

THE *FURY* OF SPACE STORMS

SHOCK WAVES FROM THE SUN CAN TRIGGER SEVERE TURBULENCE IN THE SPACE AROUND THE EARTH, ENDANGERING SATELLITES AND ASTRONAUTS IN ORBIT. NOW A NEW SPACECRAFT IS SHOWING HOW SPACE STORMS DEVELOP
BY JAMES L. BURCH

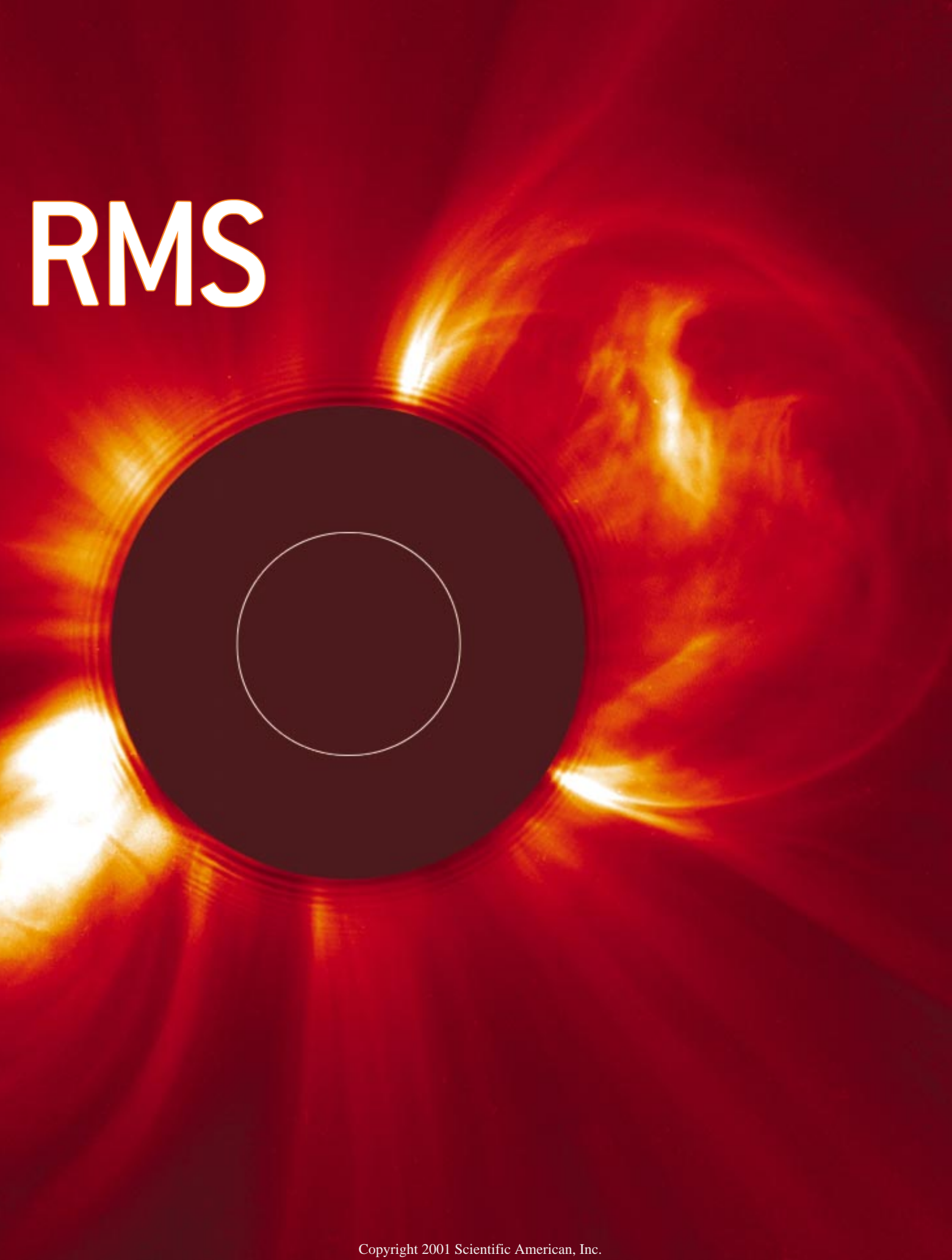
T

HE TEMPEST BEGAN ON A DATE KNOWN FOR ITS VIOLENT EVENTS: Bastille Day, the anniversary of the beginning of the French Revolution. On the morning of July 14 last year, the Space Environment Center in Boulder, Colo., detected a warning sign from the GOES-8 satellite, which monitors x-rays from the sun as well as weather conditions on the earth. At 10:03 Universal Time the center's forecasters saw a sharp jump in the intensity of x-rays emanating from active region 9077, a section of the sun's surface that had been roiling for the past week. The data indicated the onset of a solar flare, a brief but powerful burst of radiation.

The flare, which reached its maximum intensity at 10:24 UT, was also sighted by the Solar and Heliospheric Observatory (SOHO), a spacecraft stationed between the sun and the earth, about 1.5 million

VIOLENT ERUPTION in the sun's outer atmosphere on November 8, 2000, spewed billions of tons of charged particles toward the earth. The event was observed by the Solar and Heliospheric Observatory (SOHO); the spacecraft's coronagraph uses a disk (*dark circle*) to block direct light from the sun (*white circle*) so that its atmosphere can be seen.

RMS



kilometers from our planet. Half an hour later, as the flare was waning, SOHO observed an even more ominous phenomenon: a bright, expanding cloud that surrounded the sun like a halo. It was a coronal mass ejection (CME), an eruption in the corona—the sun’s outer atmosphere—throwing billions of tons of electrically charged particles into interplanetary space. The halo signature meant that the particles were heading directly toward the earth, at an estimated speed of 1,700 kilometers per second.

