As the sun climbs toward its 11-year activity peak, clouds of plasma and bursts of radiation are buffeting the planet. Reliable predictions may be on the way too

Forecasting the Storms and Showers of Space

A solar storm can be a fearsome thing. A billowing cloud of plasma and magnetic field, millions of kilometers across, descends from the sun. Far out in space, the envelope of charged particles trapped in Earth's magnetic field shudders under the impact. Nearer to Earth, particles showering from space can expose astronauts and passengers on commercial jets to high radiation levels and disrupt some radio communications. Currents surging through the atmosphere and the ground play havoc with technology, knocking out satellites and even entire electric power grids. In March 1989, for example, a particularly nasty solar storm took out the electricity in the entire province of Quebec for 9 hours.

That storm took place during the last peak of the sun's 11-year activity cycle. Next year, the cycle will reach another peak, and the frequency of solar storms will again rise from several each month to several each week. Most of these storms will have only minor consequences, but the most potent could match the 1989 storm or even surpass it. And with the growth of electric power grids and the increasing number of satellites in orbit (800 by the end of next year), not to mention the astronauts who will be building the international space station, society is more vulnerable than ever to the heaviest weather from space. "It's almost a given that bad things are going to happen due to space weather events. Satellites will fail; power grids will go down," says Richard Behnke, head of the upper atmosphere research section at the National Science Foundation (NSF) and co-chair of the National Space Weather Program.

Just as a storm warning gives time for boats to be secured and windows checked, space weather warnings could allow engineers to avert some damage. Power networks, for instance, can be run at less than capacity to absorb power surges caused by the storms; companies running communication satellites can prepare for potential satellite failures or malfunctions. "It can make a dramatic difference if they have even a short warning," says Ron Zwickl, deputy director of the Space Environment Center (SEC) at the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado. For power companies, "even an hour will make a dramatic difference."

Yet space weather experts are no better at predicting solar storms than meteorologists in the 1960s were at forecasting weather on Earth, say experts. For 35 years, the SEC in Boulder has issued gradually improving 24-hour advance predictions of a phenomenon associated with space weather: solar flares, which are explosions in the sun's atmosphere apparently triggered when pent-up magnetic energy is released. But the only reliable warnings of the storms that do the most damage come just an hour out, when a cloud passes the Advanced Composition Explorer satellite, known as ACE, which sits 1.5 million kilometers sunward of Earth. "We are pretty good with 1-day forecasts of solar flares," says Ernie Hildner, director of SEC, and "we can be 90% certain with predictions based on 1-hour advance in situ measurements upstream." But he adds, "We are not very good with multiday forecasts of solar storms."

Solar fury. A flare erupts in the solar corona, spewing x-rays, ultraviolet light, and energetic particles.

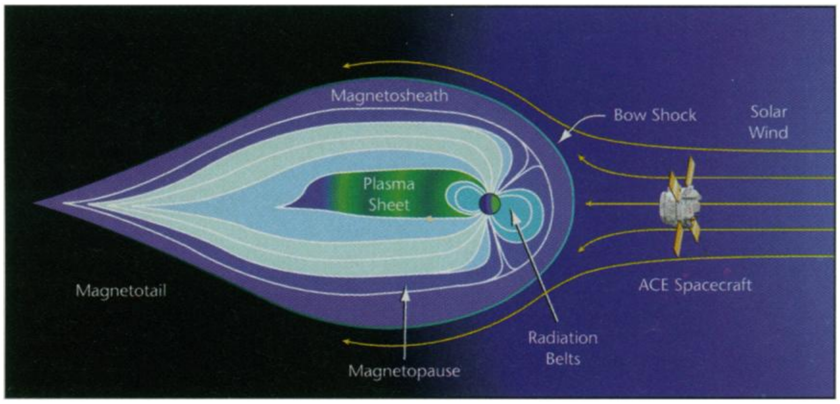
CREDIT: ACE/NASA

Fortunately, "tremendous improvements" in predictive capability are on the way, says Hildner, although not in time for next year's solar max. NASA is planning to send up new research satellites to track solar storms from the sun to Earth, and a partnership between NOAA and the U.S. Air Force will put new instruments on weather satellites to provide critical information for improving predictions. The data will feed into a program that has been under way since 1995, when NSF, NASA, NOAA, and the Departments of Defense, Energy, and the Interior launched the National Space Weather Program with the goal of getting accurate and reliable space weather forecasts within a decade. Two years ago, these agencies began to form the Community Coordinated Modeling Center, run out of NASA's Goddard Space Flight Center in Greenbelt, Maryland, to create a single comprehensive computer model that can predict the eruption of storms on the sun and their effects on satellites and power networks on the ground. When complete, participants hope, the model will do for space weather what the computer models of the National Weather Service do for more mundane weather on Earth.

