National Aeronautics and Space Administration

heliophysics: the science of space weather

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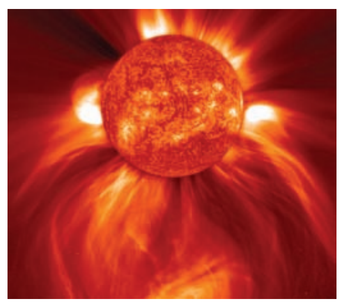
Space Weather at NASA

The National Aeronautics and Space Act of 1958 was a United States federal law that created the National Aeronautics and Space Administration to provide for research into problems of flight within and outside Earth's atmosphere, and for other purposes. Space exploration has transformed our understanding of the solar system. It has revealed a fascinating system of systems, so closely connected that an explosive event on the sun produces measurable effects that span the entire solar system. As we approach the 50th anniversary of NASA, we have established an extensive suite of spacecraft and observatories, known as the "Heliophysics Great Observatory," which places us on the verge of a system-wide understanding of the entire interconnected Sun-Earth system. Using the missions of the Heliophysics Great Observatory, we have achieved system surveillance over parts of the heliosphere and have been able to examine causal linkages between its elements. In late 2003 we observed spectacular solar activity, power outages on the Earth, degradation of spacecraft solar panels and circuits, destruction of atmospheric ozone, inflation and ablation of planetary upper atmospheres, fatal damage to instrumentation in Mars orbit, auroral displays on Saturn, and months later, radio disturbances at the edge of the solar system where it meets the interstellar medium. In short, we have observed that space contains weather and that it can affect us. Heliophysics is the science of space weather. It unites the disciplines that study the linked phenomena in the region of space influenced by the Sun, our star.

The Variable Sun

Looking at the sky with the naked eye, the Sun seems static, placid, and constant. But our Sun gives us more than just a steady stream of warmth and light. The Sun regularly bathes us and the rest of our solar system in energy in the forms of light and electrically charged particles and magnetic fields. The result is what we call space weather. The Sun is a huge thermonuclear reactor, fusing hydrogen atoms into helium and producing million degree temperatures and intense magnetic fields. The outer layer of the Sun near its surface is like a pot of boiling water, with bubbles of hot, electrified gas—electrons and protons in a fourth state of matter known as plasma—circulating up from the interior and bursting out into space. The steady stream of particles blowing away from the Sun is known as the solar wind.



Blustering at 800,000 to 5 million miles per hour, the solar wind carries a million tons of matter into space every second (that's the mass of Utah's Great Salt Lake) and reaches well beyond the solar system's planets. Its speed, density and the magnetic fields associated with that plasma affect Earth's protective magnetic shield in space (the magnetosphere). Most of the time the effects are benign, but when sunspots appear, it is a potential sign of a space weather storm. Sunspots are dark splotches on the Sun caused by the appearance of cooler (4000° C) areas amidst the roiling gases on the surface (6000° C). Space weather forecasters closely watch sunspots because, like high and low pressure systems on Earth, they hold signs of the severity of what's to come.

The solar magnetic field changes on an 11-year cycle. Every solar cycle, the number of sunspots and solar storms increases to a peak, known as the solar maximum. Then, after a few years of high activity, the Sun will ramp down for a few years of low activity, known as the solar minimum.

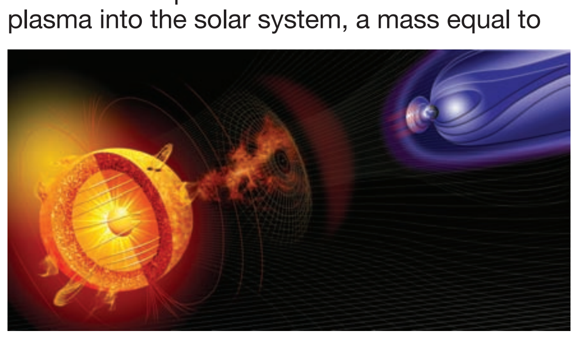
Solar Storms

Solar flares and coronal mass ejections (CMEs) are two kinds of solar storms. Solar flares appear as explosive bright spots on the surface of the Sun. Flares occur when magnetic energy built up in the solar atmosphere near a sunspot is suddenly released in a burst equivalent to ten million volcanic eruptions. Radiation—including radio waves, X rays, and gamma rays—and electrically charged particles blast from the Sun following a solar flare. The strongest flares occur just several times per decade, while weaker flares are relatively common, with as many as a dozen a day during the Sun's most active periods.