As the CME plowed into the solar wind—the flow of ionized gas continuously streaming from the sun—it created a shock wave that accelerated some charged particles to even higher velocities. In less than an hour a deluge of high-energy protons struck SOHO, temporarily blinding its instruments. The bombardment also damaged the spacecraft’s solar arrays, causing a year’s worth of degradation in 24 hours. But this torrent of particles was only the leading edge of the squall. The CME-driven shock wave arrived the next day, slamming into the earth’s magnetic field at 14:37 UT. The impact marked the start of a severe geomagnetic storm, whose full fury was unleashed by the arrival, a few hours later, of the CME itself. According to the index of geomagnetic activity used by the Space Environment Center, the Bastille Day storm was the largest such event in nearly a decade.

Most people on the ground were completely unaware of the celestial fireworks, but researchers were following the tempest

closely, collecting data from instruments on the earth and in space. Among the satellites tracking the storm was the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), which the National Aeronautics and Space Administration had launched just four months earlier. IMAGE is the first satellite dedicated to obtaining global images of the magnetosphere, the region of space protected by the earth’s magnetic field. By providing an overall picture of the activity in the magnetosphere, IMAGE does for space what the first weather satellites did for the earth’s atmosphere.

In 1996 I had been selected by NASA to lead a team of engineers and scientists in developing the IMAGE spacecraft and analyzing the data that it transmits. As the Bastille Day storm progressed, we received astounding images of ions circling the earth and pictures of the brilliant aurora borealis—the Northern Lights—that occurred when the charged particles struck the upper atmosphere. The results will help scientists answer long-standing questions about how CMEs and the solar wind interact with the earth’s magnetosphere. The findings may also have practical applications. Space storms can disable satellites, threaten the safety of astronauts and even knock out power grids on the ground [see box at left]. Indeed, the Bastille Day storm caused the loss of the Advanced Satellite for Cosmology and Astrophysics, an x-ray observatory launched in 1993 by the Japanese space research agency. In hopes of mitigating such effects in the future, scientists are keenly interested in improving the accuracy of space weather forecasts.

OVERVIEW THE EFFECTS OF SPACE STORMS

DURING GEOMAGNETIC STORMS, charged particles swirl around the earth and bombard the upper atmosphere, particularly at the higher latitudes. The gusts of particles can have severe effects on:

■ **POWER GRIDS.** As electrons cascade toward the earth, they create a strong current in the upper atmosphere called the auroral electrojet. This current causes fluctuations in the geomagnetic field, which can induce electrical surges in power lines on the ground. During an intense geomagnetic storm on March 13, 1989, a surge knocked out the Hydro-Quebec power grid, plunging large parts of Canada into darkness.

■ **SATELLITES.** When particles strike a satellite, the craft’s surface becomes charged. This buildup sometimes triggers sparks that can short-circuit the satellite’s electronics. Also, space storms heat the earth’s atmosphere, causing it to expand. If the atmospheric density at a satellite’s orbit becomes high enough, friction will slow the craft and drag it downward. This process led to the premature fall of Skylab in 1979.

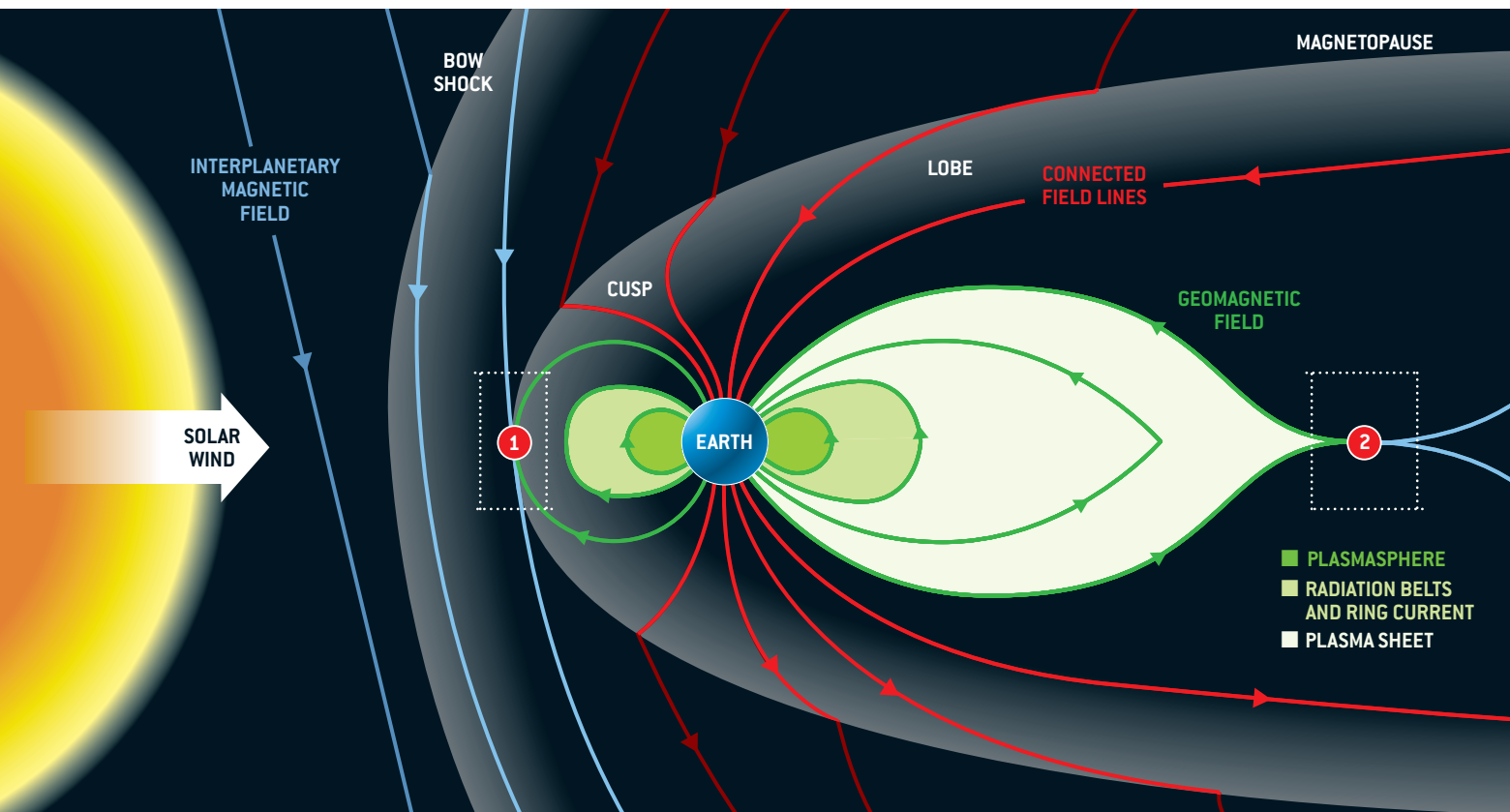
■ **ASTRONAUTS.** A severe storm could expose the International Space Station to protons that could penetrate a spacesuit or even the station’s walls. To protect its astronauts, NASA monitors space weather data. If an oncoming storm poses a risk, NASA will postpone or cancel any planned space walks and may order the astronauts to seek shelter in a shielded part of the station.