Windy; showers possible

Three solar phenomena drive most space weather. The least serious of the three are coronal holes, features of the sun's corona, or upper atmosphere, that appear darker than the surrounding regions if viewed in extreme ultraviolet or x-rays. Solar coronal holes are places where the sun's local magnetic field connects its surface directly to interplanetary space, allowing the particles of solar wind to blast outward unimpeded—like fire hoses, says Hildner—rather than being slowed, as elsewhere, by coiled loops of field. As the sun rotates, these coronal holes rotate with it, occasionally sweeping the fire hose of outflowing plasma across Earth's path. Earth's magnetosphere—the vast region of charged particles trapped in the magnetic field—contracts and expands as the fire hose hits and then passes by, causing electromagnetic disturbances on Earth.

Solar flares, phenomenon number two, bombard the upper atmosphere with a shower of energetic particles, x-rays, and extreme ultraviolet light, which can be 1000 times



Sentinel spacecraft. The ACE probe hovers 1.5 million kilometers sunward of Earth, beyond the bow of its magnetosphere, monitoring gusts in the solar wind.

more intense than the levels emitted by the sun during quiescent periods. The x-rays and ultraviolet light knock electrons off atoms in the upper reaches of Earth's atmosphere. The resulting low-energy electrons can charge up the surface of a spacecraft, in a phenomenon equivalent to what happens "when you walk across a shag run in your socks," says Zwickl. When the static buildup discharges, it can damage satellite electronics.

High-energy protons and heavier nuclei arrive from 20 minutes to a few hours after the x-rays, bringing more trouble. They can have a million times as much energy as the ions of the usual solar wind. Fortunately, most are deflected by Earth's magnetic field, but a fraction are able to penetrate into the magnetosphere. Satellites or astronauts without adequate shielding can be in danger. "These energetic particles can increase more than 10 million times above background in the largest events," says Zwickl. "This presents a radiation hazard for anything flying in space, man or machine."

The roughest space weather is triggered by the third phenomenon, coronal mass ejections. CMEs are often associated with solar flares, although not always. CMEs are erupting bubbles of solar gases containing tens of millions of tons of solar material as well as a portion of the solar magnetic field, and they expand quickly as they blow out into space. "The current belief is that they are magnetically driven," says Hildner, "and the sun finds it energetically favorable to reduce its energy by kicking off a blob of its own atmosphere that is permeated by magnetic field."

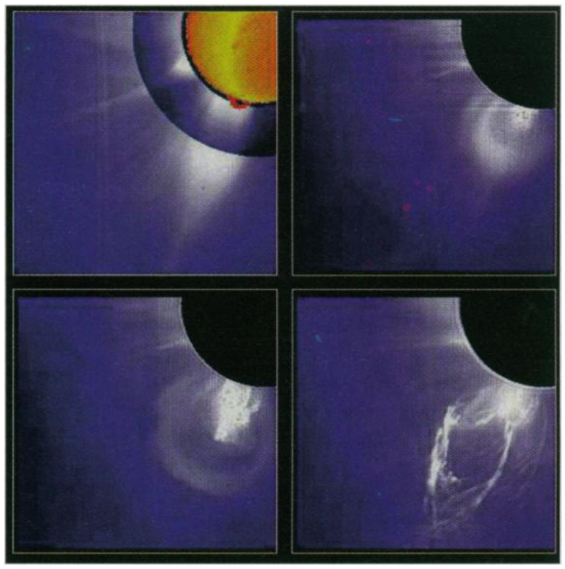
When the expanding, magnetized bubble of a CME crashes into Earth's magnetosphere, a few days after leaving the sun, "all hell breaks loose," says Zwickl. Researchers have assembled a portrait of the havoc from magnetometers and radiation meters riding aboard satellites. Depending on how the bubble's magnetic field is oriented relative to Earth's, the collision can produce a massive distortion of Earth's field. Because a moving magnetic field induces an electric current, the thrashing field lines create a current in the ionosphere—the ionized region of Earth's upper atmosphere—which in turn heats up and expands, increasing the drag on any spacecraft in low orbits. The recoiling magnetic field can also accelerate electrons in the ionosphere, turning them into so-called killer electrons, which can bore deeply into a satellite and permanently disable it.

On Earth's surface, the recoiling field induces current surges in power lines. The greater the magnetic field in the storm, the more rapidly it varies over the power lines, and the longer the power lines on Earth, the greater the induced current becomes. This direct current can unbalance the alternating current on the grid, so that voltage regulators shut down, circuit breakers trip, and the whole system crashes, as happened in Quebec a decade ago.

