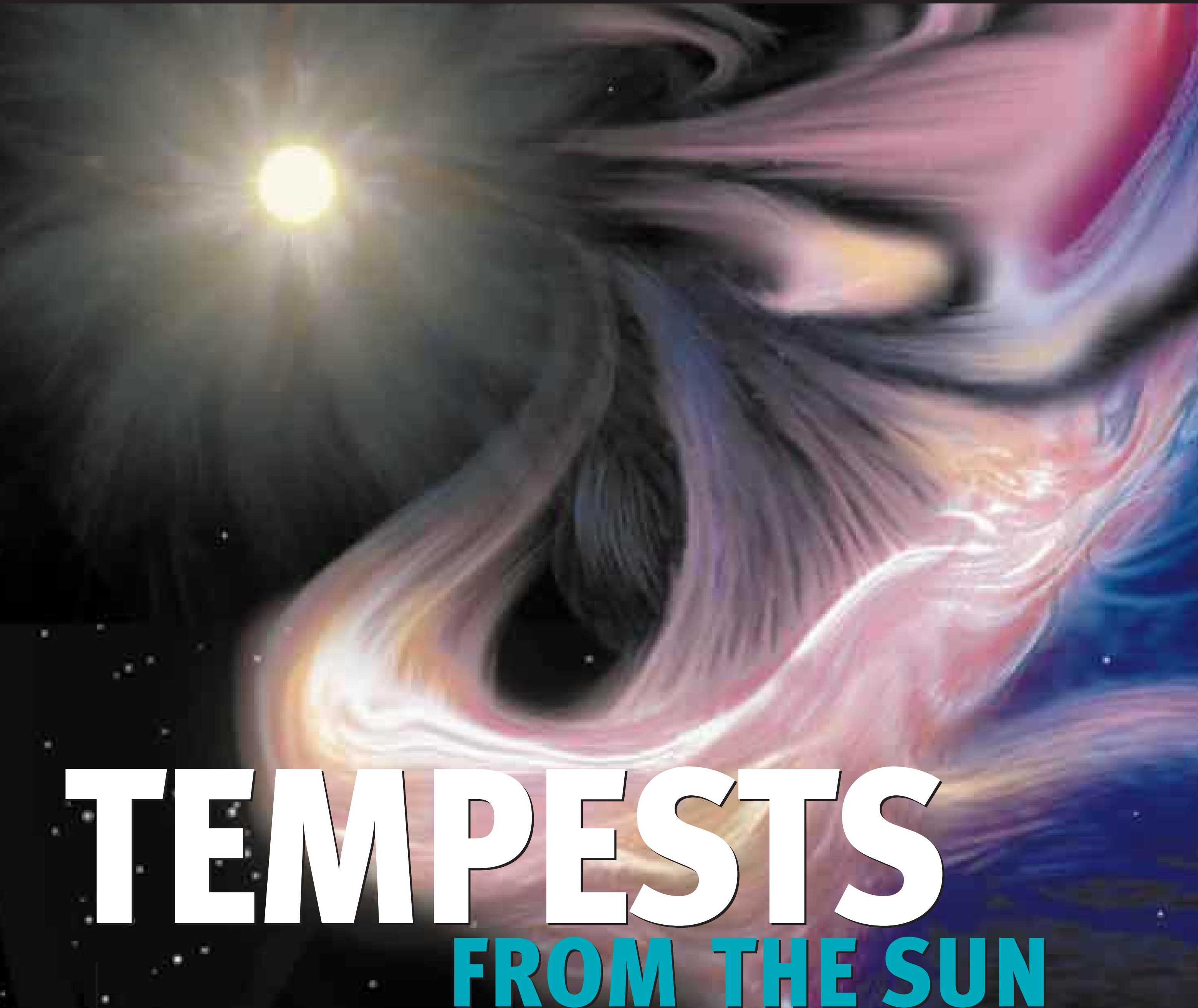


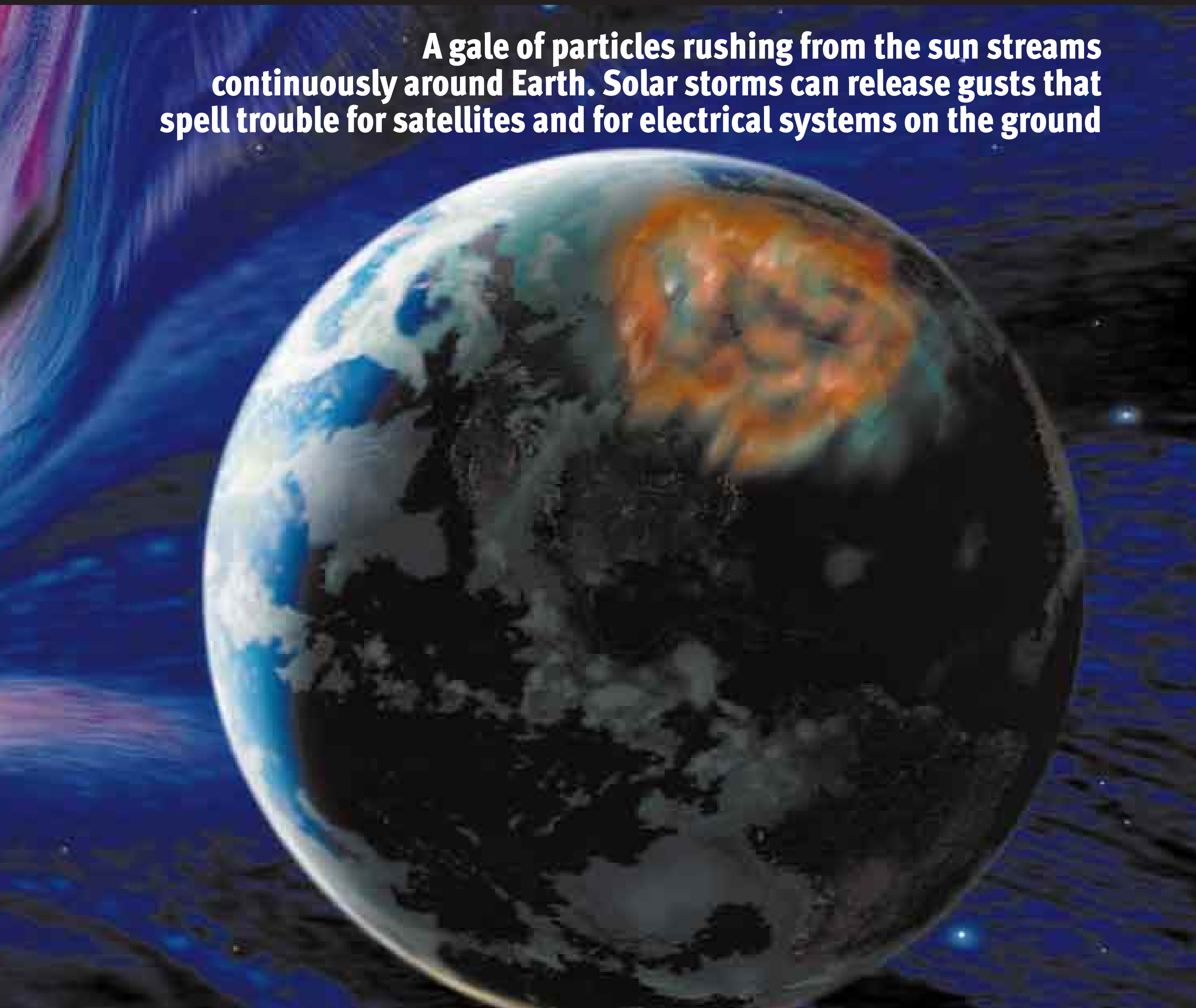
TEMPESTS FROM THE SUN

by TIM BEARDSLEY

In a sheltered Arctic valley in Greenland, a pulsing radar beam emanates from a 32-meter dish antenna. As I watch, the dish sweeps across the night sky, probing the ionosphere, a huge part of the atmosphere above 50 kilometers where atoms dissociate into electrons and ions. The antenna collects faint reflections that reveal distinct layers where electrons and ions swirl in unusual numbers.

An hour earlier the radar, located at the Sondrestrom Upper Atmospheric Research Facility, had detected prominent signals bouncing back from 140 kilometers up. They were coming from the aurora borealis, visible patches in the ionosphere where high-energy particles from space strike oxygen and nitrogen atoms. The collisions excite the atoms and cause them to emit light of different colors, producing the spectacular displays known as the northern lights. But now, as midnight approaches, the aurora has dissipated. It is a quiet night in Earth's near-space environment.

A gale of particles rushing from the sun streams continuously around Earth. Solar storms can release gusts that spell trouble for satellites and for electrical systems on the ground



