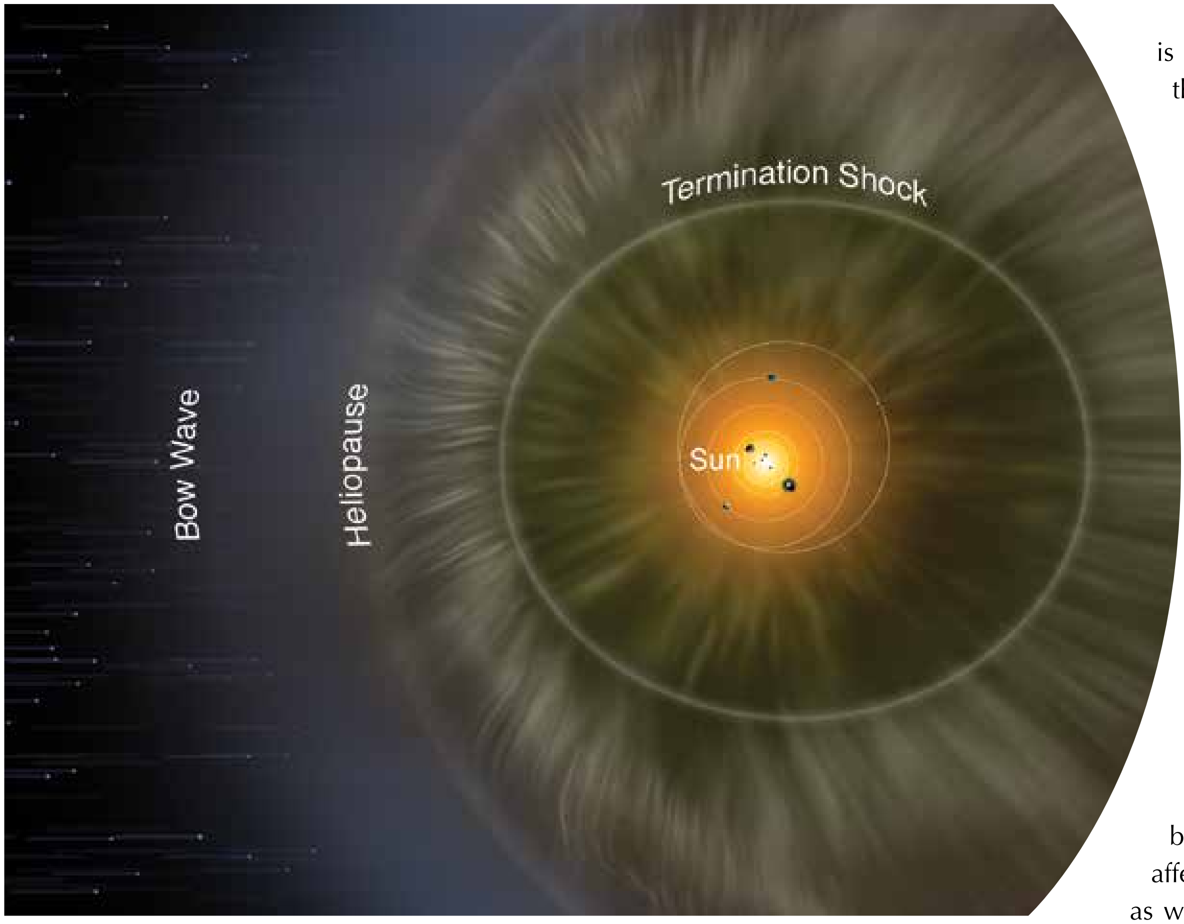
United States and international programs in solar and space physics seek to improve scientific understanding of the Sun and its variation over time; the relationship between the Sun and Earth's environment; and the impact of solar activity and space weather events on human activities as well as the Sun's connections with other bodies in the solar system and to the galaxy beyond. By directly measuring phenomena that occur in our own solar system, solar and space physicists draw connections between experiments in the laboratory and processes observed in remote astrophysical locations. The disciplines that comprise solar and space physics are intellectually rich and vital to a society increasingly dependent on technologies sensitive to the near-Earth space environment.

In 2010, NASA and the National Science Foundation asked the National Research Council to assemble a committee of experts (the "decadal survey committee") to develop an integrated national strategy that would guide agency investments in solar and space physics (or "heliophysics" in the terminology used by NASA) for the years 2013-2022. That strategy, the result of nearly 2 years of effort by the survey committee, which worked with more than 100 scientists and engineers on eight supporting study panels, is presented in the 2013 publication, *Solar and Space Physics: A Science for a Technological Society* (http://www.nap.edu/catalog.php?record_id=13060). This booklet, designed to be accessible to a broader audience of policymakers and the interested public, summarizes the content of that report but does not replace, nor should it be construed, as a substitute for the findings and recommendations of the actual report.



View of the aurora from the International Space Station as it crossed over the Southern Indian Ocean on September 17, 2011.

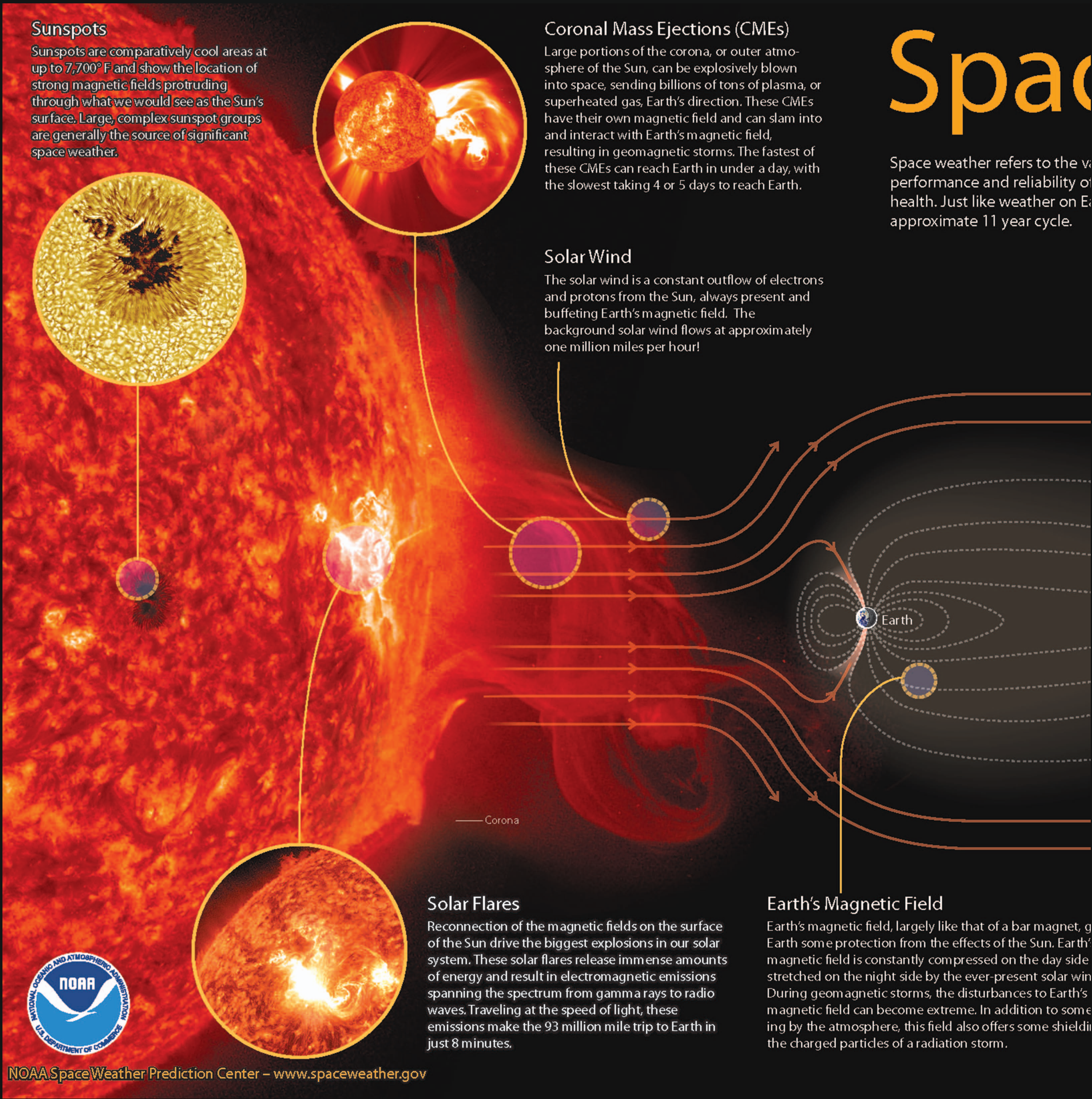
We live on a planet immersed in the tenuous outer atmosphere of a variable magnetic star, the Sun. As the Sun's outer atmosphere expands supersonically outward, it envelops Earth and shapes the terrestrial environment. This gusty solar wind flows past the planets, carving out a cavity in our galaxy that extends several times the distance from Pluto to the Sun. Earth and the other planets of our solar system are embedded deep within this extended cavity, called the heliosphere. This is the domain of heliophysics.



The new view of the heliosphere. Illustrated here are the termination shock, the boundary layer where the expanding bubble of solar wind particles abruptly slows down when it begins to press into the interstellar medium; the intermediate zone of slower-moving solar wind particles that forms the heliosheath; and finally the heliopause, the boundary between the solar wind and the interstellar medium.

Although the total energy output of the Sun is remarkably constant, magnetic activity on the Sun causes "space weather"—an analog to the more familiar terrestrial weather—severe space weather events have the potential to disrupt or cause failure in the space- and ground-based technological systems that modern society relies on. The primary drivers of hazardous space weather are the radiation, particles, and fields associated with solar flares—tremendous explosions in the low solar atmosphere—and coronal mass ejections—immense clouds of magnetized plasma launched into space at high speeds.

The heliosphere and planetary environments are elements of a single interconnected system that evolves in response to solar, planetary, and interstellar conditions. For example, Earth's magnetosphere, the area of space controlled by our planet's magnetic field, is profoundly affected by disturbances in the solar wind, as well as by changing conditions in the atmosphere below. Interactions in the magnetosphere involving neutral gas, electrically charged particles, and plasma waves occur over a broad range of scales in both space and time. The transport of energy and momentum through this environment exhibits varying degrees of complex feedback, requiring research techniques that treat heliophysics as a coupled system: heliophysics is thus inherently a system science.


Sunspots
Sunspots are comparatively cool areas at up to 7,700° F and show the location of strong magnetic fields protruding through what we would see as the Sun's surface. Large, complex sunspot groups are generally the source of significant space weather.
Coronal Mass Ejections (CMEs)
Large portions of the corona, or outer atmosphere of the Sun, can be explosively blown into space, sending billions of tons of plasma, or superheated gas, Earth's direction. These CMEs have their own magnetic field and can slam into and interact with Earth's magnetic field, resulting in geomagnetic storms. The fastest of these CMEs can reach Earth in under a day, with the slowest taking 4 or 5 days to reach Earth.
Spac
Space weather refers to the va
performance and reliability of
health. Just like weather on Ea
approximate 11 year cycle.
Solar Wind
The solar wind is a constant outflow of electrons and protons from the Sun, always present and buffeting Earth's magnetic field. The background solar wind flows at approximately one million miles per hour!
Earth
Corona
Solar Flares
Reconnection of the magnetic fields on the surface of the Sun drive the biggest explosions in our solar system. These solar flares release immense amounts of energy and result in electromagnetic emissions spanning the spectrum from gamma rays to radio waves. Traveling at the speed of light, these emissions make the 93 million mile trip to Earth in just 8 minutes.
Earth's Magnetic Field
Earth's magnetic field, largely like that of a bar magnet, g
Earth some protection from the effects of the Sun. Earth'
magnetic field is constantly compressed on the day side
stretched on the night side by the ever-present solar win
During geomagnetic storms, the disturbances to Earth's
magnetic field can become extreme. In addition to some
ing by the atmosphere, this field also offers some shieldi
the charged particles of a radiation storm.
NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE
NOAA Space Weather Prediction Center – www.spaceweather.gov

ce Weather

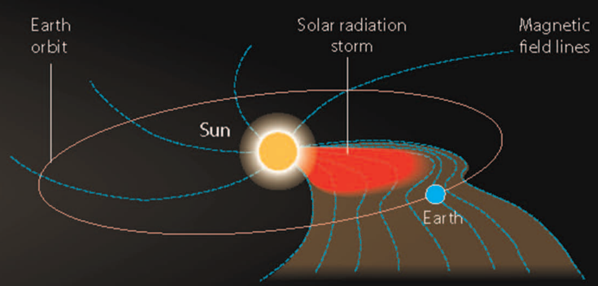
ariable conditions on the Sun and in the space environment that can influence the
f space-based and ground-based technological systems, as well as endanger life or
arth, space weather has its seasons, with solar activity rising and falling over an

Sun's Magnetic Field

Strong and ever-changing magnetic fields drive the life of the Sun and underlie sunspots. These strong magnetic fields are the energy source for space weather and their twisting, shearing, and reconnection lead to solar flares.