Sun-gazing

When NOAA got into the space weather business during the Apollo years, researchers tried to forecast these events by looking for erupting solar filaments—bright ribbons of gas rising from the solar disc. These filaments occasionally detach and vanish into the upper reaches of the solar atmosphere, an event that is thought to indicate a change in the structure of the solar magnetic field and that sometimes coincides with a CME. When a filament vanished, says Joe Kunches, lead forecaster at the SEC, the NOAA space weather forecasters concluded that a CME had been emitted—although they couldn't say whether it was heading our way. Kunches describes the prediction as akin to a "wild guess."

Today, the SEC's Web site (www.sec.noaa.gov) posts outlooks of space weather conditions a week in advance, forecasts a day in advance, and alerts and warnings of space weather storms that are imminent or under way. Underlying these bulletins are data from instruments on weather satellites and ground-based devices, as well as from two key spacecraft: the Solar and Heliospheric Observatory (SOHO), launched in late 1995, and ACE, which went up 2 years later. Neither was dedicated to space weather, but both have instruments that are now used for that purpose.



The sun blows a bubble. A coronal mass ejection erupts in a 1980 sequence from the Solar Maximum Mission.

The predictive power of SOHO, which also hovers 1.5 million kilometers sunward of Earth, comes mainly from a telescope called the Large Angle Spectrometric Coronagraph (LASCO), which blocks out the body of the sun with a small occulting disc, creating an artificial eclipse, and then observes the sun's much fainter corona. Through LASCO, CMEs look like bright bubbles emerging from the corona, explains Simon Plunkett, a solar physicist with the Naval Research Laboratory who works with the SOHO satellite. If a CME is aimed either directly toward or directly away from Earth, it appears as an expanding white ring, a "halo CME." The catch is that LASCO alone can't tell whether the CME is coming or going.

To help distinguish between the two directions, the SOHO scientists use a second instrument, called the Extreme Ultraviolet Imaging Telescope, which observes the sun in ultraviolet wavelengths, looking for signs of a CME heading this way. For instance, a depletion in ultraviolet intensity suggests that hot material has left the corona and is moving outward. If the dimming is seen near the sun's center, it implies that the radially moving ejected material is moving Earth-ward. "It gives us a reasonably good prediction that we have a CME that might impact Earth," says Plunkett. "By combining the capacity to

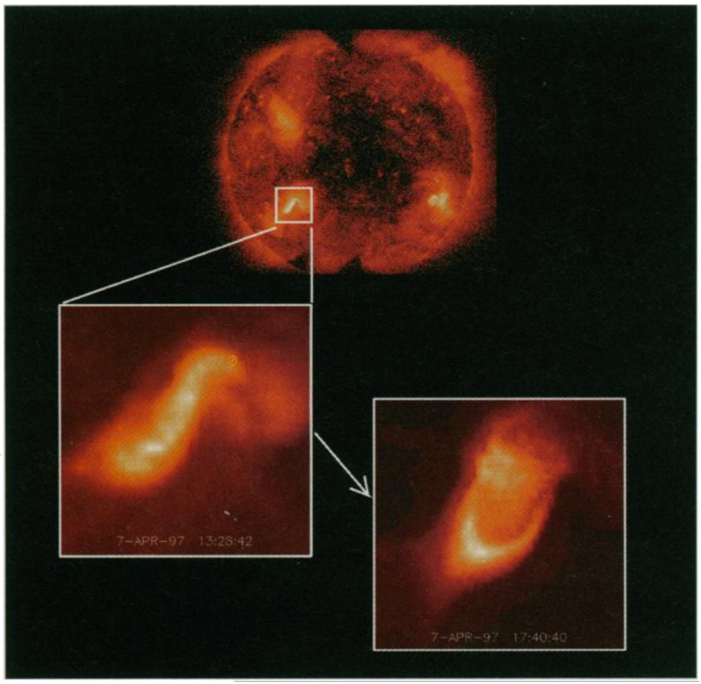
CREDITS: (TOP TO BOTTOM) ACE/NASA; HAO/SMM C/P PROJECT TEAM & NASA image the disc and outer corona, we can tell where the CME comes from and how it's progressing as it moves outward." Almost always, Hildner says, an ejection seen as a halo CME causes at least some reaction in Earth's magnetic field when it arrives. But predicting an extreme storm requires knowing whether or not the cloud's magnetic field is aligned opposite to Earth's, which allows them to couple. And SOHO can't determine the alignment.