SPACE WEATHER IN SPADES: A bundle of plasma (ionized gas), known as a coronal mass ejection, may escape from the sun (*far left*) during cataclysmic disturbances on its surface. The plasma—which weighs billions of tons but is too sparse to see—arcs through space and may pass by Earth, where it can trigger electrical storms in Earth's space neighborhood.

DON DIXON

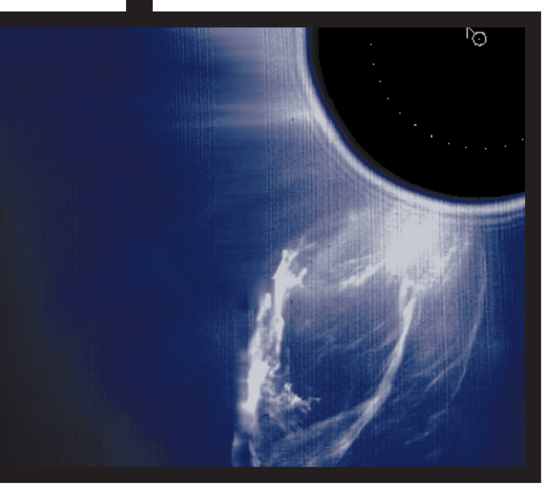
Inside the facility, though, scientists are still active. The radar, originally built to monitor aboveground nuclear explosions, is today a key component of a worldwide effort to understand space weather and its effects. Investigators at the research station—which is run by the Danish Meteorological Institute and SRI International on behalf of the National Science Foundation—hope the information they collect will provide clues about processes not only in the ionosphere, which ends at about 600 kilometers, but also far beyond it.

Earth has a magnetic field that extends all the way through the atmosphere and then tens of thousands of kilometers farther into space. In different parts of this vast region, called the magnetosphere, electrically charged particles whiz around in complicated patterns that can change or intensify in response to conditions on the sun. These effects out in space often induce changes nearer to Earth, in the ionosphere—at times causing all manner of trouble for enterprises on the ground and for the satellites on which we have become increasingly dependent. A better understanding of space weather should help researchers devise ways to avoid or limit its destructive effects.