A CME is the violent eruption of a huge magnetic cloud of plasma from the Sun's outer atmosphere, or corona. The corona is the gaseous region above the surface that extends millions of miles into space. Temperatures in this region exceed one million degrees Celsius, 200 times hotter than the surface of the Sun.

A number of theories attempt to explain the occurrence of a CME. The magnetic fields in the corona are affected by both new fields emerging from below the surface and by the motions of the plasma at the surface, which carry the fields with them. They can become twisted, and thus energized in localized regions, often creating sunspots. Overlying magnetic fields are like a net holding down a hot-air balloon, restraining the plasma and twisted magnetic fields. Tremendous upward pressure builds. Eventually, some of the magnetic loops merge and burst through the magnetic net, creating a CME.

Observations show that a CME travels through the gulf of space at speeds of up to several million miles per hour (up to 2500 km/sec)! A typical CME can compact more than 10 billion tons of plasma into the solar system, a mass equal to

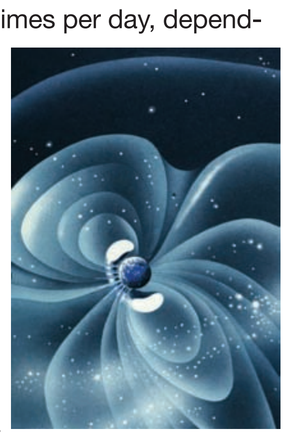


that of 100,000 battleships. A CME cloud typically grows to as wide as 30 million miles across. As it hits the solar wind, a CME can create a shock wave that accelerates some of the solar wind's particles to dangerously high energies and speeds that create radiation in the form of energetic particles.

Behind that shock wave, the CME disturbance travels through the solar system, impacting planets, asteroids, and other objects with enhanced plasmas and magnetic fields. If a CME erupts on the side of the Sun facing Earth, and if its path includes the location of Earth in its orbit, the results can be spectacular and sometimes hazardous.

Space Weather Events

Earth inevitably gets hit by CMEs from time to time because CMEs occur at a rate of a few times a week to several times per day, depending on how active the Sun is. Fortunately, our planet is protected from the most harmful effects of the radiation and hot plasma by our atmosphere and by an invisible magnetic shell known as the magnetosphere. Produced by Earth's internal magnetic field, the magnetosphere shields us from 99% of the Sun's plasma by deflecting it into space. But some magnetic energy is transferred from the solar wind and CMEs to our magnetosphere, often funneling in near the North and South Poles, where the magnetic field lines meet the surface and the magnetosphere is partially open to space. The flow of energy into our magnetosphere can induce geomagnetic storms, alter Earth's magnetic field as measured on the ground, and produce the phenomena known as auroras.



A lot of energy is being dumped into the Earth's magnetic system. When stimulated by plasma from the Sun or from the far reaches of the magnetosphere, the electrons, protons, and oxygen ions surrounding Earth become denser, hotter, and faster. These particles produce as much as a million amperes of electrical current. Some of that current flows along Earth's magnetic field lines and into the upper atmosphere.

Also, excited particles inside the magnetosphere can plunge into the upper atmosphere, where they collide with oxygen and nitrogen. These collisions—which usually occur between 40 and 200 miles above ground—electrically excite the oxygen and nitrogen so that they emit light. The result is a dazzling dance of green, blue, white, and red light in the night sky, also known as aurora borealis and aurora australis ("Northern and Southern lights"). Auroras are visible evidence that something electric is happening in the space around Earth.

Space Weather Effects

Aside from bright auroras, there are more damaging effects of space weather. With the average CME dumping about 1500 Gigawatts of electricity into the atmosphere (double the power generating capacity of the entire United States), dynamic changes can occur in space.