It’s Not the Heat or the Humidity

LIKE WEATHER ON THE EARTH, weather in space is extremely variable. Conditions can turn from quiet to stormy in a matter of minutes, and storms can last for hours or days. And just as terrestrial weather changes with the seasons, space weather, too, follows its own cycles. Solar magnetic activity, which causes flares and CMEs, rises and falls every 11 years, and therefore geomagnetic storms follow the same pattern. The Bastille Day storm took place during the solar maximum, the most active part of the cycle. Space weather also varies, though less dramatically, according to the sun’s 27-day rotation period, as alternating streams of fast and slow solar wind sweep past the earth.

Space weather, however, arises from physical processes that are profoundly different from those responsible for terrestrial weather. The medium for terrestrial weather is the dense, electrically neutral gas in the earth’s lower atmosphere, whose behavior is governed by the laws of fluid dynamics and thermodynamics. The medium for space weather, in contrast, is plasma—very sparse gases consisting of equal numbers of positively charged ions and negatively charged electrons. Unlike the atoms and molecules of the atmosphere, these plasma particles are subject to the influence of electric and magnetic fields, which guide and accelerate the particles as they travel through the space surrounding the earth.

Terrestrial weather is driven by the sun’s radiation as it heats the earth’s atmosphere, oceans and landmasses. But in the



DISTURBANCES IN THE MAGNETOSPHERE occur when the interplanetary magnetic field (IMF) carried by the solar wind turns southward. In a process called reconnection, the field lines of the IMF connect with the northward geomagnetic field lines at the dayside of the magnetopause [1]. Energy and particles from the solar wind rush into the magnetosphere, enlarging its northern and southern lobes and narrowing the plasma sheet. Then the geomagnetic field lines themselves reconnect [2], accelerating ions and electrons toward the earth.

magnetosphere, weather results from the interaction between the earth's magnetic field and the solar wind. The solar wind has its own magnetic field, which travels with the outflowing plasma into interplanetary space. As the wind carries this interplanetary magnetic field (IMF) away from the sun, the field lines typically stretch out so that they are directed radially (pointing toward or away from the sun). Under certain conditions, however, the IMF's field lines can tilt out of the equatorial plane of the sun, taking on a northward or southward component. A strong and sustained southward IMF direction is a key factor in triggering geomagnetic storms. The IMF was oriented southward for many hours during the Bastille Day storm.

Protons are the dominant constituents of the solar wind, accounting for about 80 percent of its total mass. Helium nuclei make up about 18 percent, and trace quantities of heavier ions are also present. The average density of the solar wind at the earth's orbit is nine protons per cubic centimeter. The wind's average velocity is 470 kilometers per second, and the average strength of the IMF is six nanoteslas (about one five-thousandth the strength of the earth's magnetic field at the planet's surface). These properties, along with the orientation of the IMF, are

highly variable, and it is this variability that ultimately explains the changing weather in space.

All the bodies in the solar system are immersed in the solar wind, which continues flowing outward until it encounters the ionized and neutral gases of interstellar space. The solar wind does not impinge directly on the earth and its atmosphere, however. The earth is shielded by its magnetic field, which forms a kind of bubble within the stream of charged particles emanating from the sun. The shape of this cavity—the magnetosphere—is determined by the pressure of the solar wind and by the IMF [see illustration above]. The wind compresses the earth's magnetic field on the dayside of the planet—the side facing the sun—and stretches the field on the nightside to form a long tail resembling that of a comet. This magnetotail extends more than one million kilometers past the earth, well beyond the orbit of the moon.

Between the solar wind and the magnetosphere is a thin boundary called the magnetopause, where the pressure of the geomagnetic field balances that of the solar wind. On the earth's dayside, this boundary is usually located about 64,000 kilometers from the planet's center, although the distance varies

with changes in the solar-wind pressure. When the pressure increases, as occurred during the Bastille Day storm, the dayside magnetopause is pushed closer to the earth, sometimes by as much as 26,000 kilometers.

Just as the passage of a supersonic jet through the atmosphere produces a shock wave, the encounter of the solar wind with the magnetosphere forms a shock wave—known as the bow shock—some 13,000 kilometers upstream (that is, closer to the sun) from the dayside magnetopause. The region of solar-wind plasma between the bow shock and the magnetopause is known as the magnetosheath. Because of its passage through the shock, the magnetosheath plasma is slower, hotter and more turbulent than the plasma farther upstream.