Solar Radiation Storms

Charged particles, including electrons and protons, can be accelerated by coronal mass ejections and solar flares. These particles bounce and gyrate their way through space, roughly following the magnetic field lines and ultimately bombarding Earth from every direction. The fastest of these particles can affect Earth tens of minutes after a solar flare.



Geomagnetic Storms

A geomagnetic storm is a temporary disturbance of Earth's magnetic field typically associated with enhancements in the solar wind. These storms are created when the solar wind and its magnetic field interacts with Earth's magnetic field. The primary source of geomagnetic storms is CMEs which stretch the magnetosphere on the nightside causing it to release energy through magnetic reconnection. Disturbances in the ionosphere (a region of Earth's upper atomosphere) are usually associated with geomagnetic storms.

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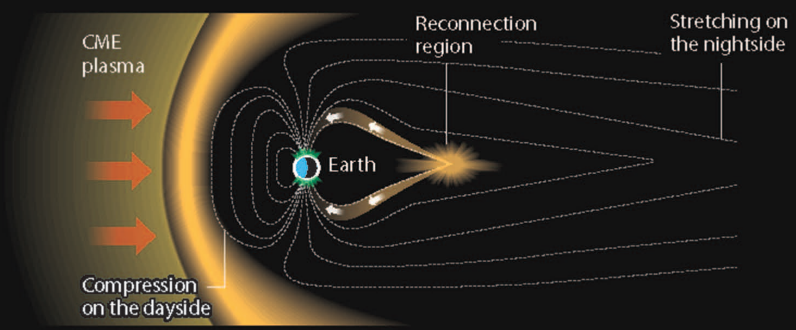


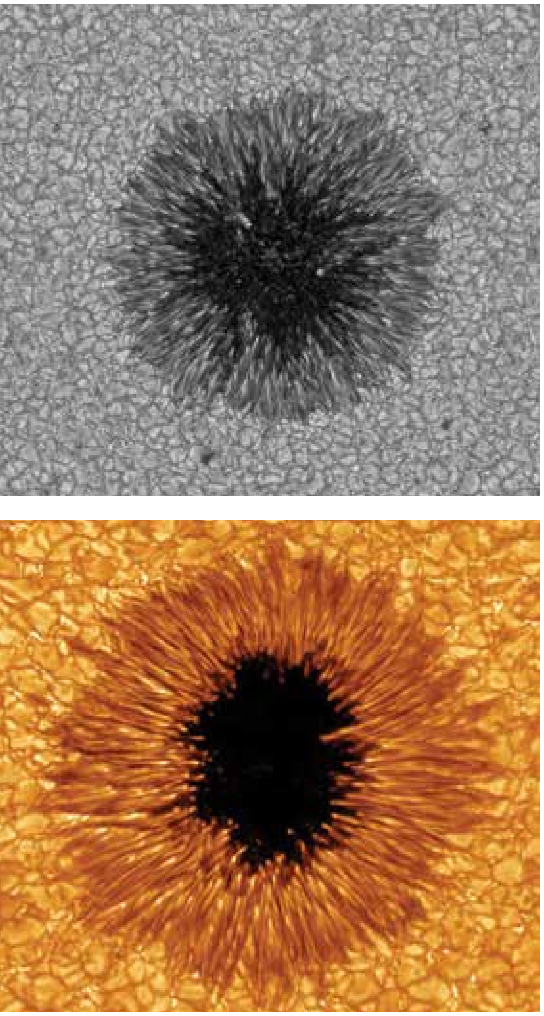
Source images: NASA, NOAA.

At the heart of heliophysics are fundamental questions of basic importance to science and society. Heliophysics research encompasses solar electromagnetic and radiative processes; the generation of solar magnetic fields and acceleration of energetic particles; the storage and violent release of magnetic energy; the origin and evolution of the solar wind and interplanetary magnetic field; and their interactions with planets and moons that have their own magnetospheres and atmospheres. Moreover, as humanity's presence extends farther into space—both by means of robotic probes and human spaceflight—and as society's technological infrastructure is increasingly linked to space-based assets vulnerable to the effects of space weather, the need to characterize, understand, and predict the dynamics of our environment in space becomes ever more pressing.

Space weather. NOAA Space Weather Prediction Center. http://www.swpc.noaa.gov/info/swx_poster_a.jpg.

HELIOPHYSICS RESEARCH SEEKS TO UNDERSTAND THE HISTORY, EVOLUTION, AND DETAILED WORKINGS OF THE SUN AND SOLAR WIND, TO CHARACTERIZE AND UNDERSTAND EARTH'S SPACE ENVIRONMENT AND UPPER ATMOSPHERE, TO DETERMINE HOW THE HELIOSPHERE INTERACTS WITH THE GALAXY BEYOND, AND TO STUDY RESPONSES AT EARTH AND THROUGHOUT THE HELIOSPHERE TO SOLAR EVENTS AND PERIODIC VARIABILITY.

How Are Solar Magnetic Fields Created and Destroyed?



Numerical simulation of a sunspot (top) and an actual photograph (bottom) from the New Solar Telescope at Big Bear Observatory, NJIT. Sunspots are a consequence of intense magnetic fields on the surface of the Sun. Large sunspots can be tens of thousands of kilometers across.

A FUNDAMENTAL PROBLEM IN SOLAR PHYSICS—AND MORE GENERALLY IN THE UNDERSTANDING OF STARS—IS THE ORIGIN OF MAGNETIC FIELDS AND THEIR VARIATIONS. MAGNETIC FIELDS LIE AT THE ROOT OF SOLAR ACTIVITY—INCLUDING SPACE WEATHER. THEY PLAY A KEY ROLE IN SOLAR FLARES AND CORONAL MASS EJECTIONS, IN HEATING THE CORONA, IN ACCELERATING THE SOLAR WIND AND ENERGETIC PARTICLES, AND IN CREATING THE HELIOSPHERE.

The Solar Activity Cycle

One of the most striking features of the Sun is the presence of dark spots. Sunspots vary in number with a roughly 11-year period—the solar activity cycle. They can range in size—many are as big as Earth—and appear dark because they are cooler than their surroundings. Although systematically studied since the invention of the telescope in the early 17th century, it was not until the early 20th century that George Hale showed that sunspots are the visible manifestation of strong magnetic fields. These active regions, ultimately generated by churning plasmas deep within the Sun, store tremendous amounts of energy and lie at the heart of hazardous solar activity associated with explosive flares and dramatic coronal mass ejections. Even though new techniques are revealing conditions beneath the solar surface, an unanticipated lull in solar activity in 2008-2009 delayed the start of Solar Cycle 24, the weakest cycle in more than a century. We apparently have only a rudimentary scientific understanding of the origins and cyclic evolution of magnetism caused by the Sun's dynamo motion.

A key question for future research is,* ***What are the detailed origins of the solar cycle?***

The Corona: A Coupled Dance of Plasma and Field

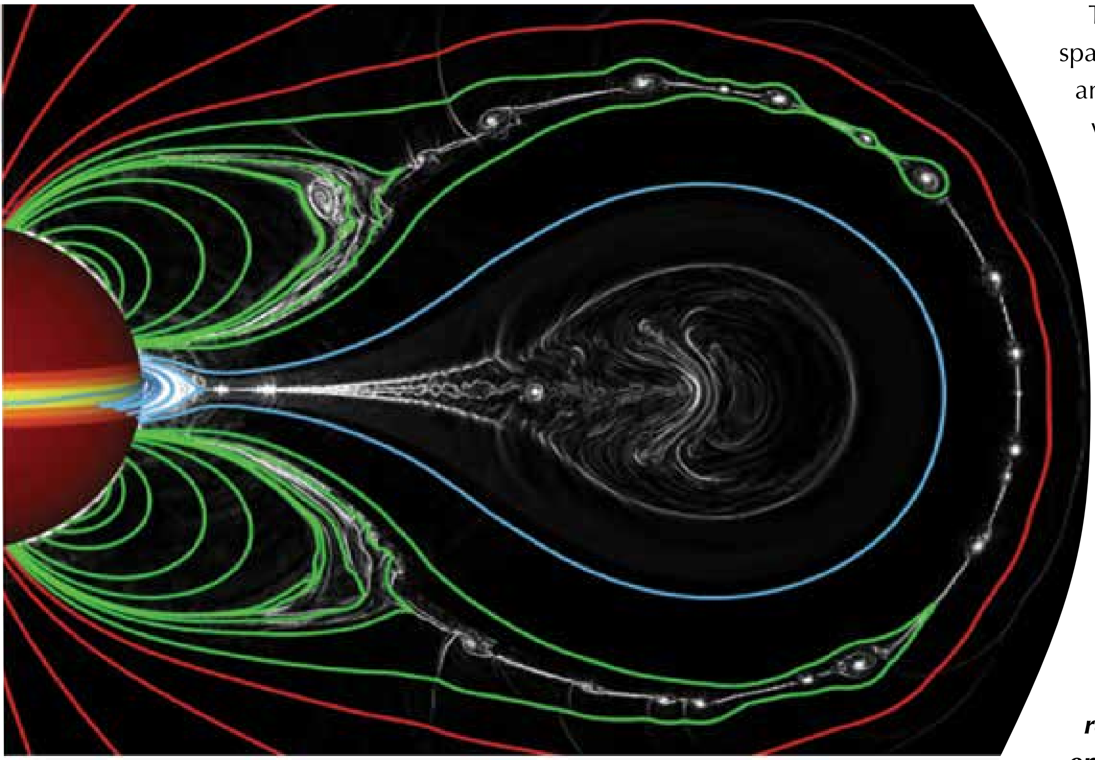
The Sun's outer atmosphere, the corona, is hundreds of times hotter than the visible surface of the Sun. In the corona, even the heaviest atoms are stripped of their electrons and form plasma, an electrically conductive gas of electrons and ions. The million-degree corona is most vividly observed in certain ultraviolet and X-ray wavelengths emitted by ions of particular elements at specific temperatures (see the figure on page 1). The Sun's magnetic field permeates the corona and dominates the plasma's dynamic behavior. The evolving field determines the coronal density and temperature structure, creates the solar wind, triggers flares and coronal mass ejections, and regulates the acceleration of energetic particles that fill the solar system. However, scientists struggle to explain just how energy flows into and through the corona, especially the thin enigmatic interface between the solar surface and corona.

A key question for future research is, ***How is energy transferred through the solar atmosphere to the rest of the solar system?***

** The key science questions are derived from the more detailed goals and challenges that are presented in the full report.*

Magnetic Explosions

The Sun's magnetic field is in a state of perpetual change. Small patches of strong magnetic field constantly emerge from deeper layers, twisting, stretching, and jostling. Energy is stored when magnetic fields interact (think about stretching tangled elastic bands). If conditions are right, oppositely directed magnetic field lines can reconnect and release some of the stored energy in a violent explosion. Near the Sun's surface, magnetic reconnection can trigger solar flares, heating the corona to 20 million degrees, producing intense X-ray radiation, and accelerating electrons and ions to nearly the speed of light. The corona's magnetic fields can also destabilize on a near-global scale, triggering a coronal mass ejection—a billion-ton eruption of magnetized plasma traveling into interplanetary space at speeds of hundreds to thousands of kilometers per second.



These space weather events threaten astronauts in space, satellites in orbit, long-distance communication, and electrical infrastructure on the ground. Particularly worrisome is the massive damage intense space weather can cause to the world's electrical grid systems. Thanks to improving instrumentation and analysis capabilities, forecasters can identify where on the Sun magnetic explosions are likely to occur, but scientists cannot reliably predict when or how large events will be or whether the energetic particles and magnetized plasma will be strongly coupled to Earth.

Magnetic reconnection is a crucial process in both the heliosphere and Earth's magnetosphere as well. A better understanding of magnetic reconnection is crucial to advancing our understanding of these and other astrophysical systems.

A key question for future research is, ***What is the role of magnetic reconnection in energy release in coronal mass ejections and flares?***

Ultra-high-resolution numerical simulation of a coronal mass ejection and associated flare. Colored loops show the magnetic field. White contours indicate regions of high electric-current density. Note the sheets of intense current at the site of the flare, above the short loops near the solar equator, where reconnection occurs. The current sheet lies at the base of the erupting plasmoid, outlined in blue. The material ejected in a coronal mass ejection takes 2 to 4 days to reach Earth.