One consequence of space weather disturbances is that the layers of free electrons in the ionosphere may shift unpredictably or fade. As a result, some radio trans-

CRAIG J. HEINSELMAN *SRI International*

PROBING THE SKIES: The Sondrestrom Upper Atmospheric Research Facility (*top*) sits in a prime location—Greenland—for studying events related to space weather. The dish antenna is part of a radar that charts phenomena occurring in the ionosphere. One of these phenomena is the aurora borealis, or northern lights (*glowing patches in sky*). The green laser beam is from a separate instrument that detects specific chemical elements in the ionosphere. The image below captures a coronal mass ejection in the process of forming.



SOLAR MAXIMUM MISSION/HIGH ALTITUDE OBSERVATORY/NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

missions that are deliberately bounced off these layers may be interrupted.

During especially violent episodes known as geomagnetic storms, particles become more energized throughout the whole magnetosphere, sometimes for several days. These electrical storms in our region of space can cause voltage swings on Earth that disrupt sensitive measuring instruments used in semiconductor manufacturing, says John W. Freeman of Rice University.

Geomagnetic storms can even take out power grids. In one of the most notorious storms, in March 1989, millions of people in eastern Canada were left without power for many hours after voltage swings brought down Hydro Quebec's grid. Even fiber-optic cables under the ocean are vulnerable to space weather events, because abnormal currents can be generated in copper wires that run alongside the cables carrying power to amplifiers.

Another space weather effect arises when storms on the sun cause it to emit more ultraviolet radiation than usual. The extra radiation can warm and swell Earth's atmosphere. In this condition, it may slow satellites that are normally beyond its clutches in low Earth orbit, including the Hubble Space Telescope and the space shuttle. Such an unexpected puffing up in 1979 caused Skylab to plummet to Earth years before it was intended to. Planners of the International Space Station assembly have had to take careful precautions against similar events.

The quest to understand space weather has gained urgency with the realization that geomagnetic storms also threaten many satellites that are in high orbits well above the atmosphere. The most susceptible are in a crowded orbit called geosynchronous, 36,000 kilometers above the equator. Satellites at this height move around Earth at the same speed as the planet rotates, so antennas on the ground can be aimed at an unmoving point in the sky.

Zap!

Unfortunately, this lofty perch places the satellites within the Van Allen radiation belts, which occupy a vast doughnut-shaped region that buzzes with energetic particles and encircles Earth's midlatitudes outside the ionosphere. During a geomagnetic storm, electrons and ions in the belts have more energy than usual. Then they deposit electrical charges in circuitry within spacecraft and charge up exterior surfaces. The buildup provokes discharges that can damage hardware and produce spurious commands.

Unmanned spacecraft are not the only orbiters at risk. Astronauts building the space station might receive substantial doses of radiation in a geomagnetic storm. Other highly energetic particles—notably protons that come directly from the sun during solar disturbances—also threaten spacefarers and can rapidly degrade solar panels on spacecraft.

Just how much space weather threatens satellites is controversial and shrouded in secrecy, because the owners of such expensive items of hardware—which may be worth hundreds of millions of dollars each—are reluctant to advertise their vulnerabilities. Some insurers may refuse to pay for a satellite lost through an "act of God." Others won't pay for satellites destroyed by weather events, so laying the blame for losses is a delicate matter.

According to Daniel N. Baker of the University of Colorado at Boulder, several notable satellite failures in recent years were caused by high-energy electrons, including major problems that occurred with two Canadian Anik communications satellites in January 1994. Baker suspects high-energy electrons may also have been involved in the failure of the Galaxy 4 satellite in May 1998 (although the satellite's owner disagrees). That event caused a widespread loss of pager services and other communications links. All in all, economic losses attributable to space weather are estimated in the high tens of millions of dollars a year—but could potentially climb much higher in a year in which storm activity is more intense.

Scientists expect some violent space weather in the months to come, because this year the sun is reaching a solar maximum: a peak in the number of violent outbursts on its surface. Such peaks occur roughly every 11 years. At these times the sun is more likely to emit energetic particles that create havoc if they near Earth.