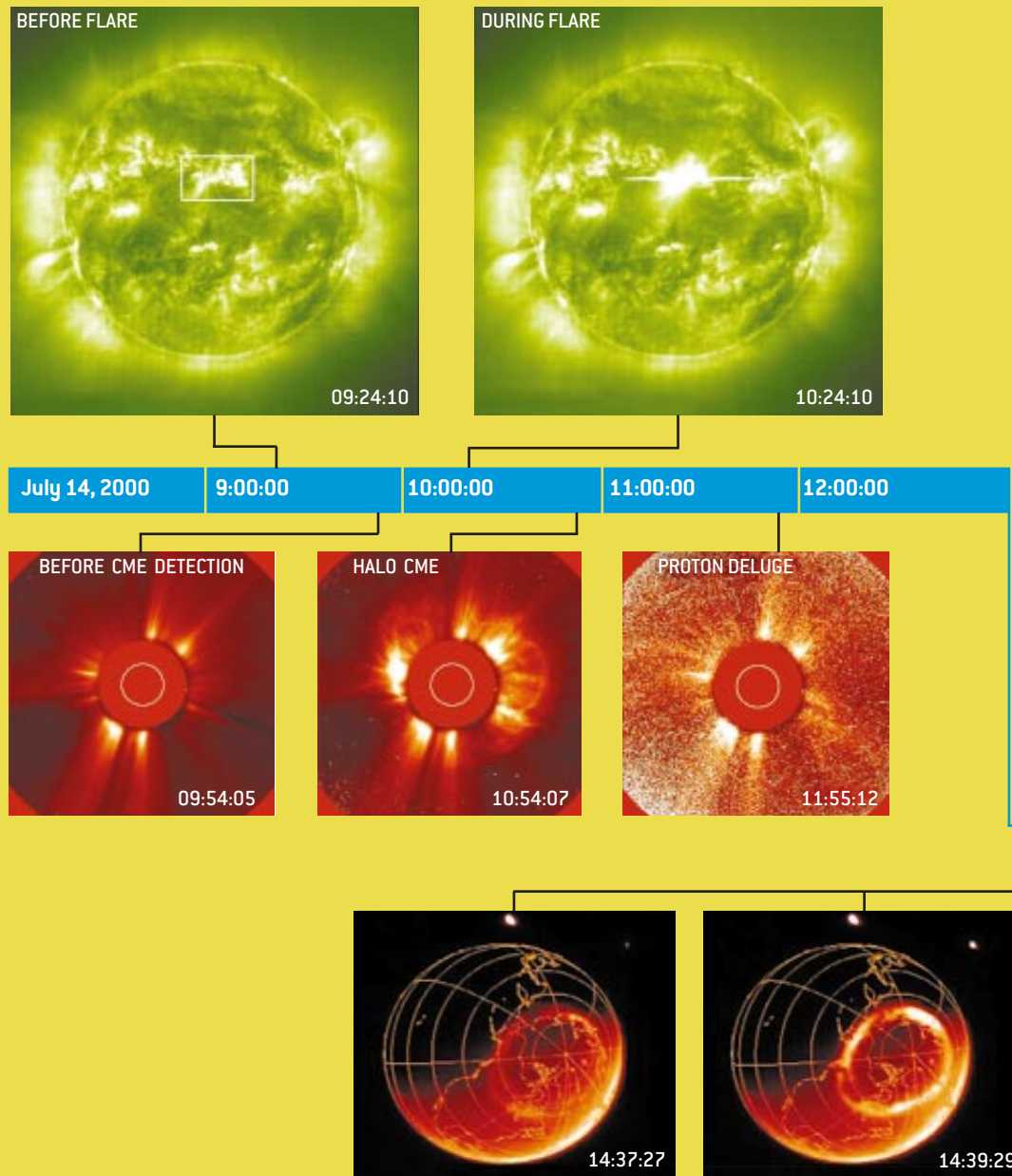
Satellite detectors have indicated that the charged particles

surrounding the earth are a mix of plasma from the magnetosheath (mostly protons) and plasma that flows out of the upper atmosphere above the North and South poles (mostly protons and oxygen ions). The proportions of this mix vary according to whether the magnetosphere is in a quiet or a disturbed state. During geomagnetic storms, charged particles bombard the earth at high latitudes. The resulting electric currents heat the upper atmosphere, pumping increased amounts of protons and oxygen ions into the magnetosphere. This plasma is stored, together with the solar-wind plasma that has gained entry into the magnetosphere, in a great reservoir known as the plasma sheet, which extends for tens of thousands of kilometers on the earth's nightside.

At the heart of the study of space weather is a question:

A SPACE STORM IN ACTION

FIRST WARNING of the Bastille Day storm was a solar flare on July 14, 2000. Images of the sun from SOHO's Extreme Ultraviolet Imaging Telescope (*top*) show active region 9077 (*in white box*) before and during the flare. At about the same time, SOHO's coronagraph observed a coronal mass ejection (CME) that soon deluged the spacecraft with high-speed protons, temporarily blinding its instruments (*middle*). The shock wave and CME slammed into the earth's magnetic field the next day, triggering auroras observed by the IMAGE spacecraft's Wide-band Imaging Camera (*bottom*) and a sharp drop in geomagnetic field strength at the planet's surface (*opposite page, middle*). In this graph, called the disturbance storm time index, zero represents the normal surface field strength. As the storm progressed, IMAGE's High Energy Neutral Atom instrument monitored the waxing and waning of the ring current around the earth's equator (*opposite page, top*).