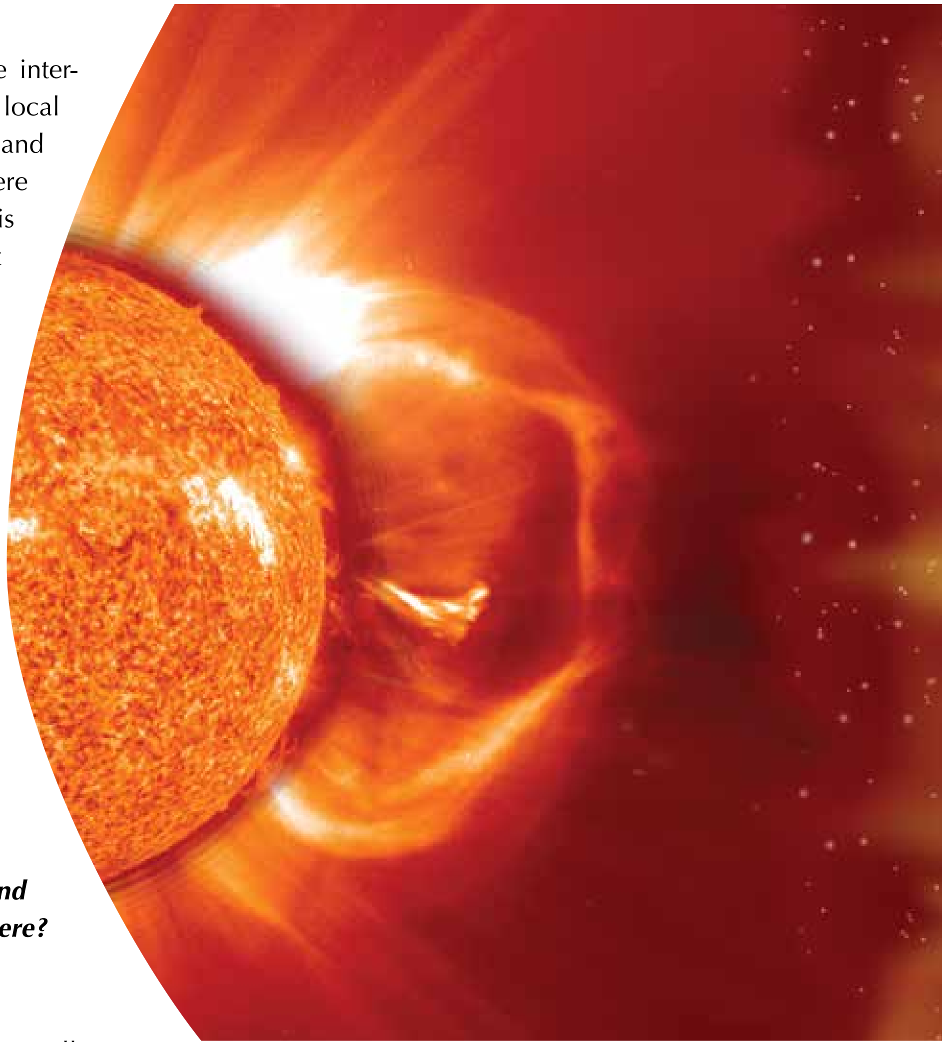
How Does Earth's Magnetosphere Store and Release Solar Energy?

Earth's Magnetic Shield

The magnetized solar wind creates the heliosphere within the interstellar medium. Likewise, Earth's magnetic field carves out its own local domain within the heliosphere. Just as the heliosphere deflects and absorbs external galactic particles and fields, our own magnetosphere deflects and absorbs solar particles and fields. The magnetosphere is the fundamental element of a complex system surrounding Earth that processes solar energy; it protects our planet from much of the solar wind and mediates the influence of solar variability on the Earth system. The lower boundary of the magnetosphere is the ionosphere, the tenuous region of Earth's upper atmosphere ionized by solar radiation.

Earth's magnetic field controls the motion of the electrically charged particles that become trapped in the magnetosphere. Shaped externally by the solar wind, the magnetosphere ordinarily extends out only 10 Earth radii—some 40,000 miles—on the sunward side of Earth, but well beyond the Moon's orbit (approximately 60 Earth radii) on the side away from the Sun, forming a much longer magnetotail. Earth's magnetosphere responds dynamically and dramatically to solar variability. It is buffeted by gusts in the solar wind and coupled by reconnecting magnetic fields to solar wind mass, momentum, and energy flow.

A key question for future research is, ***What are the interactions and feedbacks that connect the magnetosphere, solar wind, and ionosphere?***

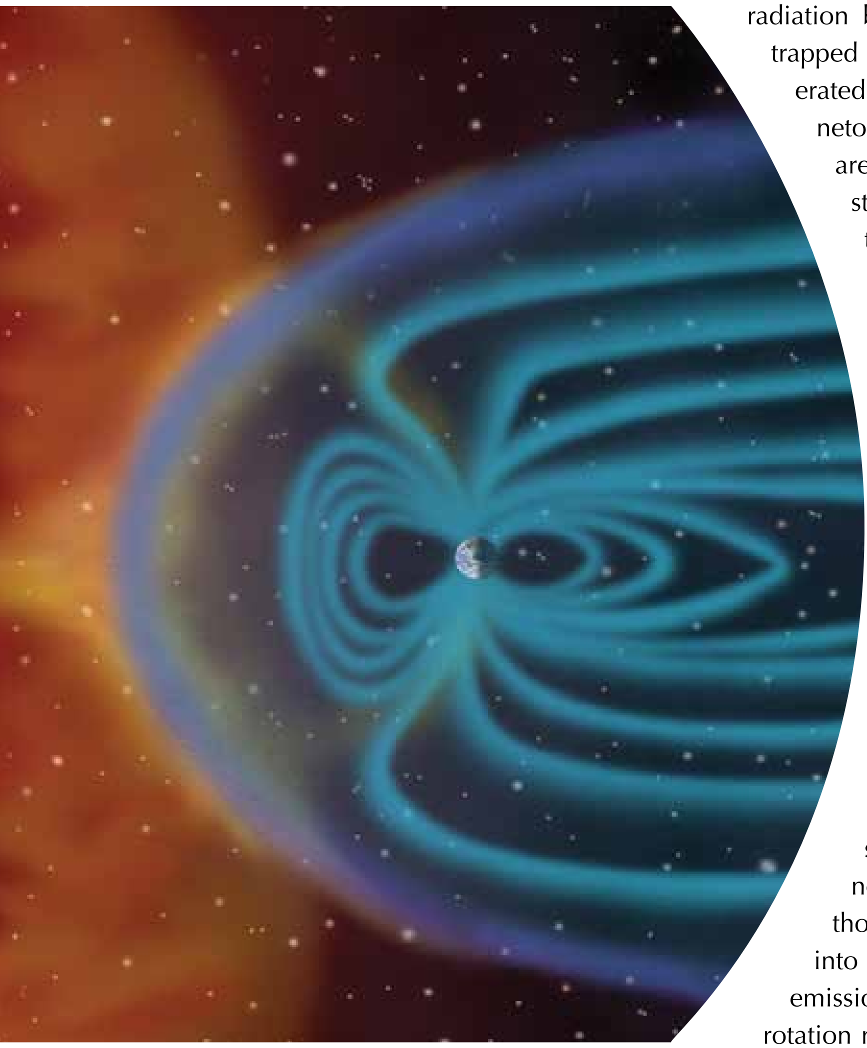


Earth's ionosphere, thermosphere, and magnetosphere react together to the arrival of a coronal mass ejection. During strong magnetic storms, ionospheric plasma (green) can flow out of Earth's polar regions and fill the magnetosphere, sometimes exceeding the density of incoming solar wind plasma (yellow) that gets through the magnetopause. Note: The Sun and the Earth are not shown to scale.

Variable Radiation Belts

The highest-energy plasma trapped within the magnetosphere collects in Earth's radiation belts. The energetic plasma particles persistently degrade satellites in high-altitude orbits, including global positioning system (GPS) and communication satellites. Earth's radiation belts are surprisingly volatile, sometimes so intense that they threaten satellites, or so weak that they seem almost to disappear. To understand these fluctuations requires better knowledge of the sources of radiation belt plasma and the processes driving that plasma.

The magnetosphere has no internal plasma sources, but traps plasma from external sources. The solar wind injects huge quantities of plasma into the



radiation belts, with lesser amounts contributed by the ionosphere below. Once trapped in the magnetosphere, the ions and electrons in the plasma can be accelerated to very high energies. Magnetic field reconnection in the tail of the magnetosphere and powerful plasma-wave interactions within the magnetosphere are two of the processes that energize radiation-belt particles. Geomagnetic storms—often caused by coronal mass ejections in the solar wind striking the magnetosphere—trigger these mechanisms, sometimes supercharging the radiation belts and threatening space- and ground-based electronics. Understanding how these processes interact and feed back in this complex system is crucial to explaining and predicting variations in the magnetosphere.

A key question for future research is, ***How are plasmas produced, lost, and energized in the magnetosphere?***

Many Magnetospheres

Six planets (Earth, Mercury, Jupiter, Saturn, Uranus, and Neptune) and at least one moon (Jupiter's Ganymede) are known to have magnetospheres. Each provides a unique laboratory for testing theories and models and, in particular, refining the scientific understanding of Earth's magnetosphere. For example, a comparison of how energy from the solar wind is coupled into the magnetospheres of Earth and Mercury demonstrates the important role of an ionosphere, which is present on Earth but not on Mercury. The moons of Saturn and Jupiter inject plasma from within those planets' large and powerful magnetospheres, providing new insights into the effects of plasma sources. Saturn's magnetosphere even emits radio emissions at regular intervals that were originally thought to represent the internal rotation rate of the planet but now appear to be affected by plasma processes. The magnetospheres of Uranus and Neptune are largely unexplored. These other systems present a suite of vastly different conditions, offering a chance to deepen our understanding of the fundamental processes at work in all magnetospheres.

A key question for future research is, ***How do other planetary magnetospheres interact with their ionospheres, atmospheres, and the solar wind?***

How Does Earth's Atmosphere Couple to Its Space Environment?

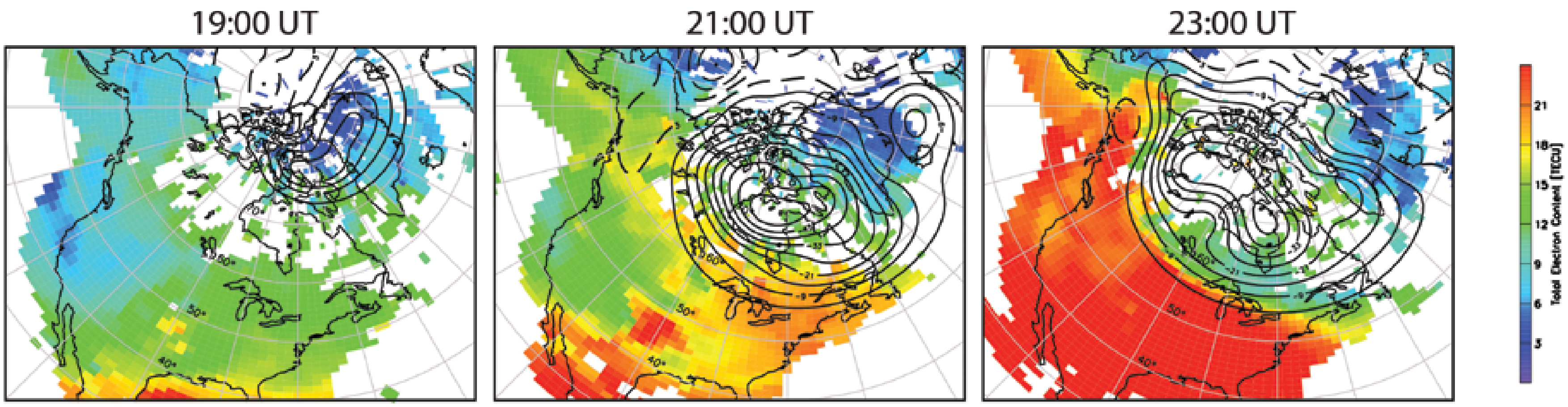
The Ionosphere-Thermosphere Connects Earth and Space

The connection between Earth's atmosphere and conditions in space can be best understood when viewed as a system. The neutral atmosphere, ionosphere, magnetosphere, the solar wind, and radiation environment interact with each other, giving rise to new behaviors. The lowest layer—the troposphere—is home to all life, weather, and 80 percent of the atmosphere's total mass. The top layer of the atmosphere—the thermosphere—consists of very low-density, high-temperature neutral gas heated by solar ultraviolet radiation. The ionosphere is the ionized component of the upper atmosphere; it overlaps with the thermosphere and is where the atmosphere begins to connect to space, at around 100 km above the surface. Both of these regions play key roles in modifying and producing space weather effects near Earth.

Understanding and being able to predict the state of the ionosphere is of central importance, because radio waves can be scattered and absorbed there. For example, GPS navigation and over-the-horizon communication used on long-duration airplane flights are affected by conditions in the ionosphere. Because the ionosphere is influenced both by conditions in space and by the atmosphere that extends down to the surface, a number of competing effects observed in this region must be understood in order to predict the behavior of the near-Earth space environment.

A key question for future research is, ***How does Earth's atmosphere couple to its space environment?***

AUGUST 3, 2010 GEOMAGNETIC STORM



A plasma storm envelops the North American continent on the afternoon of August 3, 2010. Red regions of high electron density degrade the performance of GPS systems used for navigation. Electric currents above Earth (shown by contours) also grow during the storm, inducing currents in the ground.