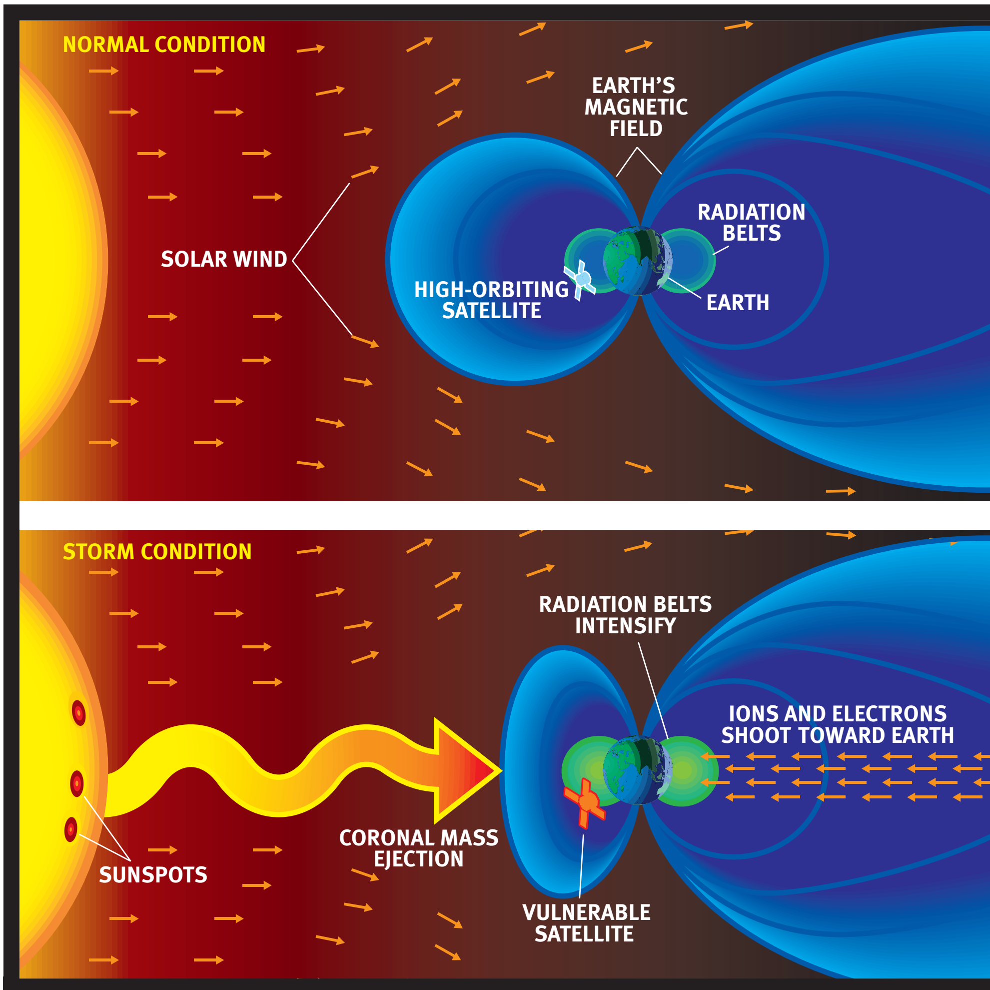
Researchers would like to issue daily forecasts that would warn of geomagnetic storms and other space weather disturbances, just as meteorologists predict storms in the lower atmosphere. Civilization is now more reliant on sensitive technological systems such as telecommunications satellites and the Global Positioning System than it was during the last solar maximum in 1989, so good forecasts could avert much damage. But scientists have a long way to go before they can produce dependable predictions.

Storm Sources

Although researchers at Sondrestrom and related facilities can hardly predict space weather disturbances, they do have some ideas about what is involved. A tenuous gale of electrons and protons—the solar wind—gusts continuously from the sun's corona, its very hot outermost layer. These particles carry a magnetic field with them from the sun. As they approach Earth, the magnetosphere normally serves as a *Star Trek*–style force field, parting and deflecting the wind so that it rushes past the planet. When storms are agitating the sun's surface, however, massive loops of ionized gas, or plasma, may blow off from the corona. The plasma energizes the solar wind and shoots through space at around one million kilometers per hour in an arc that follows the lines of the solar magnetic field. Plasma from a coronal mass ejection near the sun's midlatitudes may pass close by Earth and so trigger a geomagnetic storm.

During these extreme conditions the wind distorts the magnetosphere, and the magnetic field that the wind has carried from the sun interacts with Earth's own field to generate a backlash of particles that shoot in the opposite direction to the wind. More specifically, on the side of Earth that faces away from the sun, the magnetosphere is permanently stretched out to form a long tail. In a storm, electrons and ions moving past the tail in the solar wind somehow penetrate the tail, reverse course and zoom back toward Earth. "It's like a giant dynamo that deposits energy on Earth's dark side," says Jeffrey P. Thayer, program manager at Sondrestrom. That is why the instruments at the Greenland site operate mainly at night; some of the most interesting phenomena can be detected when the devices are looking into the sky away from the sun. Operators fueled with coffee and prepackaged frozen food often work into the hours before dawn.

The charged particles in the backlash rushing toward Earth's dark side in a storm energize the Van Allen belts, which is why the radiation levels there may suddenly rise and disturb spacecraft. The particles may also produce a titanic electric current that circulates the entire globe. It is this current that can induce fluctua-



BRYAN CHRISTIE

HOW SOLAR STORMS AFFECT EARTH: A gale of particles constituting the solar wind blows continuously from the sun, but Earth's magnetic field, shown in blue, mostly deflects the barrage (*top*). Occasionally, the sun generates a coronal mass ejection that reaches Earth (*bottom*). The ejection distorts the planet's magnetic field and makes particles from the wind rush toward Earth's night side in a backlash. These inrushing particles intensify the radiation belts around the planet, markedly increasing the danger they pose for satellites. The torrent of inrushing particles also brightens the aurora, which is not shown here. Coronal mass ejections occur most often when sunspots are visible.