Those changes adversely affect our societal infrastructure that depends on satellites, electrical power, and radio communication—all of which can be damaged and disrupted by magnetic storms. For example, a series of flares and CME in March 1989 produced intense magnetic storms that left millions of people in Quebec, Canada without power for many hours.

For the satellites orbiting through the Earth's radiation belts and the solar wind, CMEs and magnetic storms can be especially perilous. Energetic ions accelerated by a storm can degrade the solar panels used to power satellites and can upset computers on spacecraft. In 1994, two satellites were shut down during magnetic storms–telephone service across Canada was disrupted for months. Since 1996 solar storms have disrupted at least 14 satellites, causing billions of dollars in losses.

Magnetic storms also distort radio signals, which are bounced off Earth's ionosphere (the outermost layer of our atmosphere) as a sort of natural relay station. Magnetic storms can completely wipe out radio communication around Earth's poles for days. Communications from ground to satellites and back are also interrupted due to the effect of the disturbed state of the ionosphere on those signals. So much modern information is relayed by satellite, from GPS to automated teller machines, that even day-to-day business disruptions can occur.

On the ground, magnetic storms affect the strength of Earth's magnetic fields. The changes in the field can produce surges in power lines and transformers, and corrosive electrical currents in gas and oil pipelines.

Astronauts live and work in space on the International Space Station, and even when they are inside, they can get high doses of radiation during solar storms. In one week an adult can get the equivalent of 100 chest X-rays. With plans for astronauts to travel to the Moon and eventually to Mars, NASA is currently developing methods for forecasting, tracking solar storms, and providing shielding for astronauts who are exposed to space weather on a daily basis.

Except for the Apollo missions to the Moon, NASA's manned spaceflight missions have taken place within the cocoon of the Earth's magnetosphere. Between the Apollo 16 and 17 missions, one of the largest solar proton events ever recorded occurred, and it produced radiation levels of sufficient energy for the astronauts outside of the Earth's magnetosphere to absorb lethal doses within 10 hours after the start of the event. It is indeed fortunate that the timing of this event did not coincide with one of the Apollo missions. As NASA embarks on the journey of exploration to the Moon, Mars, and beyond, radiation protection for crew members remains a key technological issue.

Space weather is also a concern for the aviation industry, especially since the number of cross-polar flights has increased. Risks during high latitude and polar operations are of primary concern since the impacts of space weather can be greatest in these regions.

Solar variability can also cause changes in Earth's climate. Global cooling during the Ice Ages was partially caused by changes in the distribution and amount of sunlight that reached the Earth. During the last Ice Age, the globally averaged temperature of Earth was about 6°C colder than it is today. This may not sound like much, but the effect covered large parts of Canada, Alaska, and Siberia with huge sheets of ice up to a mile thick. It is clear that human activity is changing Earth's climate today, but solar activity may also contribute in small part to climate change and may have changed the climate in the past. In order to accurately predict how future human activities will change Earth's climate, it is critical that we understand the Sun's natural variations.

As society's reliance on technological systems grows, so does our vulnerability to space weather.