The Upper Atmosphere and Its Interactions with the Magnetosphere

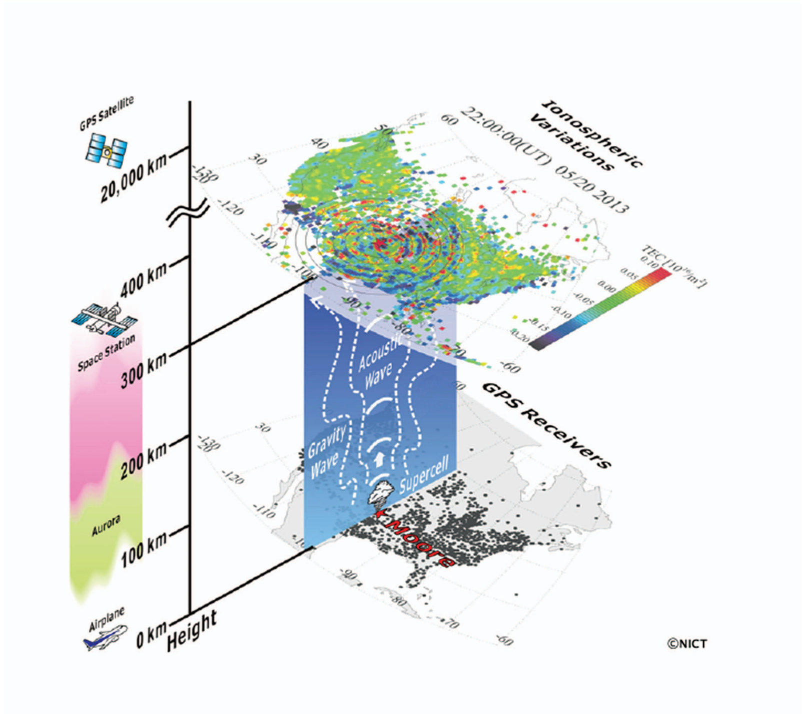
The magnetosphere acts as an intermediary between space and the atmosphere, both preventing radiation from reaching Earth and transferring energy from the high-speed solar wind to the ionosphere and thermosphere. This energy in the ionosphere-thermosphere system circulates the neutral and charged gas of the layers and affects the density of both. In addition, magnetospheric fluctuations driven by the solar wind produce auroras. Precipitation of magnetospheric plasma along the magnetic field lines down into the atmosphere leads to collisions with the neutral atmosphere that emit auroral light. The aurora in turn drives stronger winds and raises temperatures in the thermosphere. Because the thermosphere and ionosphere occupy the same region of space, this magnetospheric energy is readily exchanged between the neutral and charged gas. From this dynamic interplay between the ions and neutrals emerge behaviors of the geospace system that are currently difficult to predict; understanding the coupling between the ions and neutrals in the upper atmosphere is therefore of key importance.

A key question for future research is, ***How does the ionosphere-thermosphere system regulate the flow of solar energy throughout geospace?***

Effects of the Lower Atmosphere in Near-Earth Space

A surprising finding of the past decade is that day-to-day terrestrial weather affects conditions in space near Earth. In fact, phenomena in the lower atmosphere, including powerful storm systems, high winds over mountains, tropical rainy seasons, and even changes in the polar vortex, have all been connected to changes in the ionosphere and upper atmosphere. Energy is carried upward from these sources in atmospheric waves, and the size of these waves grows with increasing altitude to strongly influence conditions in the middle and upper atmosphere. The ionosphere is then affected by coupling between the neutral particles and charged plasma. Similar to the external disturbances driven by the solar wind, forcing from below has the potential to interfere with day-to-day use of precision GPS and other satellite-based technologies.

A key question for future research is, ***How do terrestrial weather and climate affect conditions in near-Earth space?***



A remarkable example of lower-upper atmospheric coupling is seen in the ionospheric signature of the 2011 Moore, Oklahoma, tornado. Within minutes of the formation of the supercell that spawned the F5 tornado, concentric waves were seen in ionospheric densities (measured in total electron content) over North America at 300 km altitude, emanating outward more than 1,500 km from Oklahoma for the next 12 hours.

How Does the Sun Carve Its Place in the Galaxy?

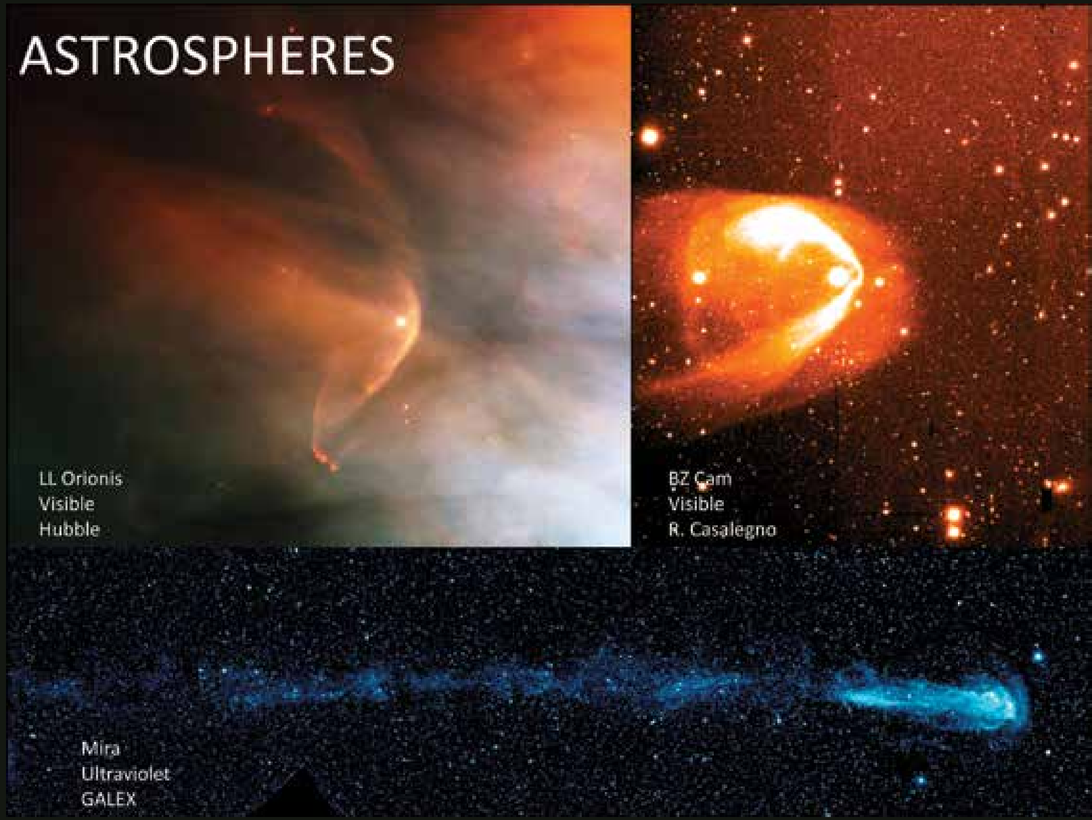
The Source of the Heliosphere

In addition to its beauty, a total solar eclipse reveals the corona, the source of the solar wind. The solar wind extends into the solar system and beyond, creating a cavity in the interstellar medium called the heliosphere, as depicted in the figure on page 3. In fact, the solar wind and heliosphere extend more than four times the distance to Pluto, where the solar wind collides with the interstellar medium. At this boundary, called the heliopause, our home in space ends and the rest of the universe begins. All the planets of the solar system, including the Earth, are embedded deep inside the Sun's extended stellar atmosphere.

Just like the Sun's magnetic field, the heliosphere is incredibly dynamic and turbulent. The Sun's magnetic field heats the corona and accelerates the solar wind toward the edge of the heliosphere, linking the solar interior to the galaxy. Explosive releases of energy stored in magnetic fields—solar flares and coronal mass ejections—can inject huge quantities of fast-moving material into the heliosphere.

A key question for future research is, ***How does the Sun's magnetic field shape the dynamic heliosphere?***

The July 11, 2010, solar eclipse reveals the magnetic structure of the inner corona. A superposed image shows the Moon blocking out the solar photosphere. Bright, closed magnetic loops generally indicate sources of high-density, slow-speed solar wind. Extended radial features are associated with high-speed streams above coronal holes at the poles and elsewhere. The shape of the Sun's atmosphere changes through the solar cycle. The coronal structure imprinted on the solar wind is ultimately carried out to the edge of the heliosphere.



Images of the heliospheres around other stars (called astrospheres) observed with a variety of telescopes.

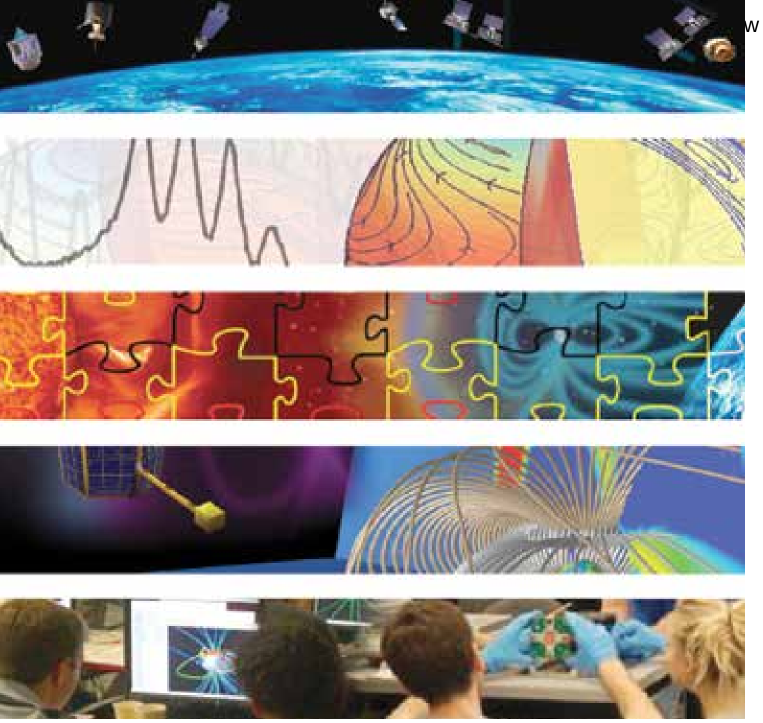
The Boundary of the Heliosphere

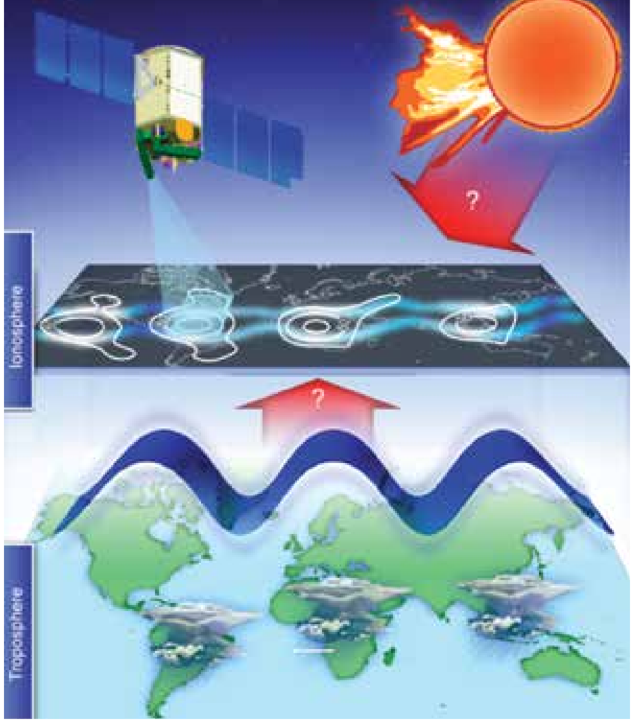
The outer regions of the heliosphere are rich in unexplored physics. One region—the heliosheath—magnetically shields the solar system from some of the galactic cosmic rays that permeate interstellar space. Because these high-energy cosmic rays consist of charged particles, the magnetic field of the heliosheath regulates their flow into the inner heliosphere. However, magnetic shocks in the outer heliosphere also energize additional, "anomalous" cosmic rays.

Cosmic rays can be harmful to life, because they can break down DNA molecules. They also stimulate evolution by increasing the rate of cell mutation. Additionally, cosmic rays may play some role in climate variability, although this relationship remains highly controversial. Though the details remain uncertain, our own heliosphere provides an astrophysical case history of the successful emergence of life in a hospitable environment. The study of heliospheres around other stars, called "astrospheres," can inform the search for habitable planets in other stellar systems. Thus, scientists seek a better understanding of our own heliosphere's role in shaping past and future conditions on Earth.

Recently, a pair of 35-year-old spacecraft, the Voyagers, collected the first direct measurements of the heliopause region, while at the same time the IBEX mission demonstrated new methods for imaging the entire outer boundary of the heliosphere from near Earth. New data from these missions are revolutionizing the understanding of the edge of our solar system. During the next decade, as the Voyager spacecraft pass through the heliopause and enter interstellar space, they will send back measurements as the first human craft to leave our solar system. Unfortunately, the Voyagers will become inoperable in the 2020s, when their electrical power becomes inadequate to support science instrument operation. Therefore, the coming decade is a critical window for discovering how the Sun interacts with the local galactic medium.