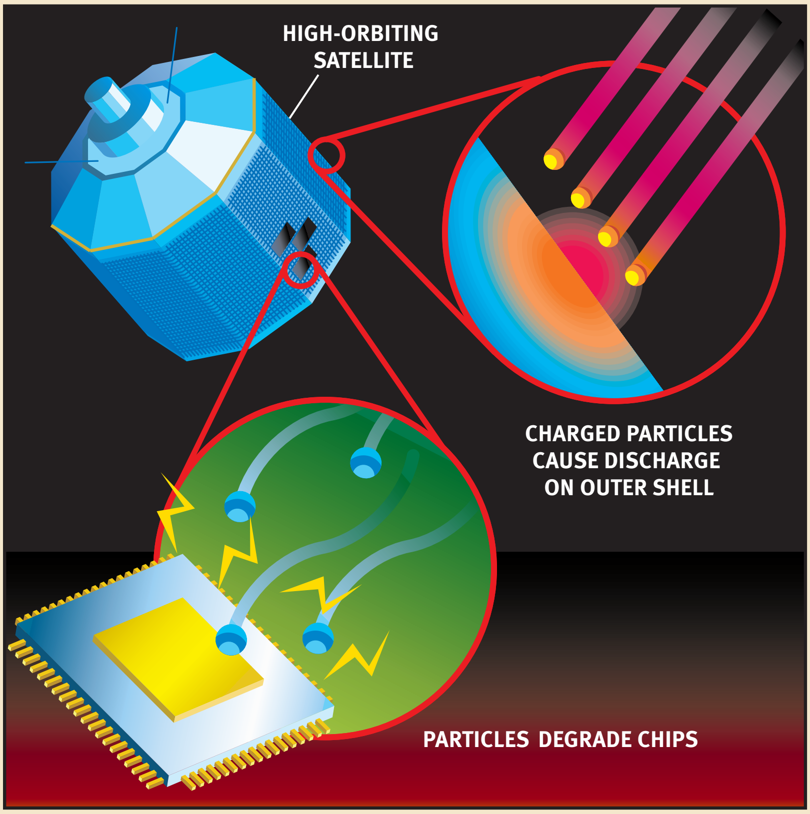
tions in sensitive instruments on Earth.

The backlash flow of ions and electrons also funnels particles onto two rings at the top of the ionosphere, one around each of Earth's magnetic poles. The rings, known as auroral ovals, are a few thousand kilometers across. Charged particles continuously plough into the ovals, creating the aurora borealis and its southern counterpart, the aurora australis, in the ionosphere. But when a geomagnetic storm is in progress, this torrent of particles intensifies, brightening the auroras. Less delightfully, a storm may give rise to tremendous electric currents in the ionosphere around the poles. These currents can then bring about the voltage swings that can knock out long-distance power lines at the terrestrial surface.

Even when the sun is being well behaved, parcels of plasma shoot sporadically toward Earth's dark side, prompting a bright aurora and intensifying radiation belts. These events, called substorms, last only a few hours, but they occur several hundred times a year and are quite capable of disrupting satellites, according to Baker. The Sondrestrom facility, near the settlement of Kangerlussuaq, is within the northern auroral oval, so it is excellently positioned to detect any ionospheric changes that happen in this sensitive part of the world. Indeed, its radar is one of only three comparable instruments studying space weather inside the Arctic Circle. Detectors at Sondrestrom continually register fluctuations in Earth's magnetic field caused by substorm-induced currents.

One of the most important capabilities of the Sondrestrom radar is that it can detect horizontal motions of plasma within the ionosphere, which is too high to be reached by balloons carrying instruments. This ability could be crucial for unveiling some of space weather's most perplexing phenomena. The ionosphere plays a crucial role in dissipating electrical energy created by the interaction of the solar wind and Earth's magnetic field, SRI's Craig J. Heinselman says. Currents arising in the ionosphere can heat the sparse plasma there and trigger bulk movements of neutral gases. Enormous patches of partly ionized gas hundreds of