That task falls to the ACE spacecraft, an hour upstream, which sounds the alarm if a CME really is going to hit and indicates whether it will hit hard. ACE also measures the density, composition, and velocity of the passing cloud. "Since we're sitting out in front of the Earth at a distance of about a million miles, we can give some advanced warning that a huge pressure wave is approaching Earth," says Ed Stone, director of the Jet Propulsion Laboratory and ACE principal investigator.

Weather eye

To improve space weather forecasting, researchers are studying the sun. They hope to learn how to predict when CMEs are about to erupt and whether, as Plunkett says, "they are going to be big, fast ones or small, slow ones of very little consequence." One way to do so is to study the strong magnetic fields on the sun's surface. "If you have opposite magnetic fields, very strong and very close to each other, you can imagine that they will try to annihilate and there will be the potential for catastrophic energy release," says Hildner. Researchers can track the strength and position of the fields with a device called a magnetograph, which measures the polarization of sunlight caused by the magnetic field. If the field is strong enough and sufficiently contorted, it is a good bet that it will, in effect, unravel, generating a CME in the process.

Last year two groups—one led by solar physicist Dick Canfield at Montana State University in Bozeman and the other by Ron Moore at NASA's Marshall Space Flight Center in Huntsville, Alabama—reported new ways of analyzing the solar magnetic field to improve CME prediction. Canfield's team used x-ray data from the Japanese Yohkoh satellite, launched in 1991. Because patches of corona with high magnetic fields are filled with hotter plasma than the surrounding areas, they emit more x-rays, an effect that highlights both the strength and orientation of the field. Canfield and his collaborators noticed that S-shaped fields, whose kinked structure suggests that they are wound up and ready to explode, were two or three times more likely to lead to CMEs than hot spots without any obvious structure—although, as Moore says, "it was not guaranteed." Moore and his colleagues noticed a similar effect when they used a magnetograph that could measure both the strength and three-dimensional orientation of the sun's field.



Wound too tight. S-shaped structures in the sun's magnetic field may foretell coronal mass ejections; these images from the x-ray satellite Yohkoh show a magnetic S before and after an ejection.

CREDIT: YOHKOH PROJECT/SXT GROUP/NASA/ISAS

To improve the data, NOAA is planning to put an x-ray imager on a future weather satellite. "Currently, we get a few x-ray images a day from the Yohkoh," says Zwickl. "The new x-ray instruments will deliver images every few minutes, 24 hours per day. For the first time, we will have continuous coverage of the sun's corona in x-rays, which will allow forecasters to see exactly the location of a flare and the start of any activity near active regions, as well as changes in the corona."

Once a CME is emitted, a pair of new satellites known as Stereo should be able to track it to Earth. One will lead Earth in its orbit around the sun and the other will follow. The twin spacecraft will observe the Earth-sun environment stereoscopically, using identical instruments. "Ideally, we will see clouds coming toward Earth, measure their velocity, and get all the information we need" to predict their effects at Earth, says Boston University space physicist George Siscoe.

Knowing that a CME is on its way and how big it is, forecasters' next step is to input that information into computer models of the magnetosphere and the ionosphere and generate specific predictions of the effects on and near Earth. The task, however, is extraordinarily complicated because the magnetosphere and ionosphere themselves are. "There is a tremendous variability in properties, ranging from the ionosphere, where it's very cold and dense with strong magnetic fields, to the outer region of the magnetosphere where it meets the onrushing solar wind. We have this huge volume of space and these vastly different properties of gases and magnetic fields that permeate the different regions," says Dan Baker, an atmospheric and space scientist at the University of Colorado, Boulder.

Some models are designed to skirt these complexities by simply predicting the impact and consequences of a solar storm based on what happened under similar conditions in the past. Others, however, model space weather from first principles, portraying the solar wind and the magnetosphere as interacting magnetized fluids. Both approaches have drawbacks: For some storms, there may be no good precedents to base predictions on, while the complex physics of space weather hampers efforts to simulate it from first principles. The goal of the recently formed Community Coordinated Modeling Center is to take the assorted models now being developed and try to combine them into a single model with the predictive power that models of terrestrial weather now provide. Michael Hesse, who directs the center, believes it can be done, but says actual numerical and localized predictions are still "a long, long, long way away."

Even when such a model is up and running, Baker adds, there will be a serious catch to its predictive power. As with terrestrial weather, the hardest things to forecast will always be the rarest, most extreme events. These are the ones that do the most damage—the space weather equivalent, for instance, of the massive flooding that resulted from Hurricane Floyd last October. "We're on a good path in space science toward the same kind of predictive capability as the meteorologists," Baker says. "But extreme events will probably still elude us to a significant degree, because they're so exceptional we either don't have any previous analogous events to base them on, or the system will get driven into some nonlinear state where we don't understand how it's behaving at all."

–GARY TAUBES