A key question for future research is, ***How does our Sun interact with the interstellar medium?***

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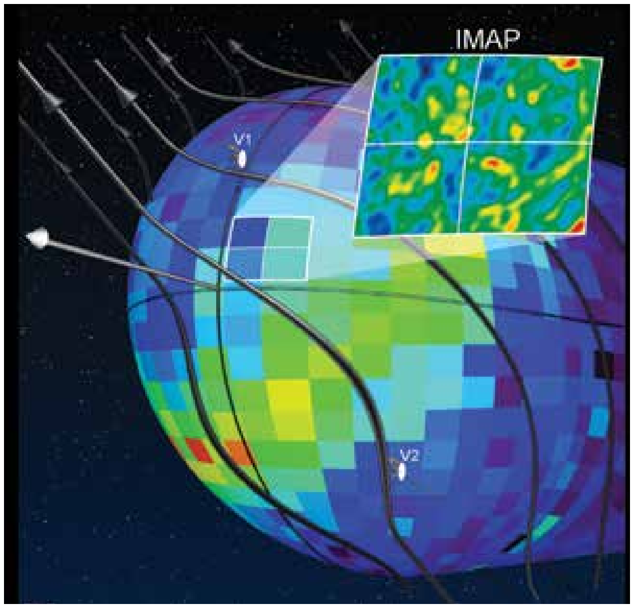
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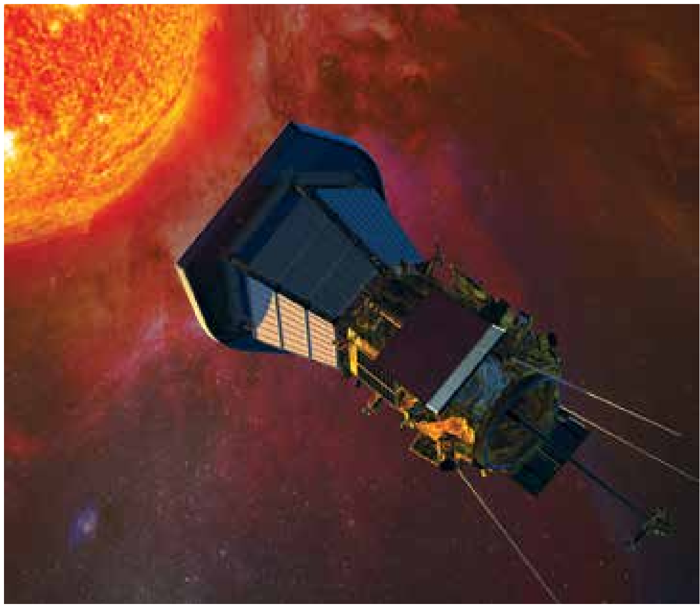
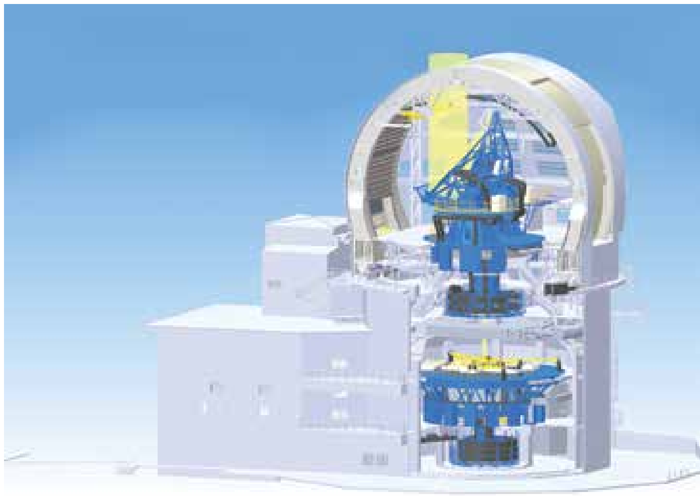




ENABLING A DECADE OF DISCOVERY AND THE DEVELOPMENT OF APPLICATIONS FOR SOCIETY

The discipline of solar and space physics has made remarkable advances over the last decade, many of which have come from the implementation of the program recommended in the 2003 solar and space physics decadal survey. New missions, observations, models, and fundamental research have yielded new insights in every subdiscipline of heliophysics.

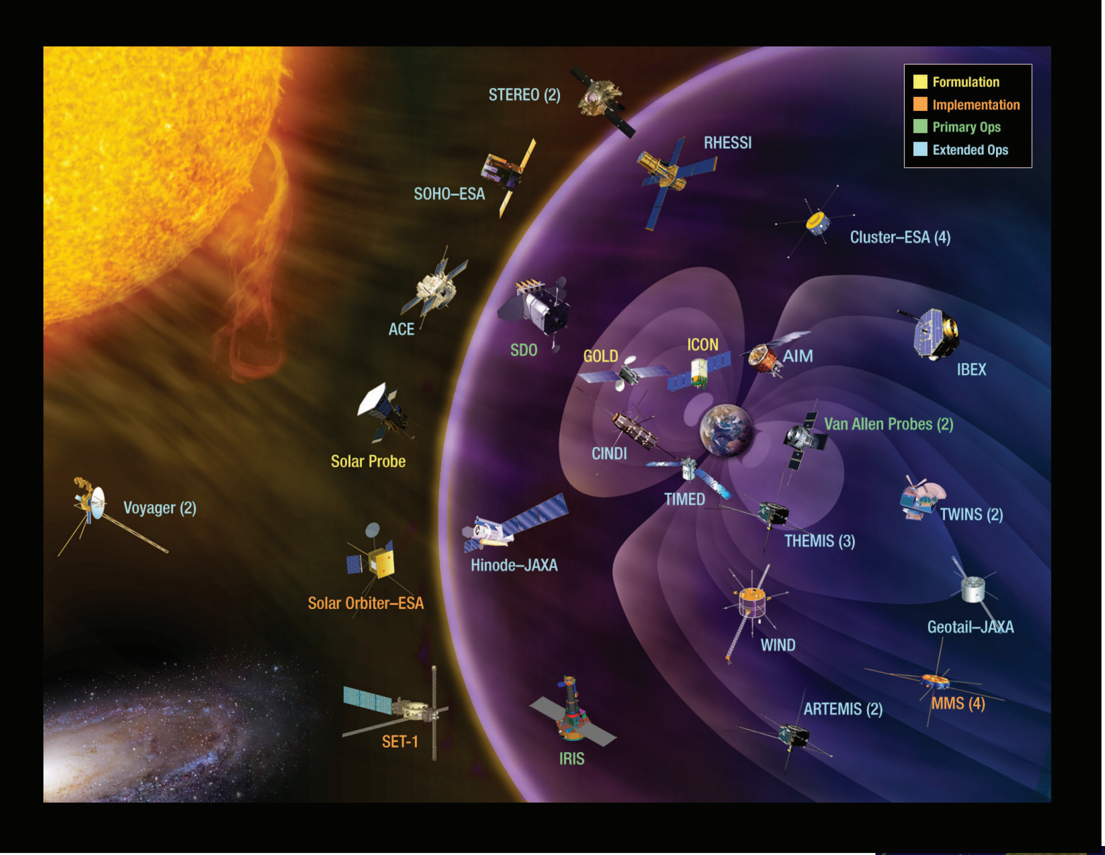
Many important scientific questions remain, and new ones have arisen. The answers to some will emerge from the research of the next decade. To guide NASA, NSF, and the other U.S. government agencies that fund this research, the decadal survey committee developed major research recommendations. After considering scientific priorities, rough estimates of project costs, and the long-term health of the research community, the committee prioritized the recommendations, indicating which programs the agencies should implement first. Ideally, all of the recommendations can be implemented in the coming decade. However, if agencies encounter limiting budgets or schedules, the prioritized recommendations provide tools with which to make tough decisions and preserve the most important research.

1. MAINTAIN AND COMPLETE THE PRESENT PROGRAM

Most importantly, the decadal survey recommends that NASA and NSF maintain and complete the current research programs in solar and space physics. The currently active or developing programs—many of which were recommended in the 2003 decadal survey—should be considered a baseline priority. For NASA, current programs include recently launched missions (Van Allen Probes and the Interface Region Imaging Spectrograph) and missions under development (Magnetospheric Multiscale Mission, Solar Orbiter, and Solar Probe Plus). For NSF, current programs include the recently deployed Advanced Modular Incoherent Scatter Radar, the Daniel K. Inouye Solar Telescope that is currently under construction (formerly the Advanced Technology Solar Telescope), and the continued operation of essential ground-based instruments.

Taken together, the NSF and NASA missions and observatories currently observing the Sun-Earth system form the "Heliophysics System Observatory" (HSO). **The decadal survey recommends continued support in the near term for the key existing program elements that constitute the HSO.** This diverse collection of space- and ground-based instruments allows simultaneous observations from distributed vantage points of a highly interconnected system. An invaluable legacy of decades of strategic investment in solar and space physics research, the HSO is an enabling tool for conducting new research, interpreting new observations, and observing space weather events.

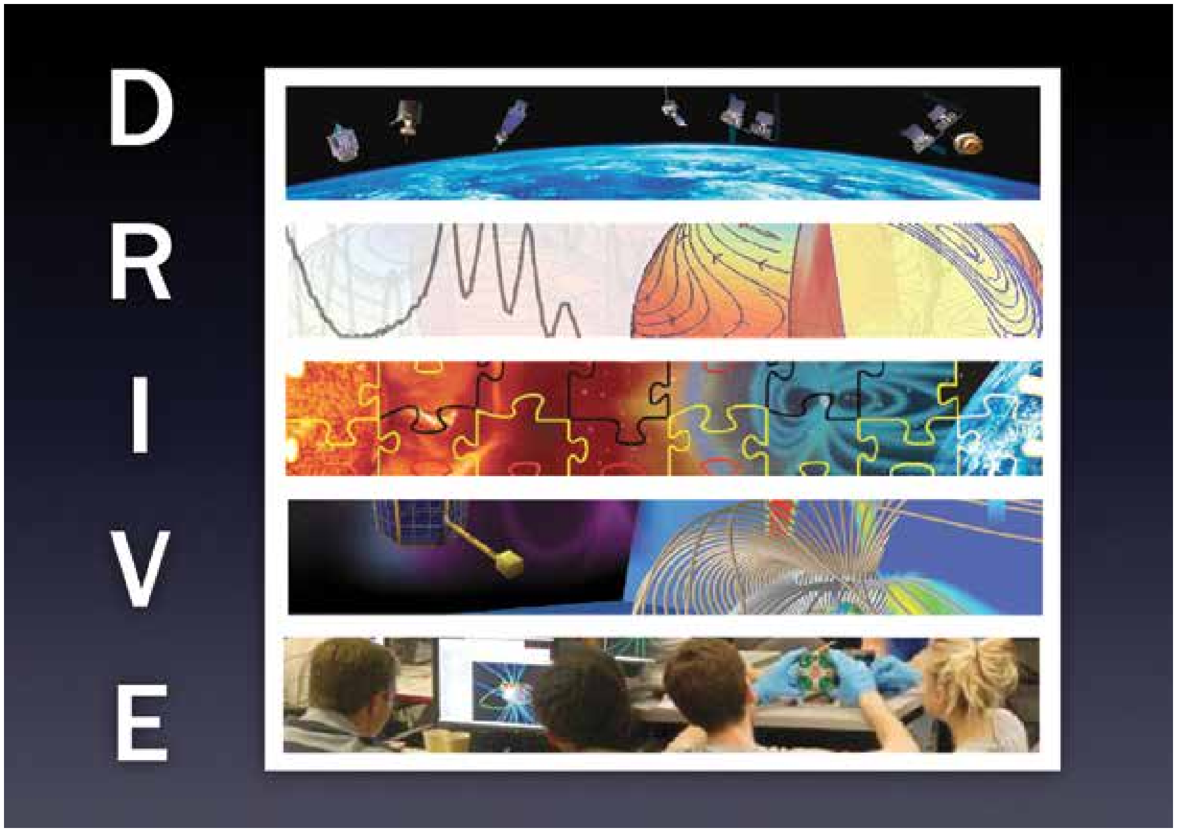
Artist's depiction of Solar Probe Plus, solar panels folded into the shadows of its protective shield, as it gathers data on its approach to the Sun in 2024. SPP will plunge to within just 6 million km of the solar surface, 25 times closer to the Sun than Earth.



NSF and NASA's current and near-future (indicated by yellow text) program of solar and space physics facilities and missions, which form the Heliophysics Systems Observatory (HSO).