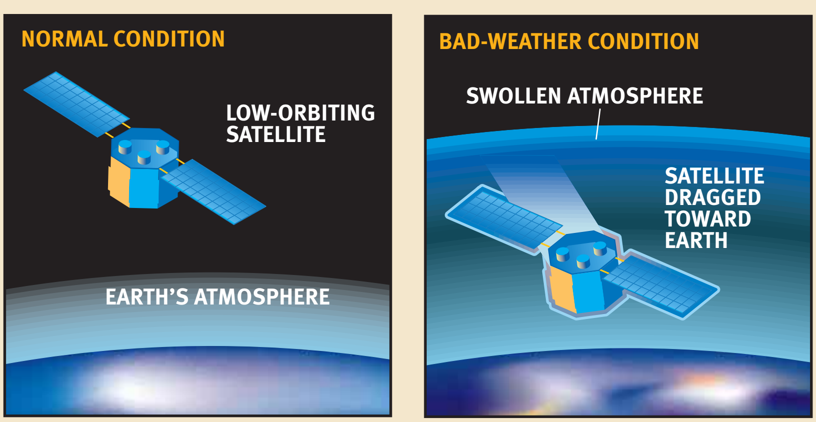
WHY SATELLITES SUFFER



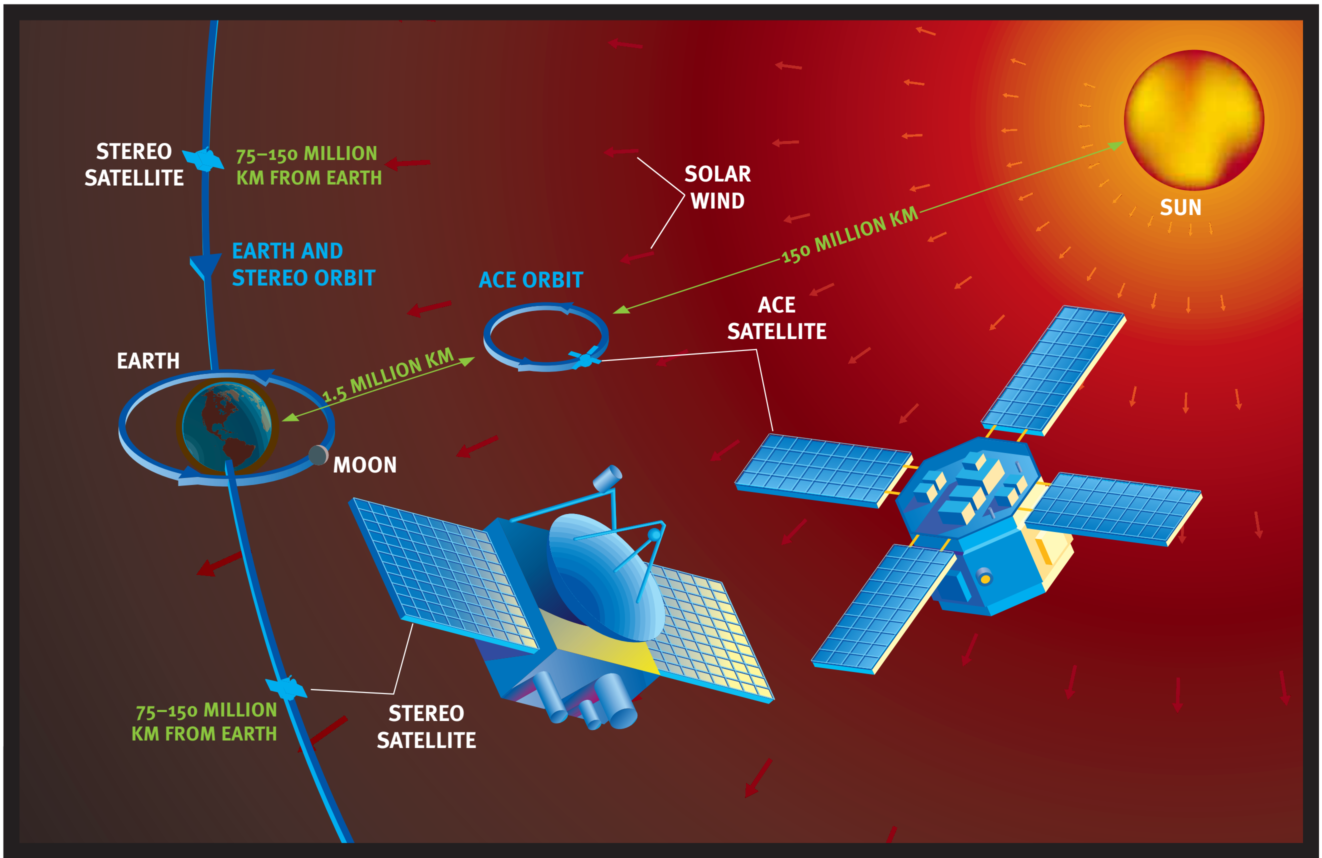
Space weather can threaten satellites in several ways.

High-orbiting satellites (*above*) pass through the Van Allen radiation belts. During bad space weather, electrically charged particles in these belts become more energetic, so they charge spacecraft surfaces, causing sparks that can damage those surfaces and disrupt circuits. Other particles directly degrade the chips in the satellites' onboard computers.

Low-orbiting satellites (*below left*) face a different space weather hazard. When the sun is disturbed, it emits more ultraviolet radiation than normal, which warms Earth's atmosphere and makes it swell. The atmosphere then acts as a brake on satellites that are normally beyond its clutches, bringing them into a lower orbit (*right*). Operators must expend valuable fuel to reboost the orbiters, thus shortening their service lifetimes.



BRYAN CHRISTIE



DEFENSIVE MANEUVERS: Specialized satellites can help predict bad space weather. ACE monitors the particles in the solar wind from its orbit directly between Earth and the sun. Gusts pass the spacecraft about an hour before they reach Earth, so ACE can radio a warning that severe space weather is on the way. Two Stereo satellites scheduled for launch in 2004 will provide stereo views of the sun from vantage points farther from Earth. Their viewing angles will enable scientists to better predict when the sun is likely to shoot off an especially vigorous burst of particles, giving perhaps a full day's warning of a potentially disruptive space weather event.

kilometers across often drift over the poles from the planet's day side to its night side, for example, interfering with satellite communications. The radar can map those movements and may thus eventually enable scientists to anticipate worrisome plasma shifts.

Keeping an Eye on the Sun

Monitoring Earth's near-space environment can help scientists understand space weather, but better forecasting also demands scrutiny of the sun, where disturbances originate. Some of the most useful instruments for observing the sun detect wavelengths of electromagnetic radiation that cannot penetrate through the ionosphere and stratosphere to Earth-based detectors; consequently, the most useful sun-watching instruments are borne by spacecraft way past even the most distant wisps of the atmosphere.