Studying Space Weather

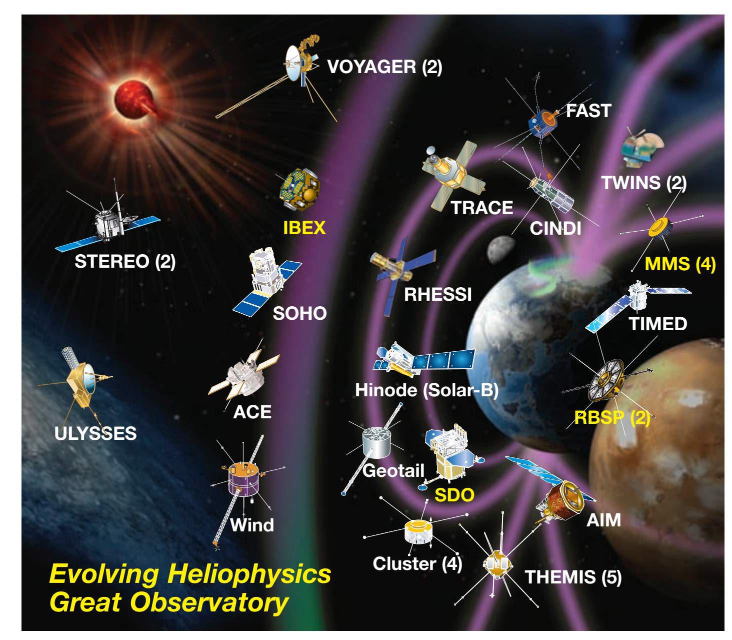
Auroras are a visible sign of the magnetic activity in our atmosphere, but beyond that, the human eye can't detect much of what we call space weather. In order to see the "unseeable", space researchers rely on missions and instrumentation from NASA's Heliophysics Great Observatory. Telescopes are used to detect visible light, ultraviolet light, gamma rays, and X rays. They use receivers and transmitters that detect the radio shock waves created when a CME crashes into the solar wind and produces a shock wave. Particle detectors to count ions and electrons, magnetometers record changes in magnetic fields, and UV and visible cameras observe auroral patterns above the Earth.

Currently the Heliophysics Great Observatory includes a fleet of satellites that study the Sun, the heliosphere, Earth, and other planetary environments as elements of a system—one that contains dynamic space weather and evolves in response to solar, planetary, and interstellar variability. The Solar and Heliospheric Observatory (SOHO) continues to observe the Sun 24 hours a day and after over 10 years in space, it has led to major advances in our understanding of space weather. The Advanced Composition Explorer (ACE) provides near real time 24/7 continuous coverage of solar wind speeds and composition and solar energetic particle intensities (space weather). ACE gives us an advanced warning of about one hour of potentially dangerous geomagnetic storms.

As new sets of scientific problems are resolved, new mysteries emerge and the Heliophysics Great Observatory evolves with the addition of new spacecraft. The two STEREO spacecraft are providing the first stereoscopic views of the Sun and inner heliosphere. The five THEMIS spacecraft are studying the mystery of what triggers geomagnetic substorms, the atmospheric events visible in the Northern Hemisphere as a sudden brightening of the Northern Lights, or aurora borealis. The Two Wide-angle Imaging Neutral-atom Spectrometers (TWINS) mission will provide stereoscopic views of the Earth's magnetosphere and the Coupled Ion-Neutral Dynamics investigation (CINDI) experiment, flying on a U.S. Air Force C/NFOS satellite, will measure space weather events in the low latitude ionosphere that can disrupt radio signals. NASA is also providing communication services for C/NOFS via the Tracking and Data Relay Satellite System (TDRSS).

In 2009, the Solar Dynamics Observatory (SDO) will image the Sun's interior, surface, and atmosphere from geosynchronous orbit and the Interstellar Boundary Explorer (IBEX) mission will remotely sense the interaction between the solar wind and the interstellar medium, complementing the measurements now being obtained by the Voyager and STEREO missions.

In the near term, observing the terrestrial response to solar activity, the Radiation Belt Storm Probes (RBSP) will investigate the processes that accelerate particles to hazardous radiation levels.



NASA Space Weather Programs and Activities

Heliophysics

The Heliophysics program aims to explore the Sun-Earth system to understand the Sun and its effects on Earth, the solar system, and the space environmental conditions that will be experienced by explorers, and to demonstrate technologies that can improve future operational systems. Heliophysics science objectives include: Opening the Frontier to Space Weather Prediction, Understanding the Nature of Our Home in Space, and Safeguarding the Journey of Exploration. These goals are being accomplished by studying the Sun, the heliosphere, and planetary environments as elements of a single connected system, one that contains dynamic space weather and evolves in response to solar, planetary, and interstellar conditions.
http://nasascience.nasa.gov/heliophysics

Living With a Star (LWS)