2. IMPLEMENT THE DRIVE INITIATIVE

A successful scientific program in solar and space physics over the next decade will balance spaceflight missions of various sizes, midscale ground-based instruments, and supporting programs and infrastructure investments. Relatively low-cost activities that maximize the scientific return of ongoing projects and enable new ones are both essential and cost effective. However, it is all too easy to forget these small-scale activities in planning discussions. To ensure a solid groundwork is developed for the coming decade and beyond, **the decadal survey recommends as its highest priority after completion of the current program an array of actions collectively known as the DRIVE initiative.** DRIVE—Diversify, Realize, Integrate, Venture, Educate—is an initiative unified not by a central management structure, but through a comprehensive set of multi-agency recommendations that will facilitate scientific discovery. System science requires new types and configurations of observations, as well as a new cadre of researchers who can cross disciplinary boundaries seamlessly and develop theoretical and computational models that extract the essential physics from measurements made using multiple observing platforms.



The DRIVE initiative.

THE COMPONENTS OF DRIVE ARE:

DIVERSIFY observing platforms with microsatellites and midscale ground-based assets

By diversifying observation platforms and facilities, a wider array of unique and complementary data can be collected over greater temporal and spatial ranges, often at relatively low cost. Additionally, more frequent, lower-cost observations provide broader opportunities for training the next generation of researchers. To achieve these goals, the decadal survey recommends that NSF create a new, competitively selected, midscale funding line to enable midscale projects and instruments that currently have no funding mechanism. Compelling examples of midscale projects include the Frequency Agile Solar Radiotelescope (FASR), designed to dynamically image space weather drivers in the Sun's atmosphere at radio wavelengths; and the Coronal Solar Magnetism Observatory (COSMO), designed to conduct synoptic observations of coronal magnetic fields. NASA should fly more sounding rockets and research balloons, and both agencies should increase funds for newly developed "cube" satellites.

REALIZE scientific potential by sufficiently funding operations and data analysis

NASA and NSF invest heavily in complex missions and projects and should ensure that the value of these efforts is fully realized once operations begin. NASA should permanently establish funding for Heliophysics System Observatory mission extensions and set aside a small budget portion of all future missions to fund guest investigators. NSF has committed to construction of the powerful 4-meter Daniel K. Inouye Solar Telescope (formerly the Advanced Technology Solar Telescope) and should maximize the investment by adequately funding its operations and instrument development.

INTEGRATE observing platforms and strengthen ties between agencies and disciplines

The study of solar and space physics is an inherently multi-disciplinary and multi-agency endeavor, combining disciplines as diverse as climatology and plasma physics to study complex systems. The decadal survey recommends that NSF ensure that funding is available for basic research that falls between its divisions. NASA and NSF should coordinate and take full advantage of their numerous ground- and space-based solar-terrestrial observational and technology programs.

VENTURE forward with science centers and with instrument and technology development

Future progress in heliophysics hinges on new observational capabilities in state-of-the-art instrumentation, access to unique vantage points in space, and new methods of collaboration. NSF and NASA should jointly establish heliophysics science centers where multidisciplinary teams can tackle key science problems. To enable future missions, NASA should consolidate and increase funding for solar and space physics instrument and technology development.

EDUCATE, empower, and inspire the next generation of space researchers

Continuing the scientific advances in solar and space physics requires support for future researchers through outreach and re cruitment, education, and employment. The decadal survey recommends that NASA and NSF continue outreach efforts and funding for undergraduate and graduate research in the space sciences. NSF should also continue its faculty development program and recognize solar and space physics as a specific subdiscipline of physics and astronomy.

By implementing the recommended DRIVE components, NASA and NSF can ensure that the next decade will be rich in new observations from diverse platforms, new science harvested from missions and projects, new synergisms between disciplines and platforms, new technologies and theories to enable future missions and projects, and talented new students to form the future workforce.

3. ENHANCE THE EXPLORER PROGRAM

Since 1958, when the first U.S. satellite—Explorer 1—discovered Earth's radiation belts, the Explorer program has produced a wealth of information about the nature of our space environment and properties of the universe. The data returned from Explorer missions have contributed to three of the Nobel Prizes awarded for NASA-directed space science. Over the years, Explorer missions have operated in different management modes, but the common feature is that a principal investigator (PI) in partnership with the NASA Explorer Program Office is tasked to ensure the overall success of the mission and is given the authority to make critical decisions to control cost and schedule. Because many of these missions have continued to provide data beyond their design lifetime, they have become cornerstones of the Heliophysics System Observatory, indispensable to basic research as well as to space weather operations.

The Explorer program's strength lies in its ability to respond rapidly to new concepts and developments in science, as well as in the program's synergistic relationship with larger-class strategic missions. Heliophysics Explorers launched since 2000 have made fundamental discoveries in space and solar physics from the edge of the heliosphere (IBEX) to flare and reconnection physics on the Sun (RHESSI) to the explosive releases of energy taking place in Earth's magnetosphere (THEMIS) to the enigmatic formation of ice clouds in Earth's polar regions (AIM). In addition, the Explorer Program is the home for missions of opportunity, including SNOE, CINDI and TWINS, instruments that have produced science benefits far beyond their cost.

The decadal survey does not recommend specific science targets for the Heliophysics Explorer program. Investigations are competitively selected to address the highest-priority science that can be accomplished with small-class missions. The Explorer Program has repeatedly proven to be one of the most cost-effective and best cost-controlled avenues for implementing space science missions.

The decadal survey recommends **increasing the cadence of the Heliophysics Explorer program to one mission every two to three years.** The decadal survey also recommends regular selections of missions of opportunity, which allow the research community to respond quickly and to leverage limited resources with interagency, international, and commercial flight partnerships. For a relatively modest investment, a renewed Explorer program can address many of the science challenges listed in the decadal survey.

Astrophysics and Heliophysics Explorers Missions

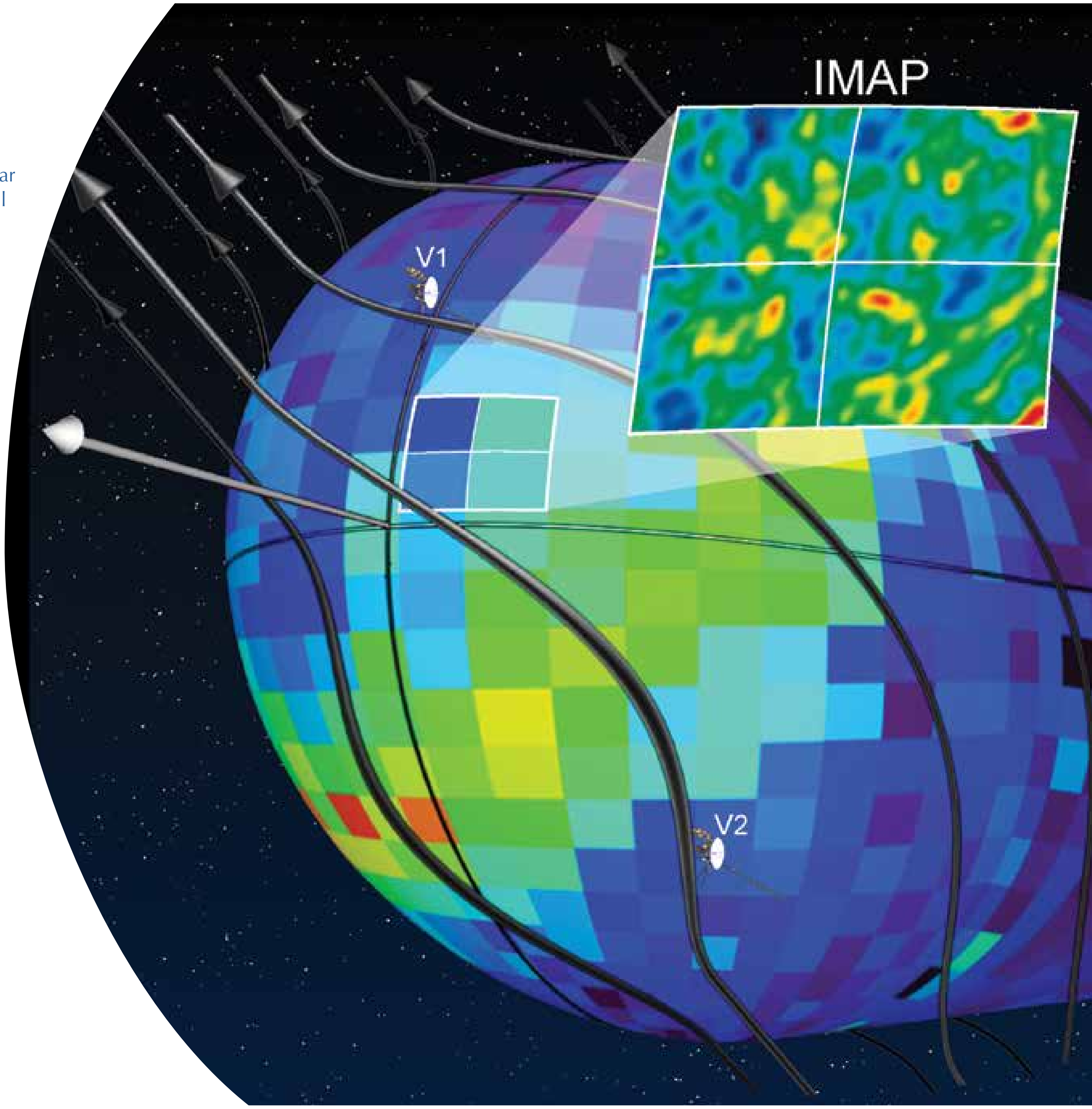
Astrophysics and Heliophysics Explorers Missions of the past 2 decades from http://explorers.gsfc.nasa.gov/missions.html.

4. SOLAR-TERRESTRIAL PROBE MISSION SCIENCE

Initially conceived as a program to implement medium-class missions, the Solar-Terrestrial Probe (STP) program has evolved into a large-scale mission program, dominated by NASA centers, with cost growth over the past decade that threatens its future viability. The decadal survey recommends that NASA's future **Solar Terrestrial Probes be restructured as moderate-scale competed, principal investigator-led (PI-led) mission line that is cost-capped at $520 million per mission.** NASA's Planetary Science Division uses this structure for its Discovery and New Frontiers programs, and these medium-class missions have a history of superior cost performance relative to larger flagship missions. STP missions should be managed likewise, with each mission's principal investigator empowered to make the scientific and mission design trade-offs necessary to remain within the cost cap. This should enable the STP program to achieve the recommended minimum cadence of one mission every four years. The decadal survey identified top scientific priorities for the program and estimated for each the cost of a notional mission. The survey recommends the scientific targets for the STP program, not the specific implementation.

The first recommended new STP science target is to understand the outer heliosphere and its interaction with the interstellar medium. A notional mission known as the **Interstellar Mapping and Acceleration Probe (IMAP)** would greatly extend the highly successful first heliospheric mapping mission, IBEX, to enable the discovery of the detailed processes and interactions between the heliosphere and the local interstellar medium. In addition, as the mission implementation requires local measurements of solar wind, magnetic fields, and energetic particles, IMAP inherently provides key observations relevant to understanding and predicting Earth's space weather. If launched on the schedule recommended in the survey, IMAP operations would overlap those of NASA's Voyager spacecraft, which are poised on the boundaries of interstellar space, but nearing the end of their lifetime. Simultaneous remote and in situ observations from IMAP and the Voyagers would enable critical comparisons that are otherwise impossible. **The survey report also recommends STP science targets to follow IMAP: First the notional Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC)** mission would provide a comprehensive understanding of the variability in space weather driven by lower atmospheric weather on Earth. Second, the notional **Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI)** mission would determine how the magnetosphere-ionosphere-thermosphere system is coupled and how it responds to solar and magnetospheric forcing.