NASA/ESA, SOHO (solar images); NASA/IMAGE FUV TEAM (auroral images); NASA/IMAGE HENA TEAM (ring current images); WORLD DATA CENTER FOR GEOMAGNETISM, KYOTO, JAPAN (graph)

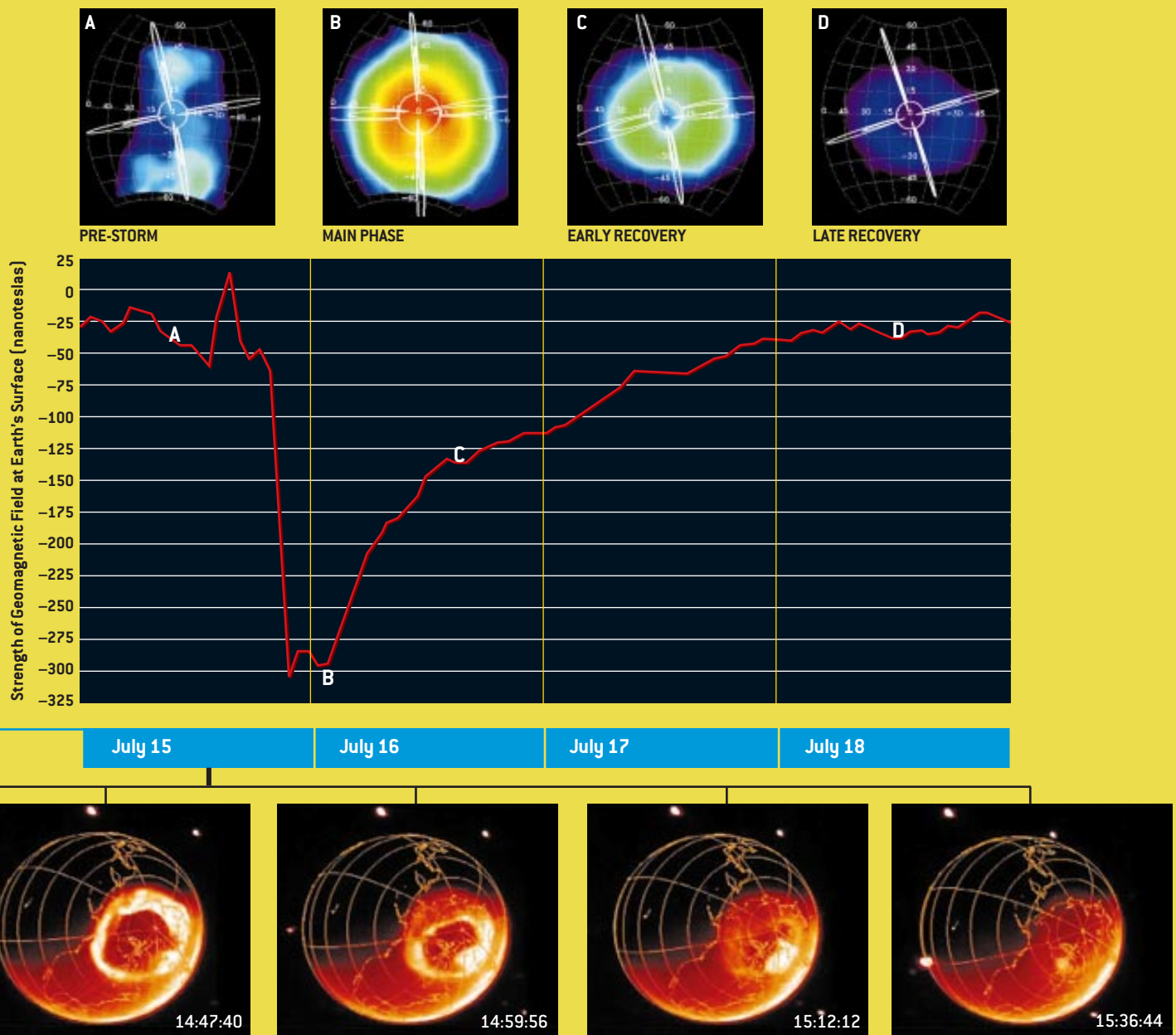
How do changes in the solar wind affect conditions in the space surrounding the earth? In other words, how can the wind overcome the barrier of the geomagnetic field and drive the motions of the plasma inside the magnetosphere?

Blowing in the Solar Wind

ONE ANSWER, PROPOSED IN 1960 by Frank Johnson of Lockheed Missiles and Space Division, is that the magnetosphere is essentially closed. According to this hypothesis, the solar wind could transfer energy and momentum to the plasma surrounding the earth only by wave motions along the magnetopause. The motions would be produced by viscous interaction between the solar-wind plasma and the magnetosphere plasma; the process is analogous to the generation of waves by the flow of

wind over water. Waves are in fact observed along the magnetopause. But they do not seem capable of driving the large-scale circulation of the magnetosphere or the great disturbances that often occur there. Such waves also would not allow the efficient entry of accelerated solar-wind plasma into the magnetosphere.

For these reasons, magnetopause waves are not considered the primary means by which the solar wind affects the magnetosphere. An alternative mechanism called magnetic reconnection—first proposed in 1961 by British physicist James W. Dungey—is generally thought to be a better explanation. In this process, the field lines of the IMF become temporarily interconnected with the geomagnetic field lines on the dayside of the magnetopause [see illustration on page 89]. This tangling of the field lines allows large amounts of plasma and magnetic ener-



gy to be transferred from the solar wind to the magnetosphere.

Reconnection is most efficient when the IMF has a component that is directed southward—that is, opposite to the northward direction of the earth’s magnetic field at the dayside of the magnetosphere. Under these circumstances, reconnection takes place along a wide equatorial belt, opening up nearly the entire outer boundary of the magnetosphere to the solar wind. For other orientations of the IMF, reconnection still happens, but it may be more localized in the higher latitudes, where the released energy mainly flows around the magnetosphere rather than into it.