In recent years a satellite known as SOHO (Solar and Heliospheric Observatory) has greatly refined ideas about links between the sun and our planet. SOHO does not orbit Earth; rather it circles around a gravitationally stable point in space about 1.6 million kilometers from the planet in the direction of the sun. From there SOHO can observe our local star 24 hours a day. It sees onrushing plasma from coronal mass ejections as a characteristic halo around the corona. Unfortunately, plasma ejected on the far side of the sun and plasma moving toward Earth present identical appearances, so SOHO images are far from ideal as predictors of episodes that might have consequences to earthlings.

Since early 1999 scientists have been able to get another type of advance warning of bad space weather. A satellite called ACE (Advanced Composition Explorer), positioned in an orbit like SOHO's directly between Earth and the sun, monitors the particles in the solar wind and its magnetic field. The spacecraft sends warnings that arrive an hour before a gust. ACE's data have to be incorporated into computer models before they can supply forecasts, but even so they provide about 30 minutes' notice of when a satellite might be vulnerable to high-energy particles. That is enough for operators to take some steps to protect sensitive systems, although they may be reluctant to reconfigure satellites that lack immediately available backups, notes Baker of Boulder. Furthermore, some of the most dangerous particles, notably energetic protons, travel from the sun to Earth in just a few minutes—too fast for any warning.

Researchers are learning some tricks to improve prediction. They can, for example, sometimes see in the corona reflected light from solar storms occurring beyond the edge of the sun's visible disk.

CHASING EXTRATERRESTRIAL STORMS

by TRACY STAEDTER

Even on its stormiest days, Earth's weather pales next to that on other worlds. Gigantic dust devils stampede across Mars. Gasolinelike liquids rain onto Saturn's moon Titan. A high-pressure system approximately the size of two Earths reels around Jupiter. And unimaginable winds rage against Neptune at more than 1,300 kilometers an hour. It's no wonder some scientists prefer to chase extraterrestrial storms rather than bother with any Earth-bound ado.

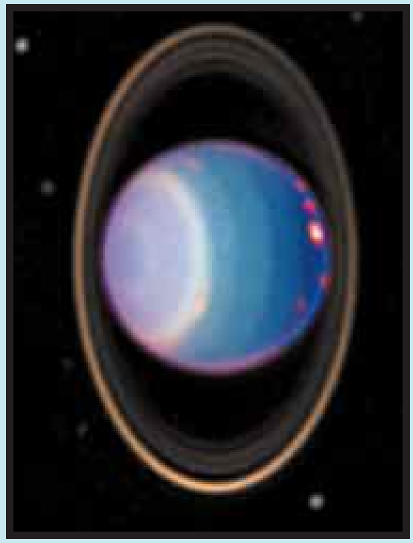
But tracking alien weather is a daunting task. Astronomers must look across vast distances of space at worlds whose very atmospheres enshroud storm activity. And any viewing from the ground must be done during brief observing sessions on just a few large telescopes. But surprisingly, scientists have gotten remarkably close to their quarry. With advanced telescopes and computer models, they are peering deeper than ever before into otherworldly atmospheres and even gaining insight into weather phenomena right here at home.

Some of the latest advances are being made on the outer planets. Recently a team of scientists from Lawrence Livermore National Laboratory used the 10-meter Keck telescope to image Saturn's moon Titan and discovered possible methane seas. The presence of these seas suggests that the tiny moon may undergo something similar to Earth's water cycle. On Earth, water condenses into clouds, then rains onto the surface. On Titan, methane could be condensing and raining onto the surface to make seas of liquid hydrocarbons.

"It's like what Earth was like four billion years ago before there was life," says team member and astronomer Bruce Macintosh. If so, Titan presents scientists with a natural laboratory for examining our own planet's earliest atmosphere.

In many cases, such parallelism is why scientists study the extreme conditions of extraterrestrial atmospheres. Those harsh environs represent how weather varies in ways that cannot be duplicated by experiments on Earth. "Generally the way we learn about how true our models are is by having more conditions to compare them to," Macintosh notes. The more comparisons scientists can make out there, the more they understand how things work down here.

Take lightning. On both Jupiter and Earth the phenomenon seems to occur only in



ERICH KARKOSCHKA *University of Arizona* AND NASA

URANUS: This false-colored 1998 Hubble Space Telescope image highlights clouds toward the right of the sphere.

water clouds, says theoretician Seran Gibbard of the Livermore laboratory. Observing bursts on more than one planet has helped scientists to narrow down the conditions that create lightning.

Some phenomena are not so clear-cut, however. One thing that remains a mystery is how the outer planets generate weather so far from the storm-producing energy of the sun. On Earth the sun's radiation warms the planet's surface considerably, creating clouds and winds that eventually lead to

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And one team of investigators, headed by Richard Canfield of Montana State University at Bozeman, has identified a particular visible structure that often appears on the sun's surface before a violent outburst. The pattern, evident in images made with soft x-rays, is an S-shaped bright region. Canfield and his collaborators believe it represents a twisted magnetic field that is readying to resolve itself into a coronal mass ejection.

Above the Crowd

The growing concerns about space weather have spurred several new initiatives. The government has inaugurated a national space weather program, and additional specialized satellites are in the works. One, not yet funded, is called Geostorms. Like ACE and SOHO, it would be positioned directly between Earth and the sun. But because it would have a solar sail to intercept energy from the sun, it could hover about twice as far from Earth as those spacecraft, which must remain close to a specific gravitationally stable point. Geostorms could thus extend notice of a threatening blast of solar wind to a couple of hours—enough for utility companies to put circuits in their safest configurations and to alert personnel.