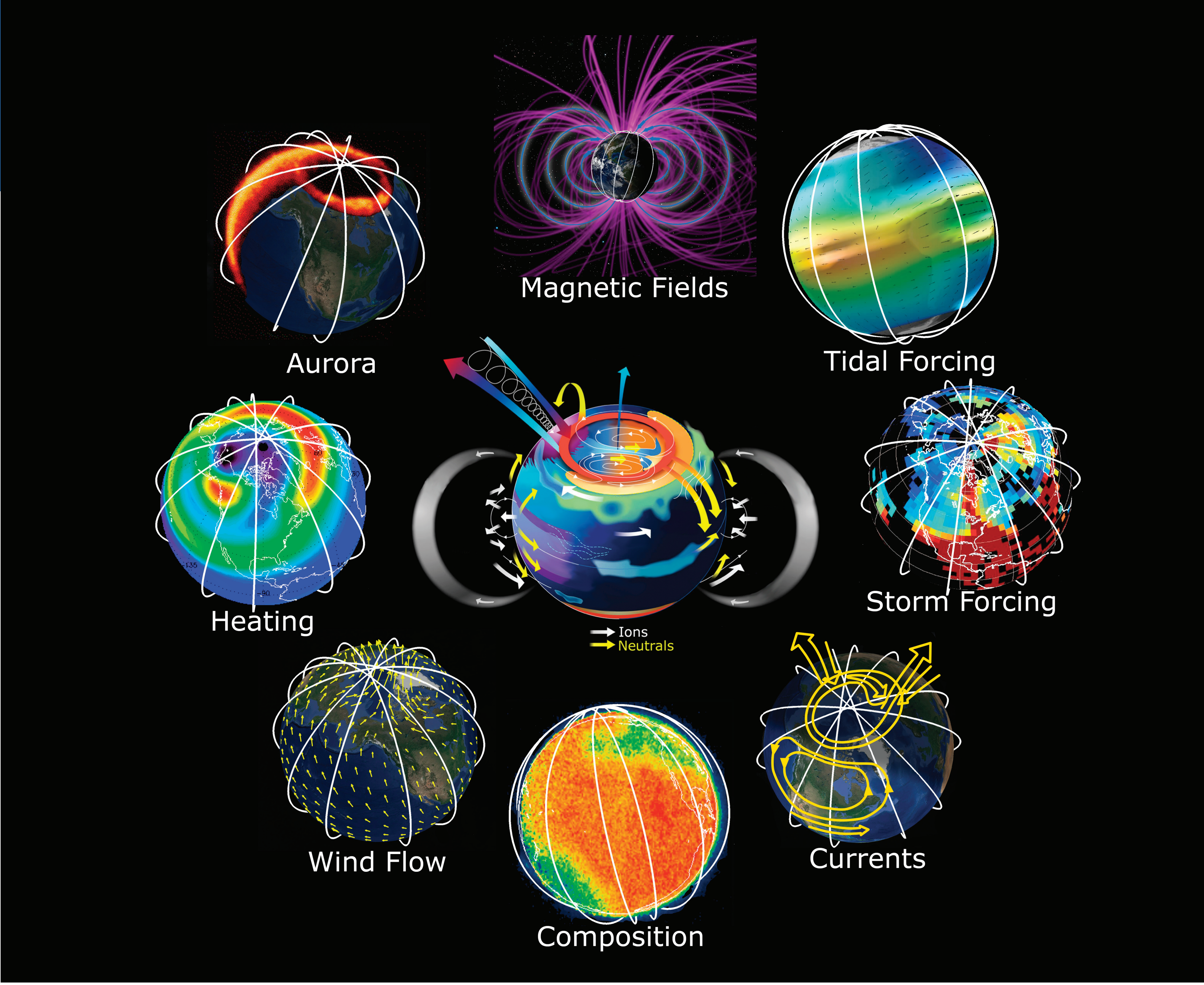
The next STP mission, the notional Interstellar Mapping and Acceleration Probe (IMAP), will solve fundamental mysteries of the heliosphere's interaction with the interstellar medium and particle acceleration in the solar wind. Projected onto the outer boundary of the solar system, measurements from the Interstellar Boundary Explorer (IBEX) mission, launched in 2009, revealed an unexpected source of high-energy particles, which are shown here in yellow and green. This enigmatic "ribbon" raises basic and profound questions about its unexplained origin, the nature of the outer boundaries of our solar system, and the surrounding galactic medium. With more than 20 times the resolution, IMAP will probe the detailed source of the ribbon. Shown in the figure inset is a representation of substructure that scientists can presently only hypothesize. The gray arrow indicates the direction the solar system moves through interstellar space. The dark lines suggest how interstellar magnetic field lines may be draped across the bow of the heliosphere. Icons show the locations of the two Voyager spacecraft.



5. LIVING WITH A STAR MISSION SCIENCE

Certain scientific problems can be addressed only by missions that are relatively complex and more costly. Solar Probe Plus, which will travel closer to the Sun than any previous spacecraft, is an example of this type of mission; future constellation missions that would utilize multiple spacecraft to provide simultaneous measurements from broad regions of space (in order to separate spatial from temporal effects and reveal the couplings between adjacent regions of space) are another. As research evolves naturally from the discovery-based mode to one focused increasingly on quantification and prediction, missions benefit strongly from an integrative approach, whereby the knowledge obtained from prior research can be combined with new, innovative measurements for the development of understanding of the global machinery of the system. This effort may naturally require a larger mission, and it also accords with the societal-relevance theme of NASA's Living with a Star (LWS) program. In the survey committee's plan, major missions are thus appropriately undertaken via NASA's LWS program and would continue to be executed by NASA centers, whereas the STP program should be considered a community program, like the Explorer program.

For the next LWS mission, the survey committee recommends a comprehensive investigation of how Earth's atmosphere absorbs solar wind energy. The notional Geospace Dynamics Constellation (GDC) mission would determine how solar wind energy is regulated throughout geospace. Geospace is the region surrounding Earth, including its upper atmosphere, that is influenced by the particles and fields coming from the Sun. GDC uses a constellation of satellites to differentiate between spatial and temporal changes in energy flow and mass transport. With simultaneous multipoint measurements, the six identical satellites of GDC would offer a comprehensive view of the global effects of geomagnetic storms on Earth's atmosphere and reveal the links between the atmosphere, ionosphere, and magnetosphere. GDC would address fundamental physical processes and make comprehensive measurements needed to improve space weather forecasting and models of the ionosphere and upper atmosphere.



Better understanding of how Earth's atmosphere interacts with the space plasma environment requires that a number of key measurements be made simultaneously all around the globe. GDC will directly measure these parameters where the plasma density is highest. This comprehensive view will enable prediction of complex behaviors that emerge under constantly varying conditions in space and reveal how Earth's atmosphere affects space weather.

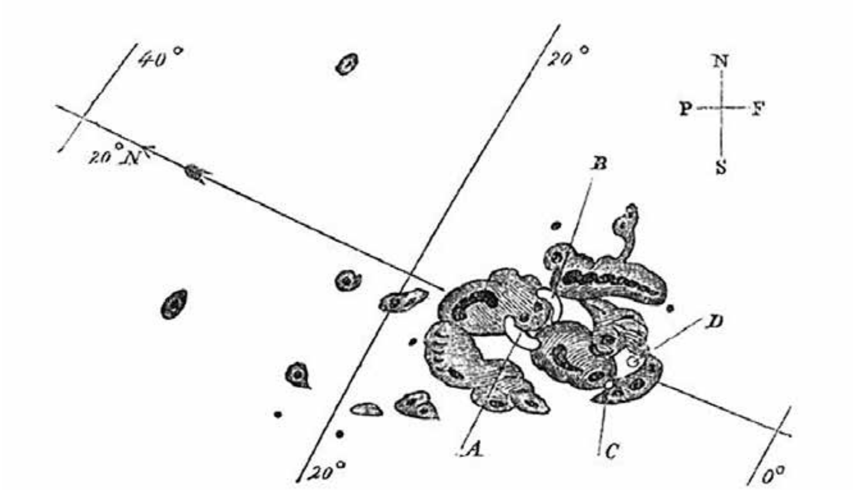
SPACE WEATHER AND SPACE CLIMATOLOGY

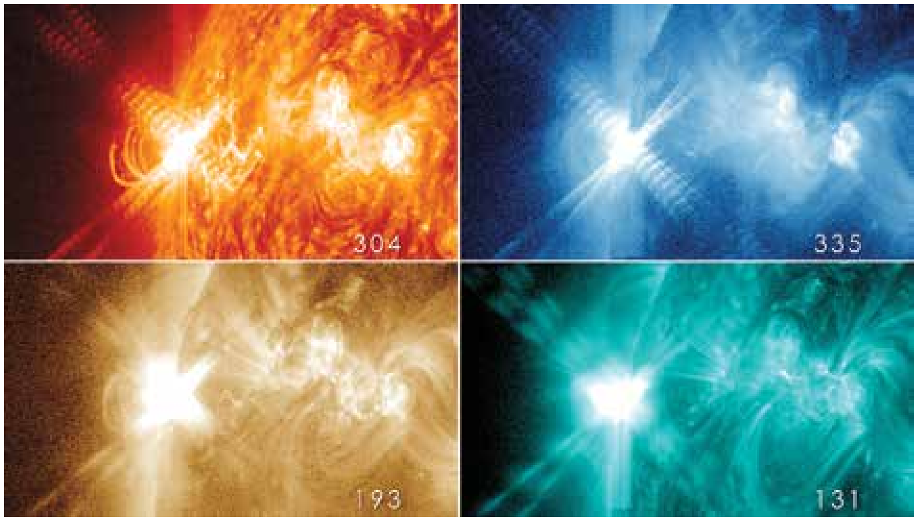
Just as severe or unexpected weather can disrupt economic and security-related activities throughout society, so too can space weather. The Sun's activity drives major fluctuations in Earth's environment on both long and short time scales. Severe solar storms can produce radiation and cause disturbances in the solar wind that may impact geospace for days.

Space weather storms rage through Earth's environment, intensifying the Van Allen radiation belts, distorting the ionosphere, and creating large fluctuations in the magnetic field at Earth's surface. These disturbances can damage spacecraft electronics, create a radiation hazard for astronauts, interfere with high-frequency radio communication, degrade GPS positioning and navigation, and disrupt electric power transmission.

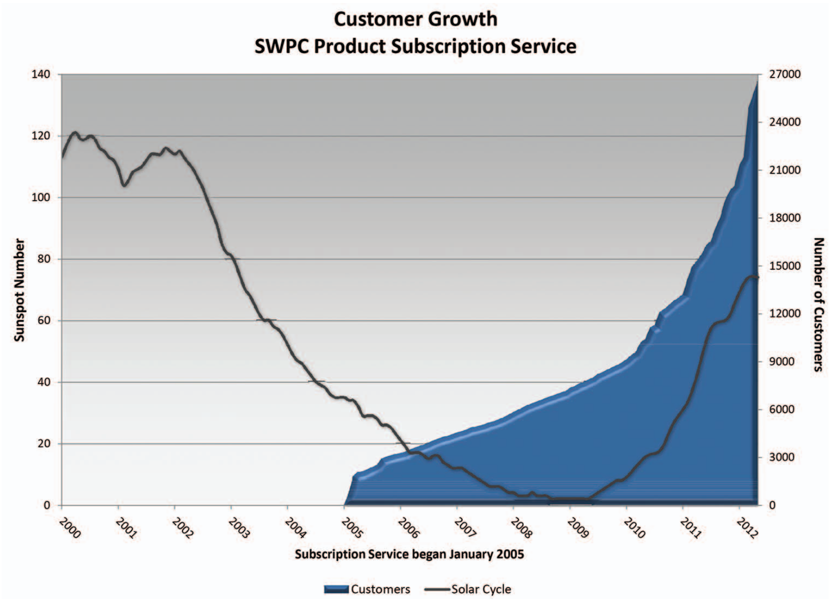
A comprehensive program consisting of observations, analyses, and numerical prediction models is essential to advancing space weather forecasting capabilities. Continuously observing the space environment is crucial, as is analyzing, interpreting, and distilling the data into meaningful operational products. The imperative to improve space weather prediction capabilities underlies much of the research recommended in the decadal survey. In addition, the nation requires applied research specifically focused on the development of applications with direct societal benefit. **To that end, the decadal survey recommends that NOAA establish a space weather research program to effectively transition research to operations and that distinct funding lines for basic space physics research and for space weather specification and forecasting be developed and maintained. The survey report also includes a recommendation to recharter the National Space Weather Program (NSWP: http:///www.nswp.gov), an interagency initiative to improve coordination of space weather services.**

Today, the Heliophysics System Observatory, supported by NASA, NSF, and NOAA, collects much of the information that is essential





(Top) Sunspots producing a solar flare that contributed to the massive 1859 storm, sketched by Richard Carrington. The Carrington event started fires in long-distance telegraphs and the auroras were seen nearly at the equator. (Bottom) A solar flare captured by NASA's Solar Dynamics Observatory on May 13, 2013, in multiple ultraviolet wavelengths showing structures at different temperatures. Radiation from flares has damaged and disabled spacecraft in Earth orbit and at Mars.



Number of unique customer subscribers routinely receiving space weather services electronically from NOAA's Space Weather Prediction Center (in blue).

to maintaining continuous knowledge of space weather conditions. NASA, NSF, NOAA, DoD, FEMA, and other federal agencies, as well as private groups use these and other sources of data worldwide to conduct research and to generate operational products and services. Enabled by advances in scientific understanding as well as fruitful interagency partnerships, the capabilities of models that predict space weather impacts on Earth have made rapid gains over the past decade. Reflecting these advances and the increasing vulnerability of society to the adverse effects of space weather, the number of users of real-time space weather information services has grown exponentially.

Routine space weather observations from science missions are indispensable for operational predictions. In particular, the solar wind upstream of Earth and remote observations of the Sun's corona and photosphere are essential. Therefore, **the decadal survey recommends that critical solar wind, coronagraph, and solar magnetic field observations be continuously available.** Maintaining funding for the long-term continuity of data needed for research and operational services, as well as for the historical database necessary for space climatology, remains a significant challenge. In addition to extensive U.S. efforts, international partnerships are an important factor in ensuring the availability of the comprehensive suite of required measurements and numerical models.

As research models and theories mature, forecasts are improving; however, critical limitations in capabilities are driving new research and innovation. To improve future predictive capability, **the decadal survey recommends that new observations, locations, and observing platforms be evaluated.** The interplay between research, observations, and operations is key to advancing national capability to predict space weather and to providing adequate knowledge of space climatology, both of which are increasingly imperative for the benefit of society.