The transfer of magnetic energy from the solar wind radically alters the shape of the magnetosphere. When reconnection is initiated on the dayside magnetopause, the interconnected IMF and geomagnetic field lines are swept back by the solar wind over the earth’s poles, pouring energy into the northern and southern lobes of the long magnetotail on the nightside. As the lobes swell with the added magnetic energy, the plasma sheet that lies between them begins to thin. The process continues until the field lines of the northern and southern lobes, which have opposite directions, are pressed together and themselves reconnect.

This second reconnection releases the solar wind’s magnetic field, enabling it to continue its flow through the solar system. At the same time, it allows the earth’s magnetic field lines, which have been stretched tailward during the loading of the lobes, to snap back into their normal configuration. The abrupt movement of the field lines heats and accelerates the ions and electrons in the plasma sheet, injecting them into the inner part of the magnetosphere. Some of these particles, traveling along geomagnetic field lines, dive into the upper atmosphere above the earth’s poles, stimulating auroral emissions at x-ray, ultraviolet, visible and radio wavelengths as they collide with oxygen atoms and nitrogen molecules. The entire sequence of events—from dayside reconnection to nightside reconnection to auroras—is known as a magnetospheric substorm.

In addition to transferring magnetic energy to the tail lobes, dayside reconnection also intensifies the electric field across the magnetotail. The stronger field, in turn, increases the flow of ions and electrons from the plasma sheet to the inner magnetosphere. This flow feeds into the earth’s ring current, which is carried by charged particles circling the planet above its equator at altitudes between 6,400 and 38,000 kilometers. During longer periods of dayside reconnection—which occur when the IMF’s orientation remains consistently southward—the sustained enhancement

of the earthward plasma flow greatly increases the number and energies of the charged particles in the ring current. An extended period of southward IMF can also lead to a rapid succession of substorms, each of which injects more particles toward the earth. The resulting growth in strength of the ring current is the classic hallmark of a full-fledged geomagnetic storm.

Here Comes the Sun

THE ORIENTATION OF THE IMF turns southward quite frequently, so magnetospheric substorms are fairly common: on average, they happen a few times every day and last for one to three hours. But major geomagnetic storms such as the Bastille Day event are much rarer. Although they can occur anytime during the 11-year solar cycle, they are most frequent in the solar maximum period.

Until the early 1990s, it was widely believed that solar flares triggered geomagnetic storms. Space and solar physicists, however, had been assembling evidence that pointed strongly to another culprit, and in 1993 John T. Gosling of Los Alamos National Laboratory wove the various threads of evidence together in an article in the *Journal of Geophysical Research* that challenged the “solar flare myth.” Gosling set forth a compelling argument for the central role of coronal mass ejections in setting off large geomagnetic storms. Scientists still do not know what causes these violent eruptions in the sun’s corona, but the phenomenon most likely involves a reconfiguration of the magnetic field lines there. CMEs are often, but not always, associated with solar flares.

Not all CMEs cause geomagnetic storms. Most of the eruptions are not directed at the earth, and of those that are, only about one in six is “geoeffective”—strong enough to trigger a storm. The primary factor is the CME’s speed relative to that of the solar wind. Only fast CMEs are geoeffective. Why? When fast CMEs plow through the slower solar wind, they produce interplanetary shock waves, which are responsible for the high-energy particle showers and the severe deformations of the earth’s magnetic field. Even more important, a fast-moving CME compresses the solar wind ahead of it, thereby increasing the strength of the magnetic field in the compressed region and in the front part of the CME itself. Moreover, this draping of the field around the CME tends to tilt the IMF more along the north-south direction, which causes a stronger reconnection when the IMF encounters the earth’s magnetic field.