A more ambitious space mission, approved for launch in 2004, is Stereo (Solar and Terrestrial Relations Observatory). It would consist of two sun-gazing satellites following orbits like that of Earth's around the sun, with one of the pair leading our planet and the other, about 200 million kilometers distant, lagging. The two satellites would jointly provide a stereoscopic view of the sun that would reveal storms in three dimensions and allow scientists to see more of the sun's disk than they can from near Earth. That capability should allow them to be much more confident about which events are most likely to produce repercussions.

Stereo could also help ensure the safety of astronauts who might one day travel to Mars. An interplanetary journey will expose spacefarers to potentially dangerous quantities of high-energy solar protons. If they had some warning of a threatening solar event, however, they might be able to take refuge in a shielded compartment.

Other planned satellites will focus on deepening scientific understanding of the effects of the solar wind on the mag-

VOYAGER 2 NASA

NEPTUNE: Voyager 2 produced the first clear images of long cirrus-type clouds (white streaks) over Neptune in 1989.

dramatic storms. But the outer planets are incredibly distant from the sun.

Neptune, for example, is 30 times farther from the sun than Earth is. Yet Neptune has clouds and nearly supersonic winds. In 1989 Voyager 2 revealed cirrus-type clouds there. In May 1999 Macintosh and his team of scientists used Keck to create the highest-resolution infrared images of Neptune's clouds and of atmospheric bands in the planet's southern hemisphere. Before then, even the biggest clouds on Neptune looked like fuzzy blobs from ground-based telescopes. The secret to the improved resolution is computer-controlled adaptive optics, which dramatically reduces image distortions introduced by Earth's atmosphere.

So how do clouds and high winds form on a planet so far from the sun? Scientists speculate that even the weakest amount of sunlight can make a difference on a planet with surface temperatures of about –130 degrees Celsius. The meager energy upsets the precarious balance of temperature and chemicals in the gaseous layers of the planet, leading to atmospheric disturbance. Weather-producing energy may also come from inside Neptune. Like all the planets, Neptune formed when gases in the solar nebulae condensed and collided with one another, accreting into a planet. The energy generated during those collisions is still emanating from the interior.

But the forces apparently at work on Neptune do not convincingly explain the clouds scientists see on its neighbor, Uranus. "Uranus seems to have no internal heat source," comments planetary scientist Heidi Hammel of the Space Science Institute in Boulder, Colo. Even so, Hammel and researchers from New Mexico State University and the Massachusetts Institute of Technology found 20 clouds—one brighter than had ever been seen before—when they observed Uranus with the Hubble Space Telescope.

Scientists theorize that changes in Uranus's atmosphere might arise in part from how the planet spins. Like the other gas giants, Uranus rotates especially fast, turning full circle in less than 18 hours. The rapid spinning sets up flow patterns in the gaseous atmosphere similar to those observed in fluid dynamics. "When you spin a ball of fluid, you get streaky patterns; in between you get eddies and currents," Hammel explains. "That is the weather."

Observations made from Hubble, Keck and other telescopes, combined with computer models, offer valuable insight into extraterrestrial atmospheres. By digesting a multitude of variables such as temperature, wind speed, chemical composition and more, the models can play out plausible weather scenarios.

Ultimately, scientists would like to have one model that works for all the planets, including Earth. With such a model, they could change variables such as carbon dioxide levels and fast-forward to the most likely outcome. That would provide us with a clearer picture of our planet's atmospheric future, a forecast critical to our own well-being.

TRACY STAEDTER is managing editor of *Scientific American Explorations*.

netosphere. A notable example in that category is known as Image. Image, scheduled for launch early this year, will use specialized detectors to visualize plasma around Earth, thus providing a real-time picture of space weather's effects.

Heads Up

Space weather does ultimately affect weather down on the ground—but the link is well established only for effects that span very long timescales. From the mid-17th to early 18th century, the sun was unusually inactive, a period known as the Maunder Minimum. The result, most scientists agree, was an extended cold spell on Earth. An earlier period of heightened solar activity might explain how Europeans were able to colonize Greenland in the 11th century: the country was warmer then than it is today.

On a shorter timescale than centuries, Harry Van Loon of the National Center for Atmospheric Research in Boulder, Colo., and Karin Labitzke of the Free University of Berlin have demonstrated to the satisfaction of many scientists that the 11-year cycle of solar activity affects temperatures and pressures—and thus winds—in the stratosphere. Such an effect might, for example, explain links between winter temperature on Earth and the phase of the solar cycle. What is more, the solar cycle controls the inflow of cosmic rays to the atmosphere, through its effects on the magnetosphere. Some researchers believe cosmic rays could influence cloudiness, because they may provide nuclei for droplets to condense around. But the suggestion is controversial. Although space weather deposits a lot of energy into the upper atmosphere, very little is transported into the lower regions, says Ron Zwickl, assistant director of the National Oceanic and Atmospheric Administration Space Environment Center.

Space weather forecasting is unlikely to ever help people plan vacations or decide whether to take an umbrella to work. But as those who study it at Sondrestrom and elsewhere are well aware, its importance to civilization seems likely to grow in coming decades as systems become more complex. For electrical utilities, military and civilian communications planners and others, accurate space weather forecasts cannot come too soon. W

TIM BEARDSLEY is an associate editor of *Scientific American*.