EXPECTED BENEFITS OF THE RECOMMENDED PROGRAM

The decade 2003-2013 was a time of significant progress in all areas of solar and space physics. New spacecraft—such as the Van Allen probes, which discovered a third radiation belt—joined old spacecraft—like the venerable Voyagers, which continue to revolutionize our understanding of the solar system's edge—in an expanding and broadly capable research fleet. New observatories—such as the Solar Dynamics Observatory and the Advanced Modular Incoherent Scatter Radar in Alaska—vastly improved the spatial and temporal resolution with which we study the Sun-Earth environment.

Highlights from the past decade include new insights into the variability of the mechanisms that generate the Sun's magnetic field; a new understanding of the unexpectedly deep minimum in solar activity; significant progress in understanding the origin and evolution of the solar wind; striking advances in understanding of both explosive solar flares and the coronal mass ejections that drive space weather; and new imaging methods that permit direct observations of the space weather-driven changes in the particles and magnetic fields surrounding Earth and similar advances in remotely sensing the boundaries of the heliosphere; new understanding of the ways that space storms are fueled by oxygen originating in Earth's own atmosphere; and the surprising discovery that conditions in near-Earth space are linked strongly to the terrestrial weather and climate below.

Enabled by implementation of the program recommended in the 2013-2022 decadal survey, the coming decade of discovery promises potentially transformative scientific progress as researchers are poised to probe universal physical processes, to understand the complex dynamics of our home in the solar system, and to apply this understanding to forecast the threats posed to technological infrastructures by space weather events.

Advances Expected From Implementation of the Existing Program

- The Magnetospheric Multiscale mission (MMS) will provide the first high-resolution, three-dimensional measurements of magnetic reconnection in Earth's magnetosphere.
- Solar Probe Plus (SPP) will be the first spacecraft to enter the lower reaches of the Sun's atmosphere, repeatedly sampling coronal particles and fields to understand coronal heating, solar wind acceleration, and the formation and transport of energetic solar particles.
- The 4-meter Daniel K. Inouye Solar Telescope (formerly the Advanced Technology Solar Telescope) will resolve structures on the Sun as small as 20 km, revealing new dynamics of magnetic fields.
- Continued operation of the Heliophysics System Observatory will provide essential simultaneous observations from distributed vantage points of this highly interconnected system.

Advances Expected From New Programs and Missions

- The DRIVE initiative will greatly strengthen our ability to accomplish innovative observational, theoretical, numerical, modeling, and technological advances.
- A new funding line for mid-size projects at the National Science Foundation will facilitate long-recommended ground-based projects, such as FASR and COSMO, by closing the programmatic funding gap between large and small programs.
- Solar and space physicists will accomplish high-payoff, timely science goals with a revitalized Explorer program, including Missions of Opportunity.
- The notional Interstellar Mapping and Acceleration Probe (IMAP), in conjunction with the twin Voyager spacecraft, will better resolve the interaction between the heliosphere—our home in space— and the interstellar medium.
- The notional Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC) mission's two identical orbiting observatories will clarify the complex variability and structure in near-Earth plasma that is driven by lower atmospheric wave energy.
- The notional Geospace Dynamics Constellation (GDC) will provide the first simultaneous, multipoint observations of how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over local and global scales.
- A National Space Weather Program, re-chartered at a level of the federal government appropriate for strategic support and coordination, will bring agencies together to ensure continuity of measurements and improve space weather forecasting.

DECADAL SURVEY RECOMMENDATIONS

In its report, the survey committee's recommendations are prioritized and fit to anticipated budgets, which appear likely to be highly constrained for the foreseeable future. However, recognizing the importance of crafting a resilient program, the survey's authors also provide "decision rules" to guide programmatic changes, should they become necessary, in response to budget shortfalls or other unanticipated challenges.

In making its recommendations, the committee was guided by the following principles:

- To make transformational scientific progress, the Sun, Earth, and heliosphere must be studied as a coupled system;
- To understand the coupled system requires that each subdiscipline be able to make measurable advances in achieving its key scientific goals; and
- Success across the entire field requires that the various elements of solar and space physics research programs—the enabling foundation comprising theory, modeling, data analysis, innovation, and education, as well as ground-based facilities and small-, medium-, and large-class space missions—be deployed with careful attention to both the mix of assets and to the schedule (cadence) that optimizes their utility over time.

Tables 1 and 2 summarize the top-level recommendations of the decadal survey and indicate the agencies with primary responsibility for implementation. Although NASA and NSF were the sponsors of the decadal survey, it was conducted with the support of NOAA and the DoD. For further explanation of the recommendations and for full details on the recommended program and its implementation, please download the full report at http://www.nap.edu/catalog.php?record_id=13060.

TABLE 1 Summary of Top-Level Decadal Survey Research Recommendations

Priority	Recommendation	NASA	NSF	Other
1.0	Complete the current program	X	X	
2.0	Implement the DRIVE initiative	X	X	X
	Small satellites; midscale NSF projects; vigorous ATST and synoptic program support; science centers and grant programs; instrument development			
3.0	Accelerate and expand the Heliophysics Explorer program	X		
	Enable MIDEX line and Missions of Opportunity			
4.0	Restructure STP as a moderate-scale, PI-led line	X		
4.1	Implement an IMAP-like mission	X		
4.2	Implement a DYNAMIC-like mission	X		
4.3	Implement a MEDICI-like mission	X		
5.0	Implement a large LWS GDC-like mission	X		

TABLE 2 Summary of Top-Level Decadal Survey Applications Recommendations

Priority	Recommendation	NASA	NSF	Other
1.0	Recharter the National Space Weather Program	X	X	X
2.0	Work in a multiagency partnership to achieve continuity of solar and solar wind observations	X	X	X
2.1	Continue solar wind observations from L1 (DSCOVR, IMAP)	X		X
2.2	Continue space-based coronagraph and solar magnetic field measurements	X		X
2.3	Evaluate new observations, platforms, and locations	X	X	X
2.4	Establish a space weather research program at NOAA to effectively transition research to operations			X
2.5	Develop and maintain distinct funding lines for basic space physics research and for space weather specification and forecasting	X	X	X

Adapted from Tables S.1 and S.2 from *Solar and Space Physics* (2013), with the research recommendations renumbered.

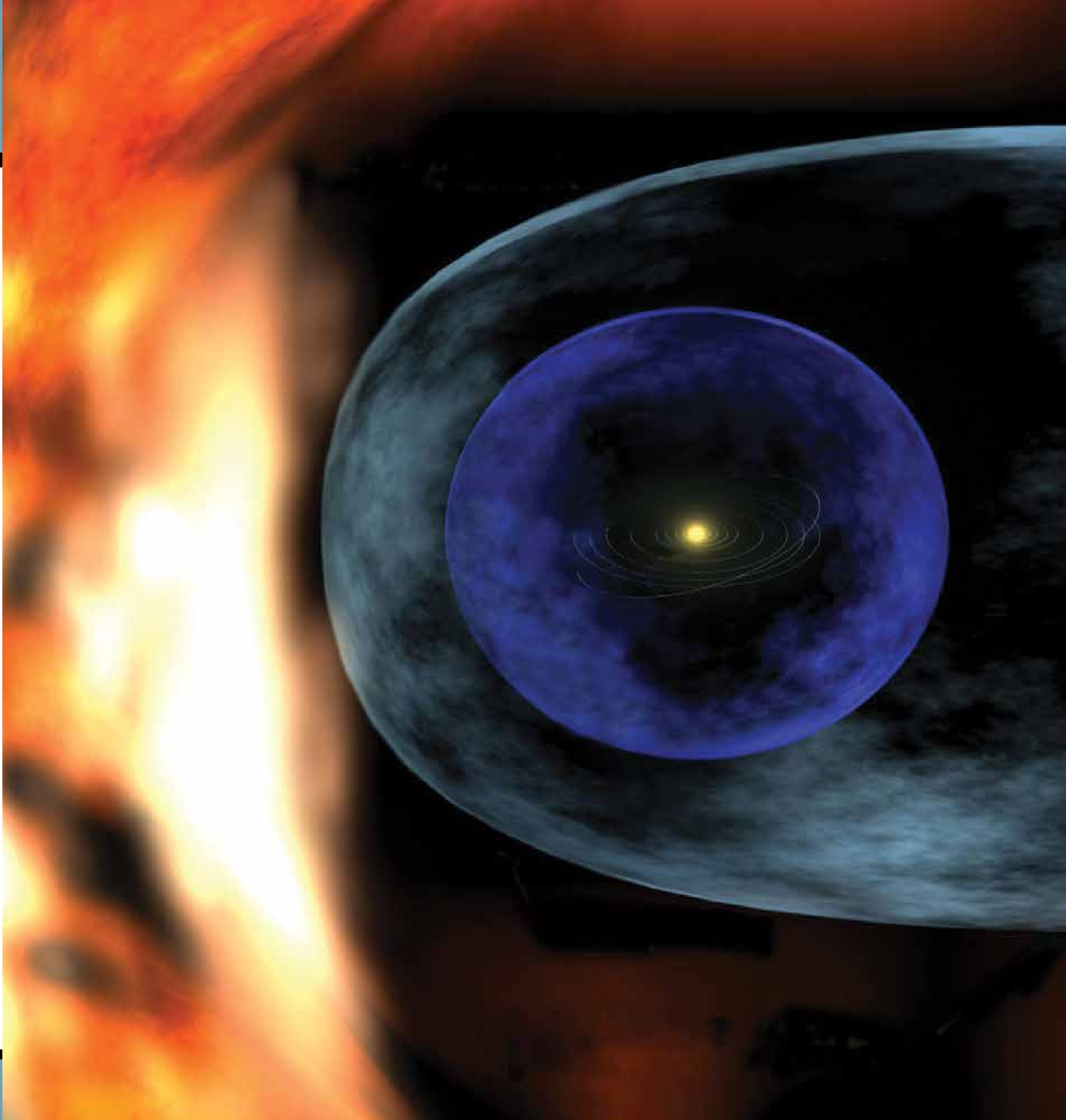


IMAGE CREDITS AND SOURCES:

Page 1	NASA.
Page 2	NASA.
Page 3	NASA/IBEX/Adler Planetarium.
Pages 4-5	NOAA Space Weather Prediction Center.
Page 6	*Top*, M. Rempel, High Altitude Observatory. Bottom, Big Bear Solar Observatory. For further information on the simulation, see M. Rempel, Numerical sunspot models: Robustness of photospheric velocity and magnetic field structure, *Astrophysical Journal* 750(1):62, 2012.
Page 7	J.T. Karpen, S.K. Antiochos, and C.R. DeVore, The mechanisms for the onset and explosive eruption of coronal mass ejections and eruptive flares, *Astrophysical Journal* 760:81, 2012. Reproduced by permission of the AAS.
Page 9	NASA.
Page 10	Anthia Coster, MIT and Evan Thomas, Virginia Tech.
Page 11	National Institute of Information and Communications Technology.
Page 12	M. Druckmüller, M. Dietzel, S. Habbal, and V. Rušin; available at http://www.predsci.com/corona/jul10eclipse/jul10eclipse.html.
Page 13	NASA/GSFC.
Page 14	*Left to right*: National Research Council, *Solar and Space Physics: A Science for a Technological Society*, The National Academies Press, Washington, D.C., 2013; the Ionospheric Connection Explorer (ICON), scheduled for launch in late 2016, will investigate how large-scale patterns in our weather system affect the near-Earth space environment (University of California, Berkeley, Space Sciences Laboratory); see page 23 credit; see page 16 credit; L. Phelps and National Solar Observatory/AURA/NSF.
Page 16	Johns Hopkins University Applied Physics Laboratory.
Page 17	*Top:* NRC, *Solar and Space Physics*, 2013; *Bottom:* NASA.
Page 18	NRC, *Solar and Space Physics*, 2013.
Page 21	NASA.
Page 23	D. McComas, Southwest Research Institute (SwRI), based on Adler Planetarium/SwRI/NASA image from D.J. McComas, F. Allegrini, P. Bochsler, M. Bzowski, E.R. Christian, G.B. Crew, et al., Global observations of the interstellar interaction from the Interstellar Boundary Explorer (IBEX), *Science* 326:959-962, 2009, doi:10.1126/science. 1180906, with mock Interstellar Mapping Probe (IMAP) data taken from taken from Wilkinson Microwave Anisotropy Probe (WMAP), courtesy of GSFC/Princeton/UofC/UCLA/UBC/Brown/NASA).
Page 25	*Central image*: Joe Grebowsky, NASA GSFC; *surrounding images:* Robert Pfaff, NASA/GSFC and Thomas Immel, University of California, Berkeley; “magnetic fields” image adapted from Bryan Brandenburg, http://www.bryanbrandenburg.net.
Page 26	*Top*: R.C. Carrington, Description of a singular appearance seen in the Sun on September 1, 1859, *Monthly Notices of the Royal Astronomical Society* 20:13-15, 1859. *Bottom*: NASA Solar Dynamics Observatory.
Page 27	Updated from E. Hildner, H. Singer, and T. Onsager, Space weather workshop: A catalyst for partnerships, *Space Weather* 9:S03006, 2011, doi:10.1029/2011SW000660.

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