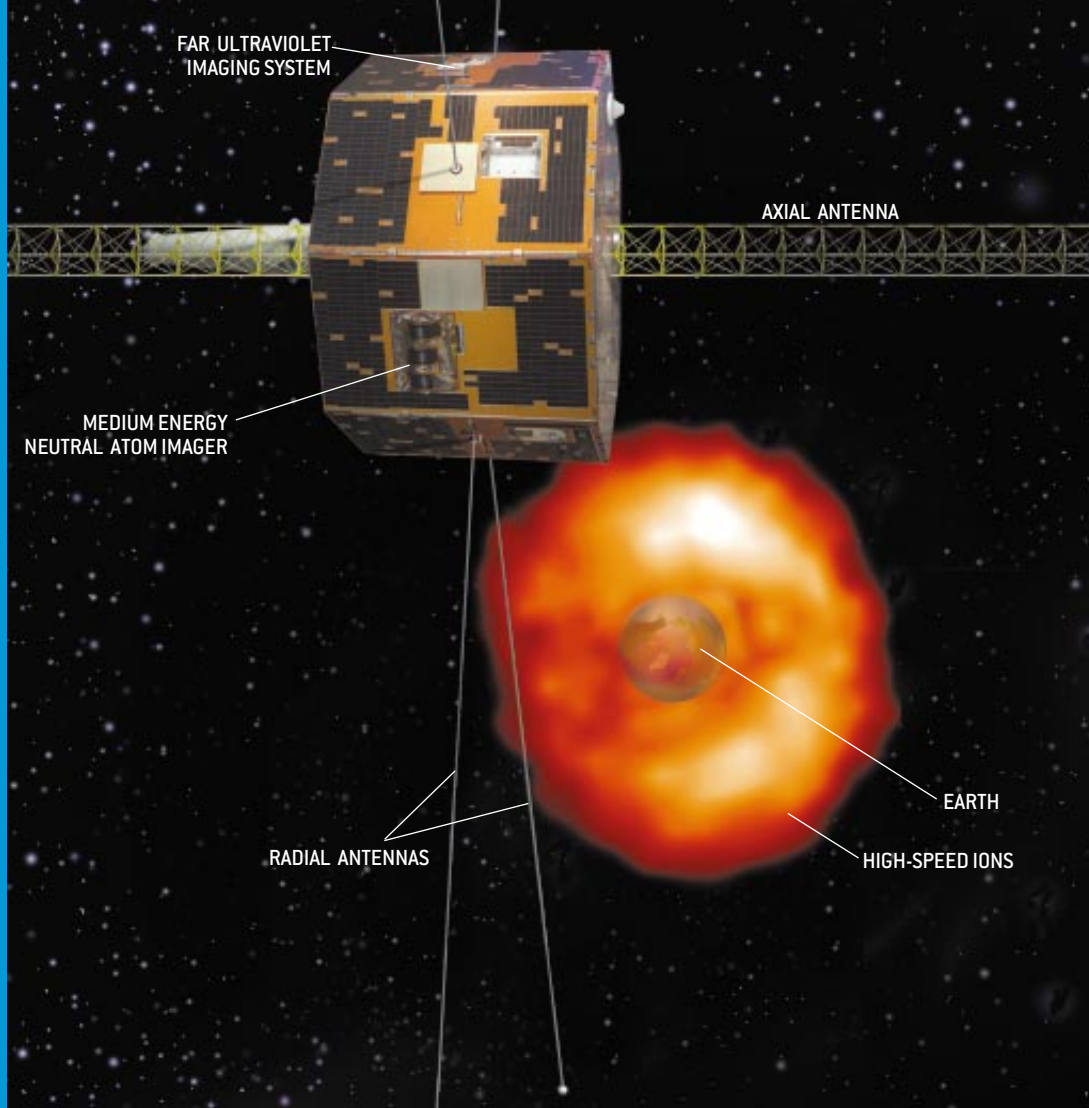
A weaker kind of geomagnetic storm occurs during the declining phase of the solar cycle and near the solar minimum period. These disturbances, which tend to recur in phase with the sun’s 27-day rotational period, are set off by the interaction between fast solar winds emanating from holes in the corona and slower winds arising from the sun’s equatorial streamer belt. Although CMEs are not the primary cause of recurrent storms, they may contribute to their intensity.

With the launch of IMAGE last year, researchers finally had the means to obtain global views of the minute-by-minute progress of a large geomagnetic storm. The satellite travels in

JAMES L. BURCH is vice president of the Space Science and Engineering Division of the Southwest Research Institute in San Antonio, Tex., and principal investigator for the IMAGE mission. Burch earned his Ph.D. in space science from Rice University in 1968. His main research interests are auroral processes, magnetic reconnection and magnetospheric imaging. He is a Fellow of the American Geophysical Union and current chairman of the Committee on Solar and Space Physics of the National Research Council.

IMAGE SPACECRAFT

is shown above a cloud of high-speed ions circling the earth in this composite illustration. Researchers produced the ion image using data from the satellite's High Energy Neutral Atom imager (the instrument is on the side of the spacecraft opposite from the Medium Energy Neutral Atom imager). IMAGE's Radio Plasma Imager charts the clouds of charged particles by sending pulses of radio waves from two 10-meter-long axial antennas and four 250-meter-long radial antennas. Although the spacecraft's body is only 2.25 meters wide, the antennas make IMAGE one of the biggest sensors ever flown in space.



an elliptical polar orbit, with its altitude varying from 1,000 to 46,000 kilometers. This orbit allows the craft to observe a large part of the magnetosphere, including the dayside magnetopause, the inner reaches of the magnetotail and the polar cusp regions, which are the main entryways for the particles from the solar wind.

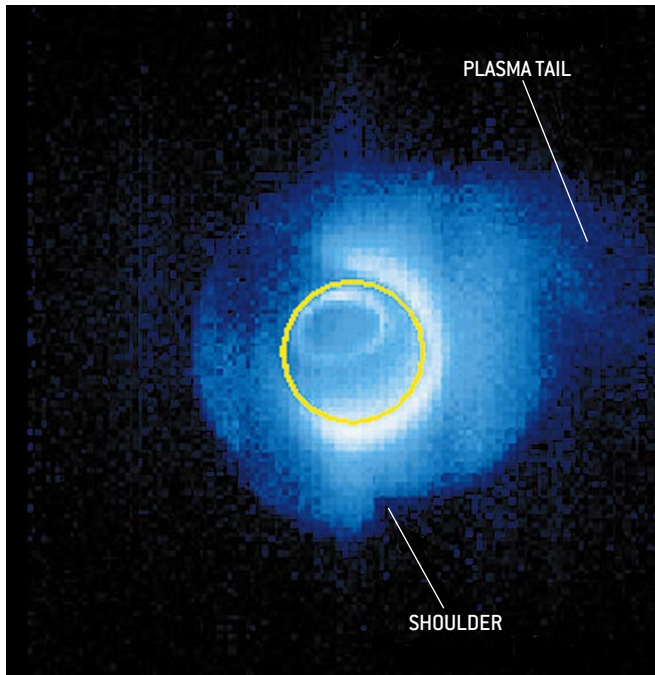
The Perfect Space Storm

IMAGE'S INSTRUMENTS ARE DESIGNED to observe the magnetosphere's plasmas, but they do so in different ways. The craft contains three Energetic Neutral Atom (ENA) imagers that indirectly measure ion flows. When a fast-moving ion (such as an oxygen ion) collides with one of the neutral hydrogen atoms in the magnetosphere, it sometimes strips away the hydrogen atom's lone electron and becomes an energetic neutral atom. Because this atom no longer carries a charge, it does not have to move along the geomagnetic field lines. Instead it travels in a straight path from where it was created. The ENA imagers record the number and energies of the neutral atoms coming from a particular region, and researchers can deduce from those data the mass, speed, direction and density of the ions in that region.