LWS is a space weather-focused and applications driven research program. Its goal is to develop the scientific understanding necessary to effectively address those aspects of the Sun and Solar System that directly affect life and society. The Program elements are a series of inter-related science missions, a targeted theory, modeling, and data analysis program, and space environment testbeds.
http://lws.gsfc.nasa.gov & http://lwsscience.gsfc.nasa.gov

Solar Terrestrial Probes (STP)

The STP program consists of missions that address fundamental science questions about the physics of space plasmas and the flow of mass and energy through the solar system. They focus on specific scientific areas required to advance our fundamental understanding of the Sun.
http://stp.gsfc.nasa.gov

Scientific Research and Analysis

Supporting Research and Technology (SR&T) comprises an ever-evolving suite of individual PI-proposed investigations that cover the complete range of science disciplines and techniques essential to achieve the Heliophysics Division objectives. The Theory Program supports larger PI-proposed team efforts that require a critical mass of expertise in order to make significant progress in understanding complex physical processes.

LWS Targeted Research and Technology Program (TR&T) uniquely satisfies two critical LWS needs. First, it tackles the major LWS science problems that cross the usual boundaries between scientific disciplines and between research techniques. Second, TR&T develops the specific, comprehensive models required to understand the LWS system, in particular those that can serve as prototypes for operational forecasting and nowcasting.
http://lwstrt.gsfc.nasa.gov

Space Radiation Analysis Group (SRAG)

Radiation protection is essential for humans to live and work safely in space. The goal of NASA's Radiation Health Program is to achieve human exploration and development of space without exceeding acceptable risk from exposure to ionizing radiation. The Space Radiation Analysis Group (SRAG) at the NASA's Johnson Space Center is responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits.

The SRAG has provided real-time flight operational support to every manned spaceflight program since the project Mercury flights. Currently the SRAG provides 365 day-a-year support for the International Space Station (ISS) and Space Shuttle (SSP) programs from Mission Control, Houston (MCC-H), as well as providing support and guidance for the Constellation program through system management and operations integration.
http://srag.jsc.nasa.gov/

International Living With a Star (ILWS)

International Living With a Star (ILWS) is a cooperative program in solar-terrestrial physics and a follow-on to the highly successful International Solar Terrestrial Physics (ISTP) program. NASA is an ILWS contributing agency along with space science agencies from more than 25 other countries. The charter of ILWS is to stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity.
http://ilws.gsfc.nasa.gov

International Heliophysical Year (IHY)

International Heliophysical Year (IHY) 2007 marked the 50th Anniversary of the International Geophysical Year (IGY) and 50 years of space exploration. In 2007, the world's science community came together for an international program of scientific collaboration: the International Heliophysical Year (IHY).
http://www.ihy2007.org

National Space Weather Program

The National Space Weather Program (NSWP) is an interagency initiative to speed improvement of space weather services. It emerged in 1994 and is a collaborative enterprise between NASA and six other federal agencies. NASA contributes to the overarching goal of the NSWP by continuing its traditional role of space exploration and study of the solar-terrestrial system.

NASA's missions in space physics, current and planned, are designed to fulfill important complementary requirements: to answer specific scientific questions; to improve and advance our empirical understanding of events and conditions in space; and to develop and use new technology. Activities include conducting remote sensing and in situ spaceflight missions for collection of new scientific data sets, the development of advanced numerical models for interpretation of these data, and the creation of national-class archives for scientific products and results.
http://www.nswp.gov

Community Coordinated Modeling Center (CCMC)

The CCMC is an inter-agency activity aimed at research in support of the generation of advanced space weather models. CCMC provides a mechanism by which research models can be validated, tested, and improved for eventual use in space weather forecasting. CCMC also provides to researchers the use of space science models through the execution of model "runs-on-request" for specific events of interest.
http://ccmc.gsfc.nasa.gov

Heliophysics Summer School

NASA and the University Corporation for Atmospheric Research (UCAR) Visiting Scientist Programs are sponsoring the Heliophysics Summer School. This series of three summer schools in 2007, 2008, and 2009 will help students and senior scientists learn and develop the basic science of Heliophysics and produce textbooks for use at universities worldwide.
http://www.vsp.ucar.edu/HeliophysicsSummerSchool/index.html

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