The satellite also carries several instruments that monitor emissions in the ultraviolet part of the spectrum. The Extreme Ultraviolet (EUV) imager measures the density of singly ionized

helium atoms in the plasmasphere—a doughnut-shaped region of the inner magnetosphere containing low-energy plasma—by detecting the solar ultraviolet light that they absorb and then reradiate. The Far Ultraviolet (FUV) imaging system has two instruments for viewing auroras—the Wideband Imaging Camera and the Spectrographic Imager—as well as the Geocorona Photometers for detecting emissions from neutral hydrogen atoms. Last, the Radio Plasma Imager sends out pulses of radio waves that bounce off clouds of charged particles. It works like a state trooper's radar gun: the returning radio signals convey information about the direction, speed and density of the plasma clouds.

During the Bastille Day event, IMAGE began recording the storm's effects less than two minutes after the CME-driven shock wave hit the earth's magnetic field on July 15. The Wideband Imaging Camera sent back stunning photographs of the aurora borealis triggered by the compression of the field [see bottom illustrations on pages 90 and 91]. A movie created from the images shows a sudden dramatic brightening of a ring above the Arctic region—the auroral oval—with brilliant emissions racing like brushfires toward the North Pole. The aurora quieted less than an hour after the storm began but flared up again when a second shock hit at about 17:00 UT. Powerful substorms followed, as energy stored in the magnetotail was



PLASMASPHERE appears as a pale blue cloud of ions surrounding the earth [yellow circle] in this picture obtained by IMAGE's Extreme Ultraviolet instrument during a moderate geomagnetic storm on May 24, 2000. The results confirmed the existence of the hypothesized plasma tail and revealed an unexpected structure that was dubbed the "shoulder."

explosively released into the upper atmosphere. Substorms and the attendant auroral displays continued through the rest of July 15 and into the morning of July 16.

During the storm's main phase, which began four hours after its start, the magnetic field strength on the earth's surface fell precipitously, dropping 300 nanoteslas below its normal value. This phenomenon, the defining feature of geomagnetic storms, resulted from the rapid growth of the ring current. IMAGE's Energetic Neutral Atom imagers produced vivid pictures of this flow of ions and electrons around the earth as it reached its peak on July 16 and then began to diminish [see top illustrations on page 91]. Once the transfer of energy from the solar wind abates, the flow of plasma into the inner magnetosphere slows, and ions are lost from the ring current more rapidly than new ones arrive. As the current weakens, the magnetic field on the earth's surface rebounds. The return to pre-storm levels usually takes one to a few days but may require more than a month in the case of major tempests.

Geomagnetic storms also change the shape of the plasmasphere. The enhanced flow of plasma from the magnetotail toward the earth erodes the plasmasphere by sweeping its charged particles toward the dayside magnetopause. When a storm subsides, the plasmasphere is refilled by ion outflow from the upper atmosphere. Scientists had hypothesized from modeling

studies that the eroded material from the plasmasphere would form a long tail extending to the dayside magnetopause and that from there it would become lost in the solar wind. Global images of the plasmasphere from IMAGE's EUV instrument have now confirmed this 30-year-old hypothesis [see illustration at left]. At the same time, the images have revealed structures in the plasmasphere that raise new questions about its dynamic response to magnetospheric disturbances.

On the Horizon

ALTHOUGH IMAGE HAS OPENED a new window on the magnetosphere, our view of space weather is still imperfect. Unlike terrestrial clouds, the clouds of plasma seen by IMAGE are completely transparent: nothing is hidden from sight, but depth perception is lacking. Thus, there will always be the need for satellites that make local measurements of the plasmas, as well as the fields and currents that govern their motion.

The next step for space weather observation will involve clusters of satellites acting like hurricane-hunter planes—they will go where the action is. The European Space Agency is conducting the first such mission, called Cluster II, which was launched in the summer of 2000. (A predecessor mission, Cluster I, was destroyed in a rocket explosion just after liftoff in 1996.) Cluster II consists of four closely grouped identical spacecraft designed to probe turbulent plasma phenomena in the magnetosphere and nearby solar wind. NASA is also planning a cluster mission for launch in 2006. The Magnetospheric Multiscale mission will study reconnection, charged particle acceleration, and turbulence at the dayside magnetopause and at specific locations in the magnetotail where substorms are triggered.

The space agencies are considering even more ambitious missions involving constellations of satellites: dozens of tiny spacecraft that will monitor large regions of space, just as the global weather networks now monitor conditions on the earth. The first constellations will most likely observe the inner magnetosphere and the dayside magnetopause, with each cake-size craft recording the basic characteristics of the plasmas and magnetic fields.

The earth's magnetosphere is at once protective and dangerous. Its strong magnetic field shields humans from penetrating radiation that would otherwise be lethal. But the field is not strong enough to ward off the most powerful shock waves from the sun. Like the tornado belt or the tropical cyclone zone, the magnetosphere is a place of sudden storms. And that's why storm watchers such as the IMAGE satellite are so important. SA

MORE TO EXPLORE

From the Sun: Auroras, Magnetic Storms, Solar Flares, Cosmic Rays.

Edited by S. T. Suess and B. T. Tsurutani. American Geophysical Union, 1998.

The 23rd Cycle: Learning to Live with a Stormy Star. Sten Odenwald.

Columbia University Press, 2001.

More pictures and data from the IMAGE mission are available at

<http://pluto.space.swri.edu/IMAGE/> and <http://image.gsfc.nasa.gov/>

General information on space weather can be found at

www.spaceweather.com/