Hope for Magnetic Storm Warnings

Puffs of plasma from the sun can create magnetic havoc on Earth. Researchers are now sharpening their ability to predict these disturbances

ON 13 AND 14 MARCH 1989, ONE OF THE worst storms in recent memory struck Earth. The storm didn't knock down any trees or flood any houses, and most people weren't even aware of it. But some couldn't help noticing: the 6 million people in Quebec who were left without electricity when a power surge caused by the storm tripped protective switches, the pilots aboard the Concorde jets where radiation alarms sounded, and the military personnel who lost track of thousands of satellites and other orbiting objects when they were knocked out of position. This was no hurricane or typhoon—it was a storm in Earth's magnetic field, triggered by winds and particles blasting in from space. But it had one thing in common with more earthly tempests. Its severity caught cos-mic meteorologists by surprise and left them wondering how they could improve their predictive powers. Now, help appears to be on the way.

Space physicists have finally nailed down a long-running but hard-to-confirm hypothesis about what causes magnetic storms. For decades, they've attributed them to the solar flares that periodically leap from the surface of the sun. But researchers are gradually coming to accept that flares aren't the cause after all. The storms, it seems, result from another type of solar disturbance, known as coronal mass ejections, in which vast balloons of plasma lift off the sun's surface and escape into interplanetary space. "It was very difficult to get rid of the notion that magnetic storms come from big flares, because flares are just so spectacular," says Jo Ann Joselyn, a space physicist at the National Oceanic and Atmospheric Administration's Space Environment Laboratory in Boulder, Colorado. But it's now clear, she says, that "major storms don't have to come with sound and light."

To Joselyn, this new picture "has really revolutionized the way we think about prediction" and will eventually pay off in better forecasts. Such forecasts would be greatly welcomed by utilities, communications companies, and the military. After all, the 1989 storm may have been just a foretaste of what's going to happen in the next year or two, when the 11-year cycle of magnetic activity driven by the sun reaches its peak and major storms may occur at intervals of days or weeks. "The big storms are yet to come," says Joselyn, who with her National Oceanic and Atmospheric Administration (NOAA) colleagues issues 3-day magnetic storm warnings. And although it's unlikely that a foolproof prediction system will be in place by then, improved warnings would mean that utilities would be better able to prepare for power surges by shifting current from heavily loaded circuits, communications satellites could get ready for storms by changing frequencies, and the military would be less likely to misinterpret curious activity in orbit.

> ***"Major storms don't have to come with sound and light."***
>
> —Jo Ann Joselyn

The new understanding that may make all this possible did not emerge overnight, of course. Researchers got their first clues to the cause of magnetic storms back in the 1960s, when space probes began venturing outside the magnetosphere, the comet-shaped magnetic cocoon that surrounds Earth. There they made the first measurements of the solar wind—the tenuous, magnetized plasma of ionized gas, mostly hydrogen, that streams outward from the sun. The measurements showed that the solar wind was gusty—at times so gusty that it developed shock waves. These gusts seemed to sweep by Earth at the same time that ground-based instruments detected the signature of a magnetic storm: a kind of convulsion in Earth's magnetic field, which first surges and then weakens, inducing currents in power grids and other conductors at Earth's surface.

But while solar wind gusts are a necessary condition for magnetic storms, which are also marked by electric currents and showers of charged particles in the upper atmosphere and nearby space, they aren't sufficient. Space physicists soon agreed on an additional factor: At the time the gust reached the magnetosphere, the solar wind's own magnetic field had to be pointed southward—opposite to Earth's field. That way the interplanetary field lines could link up with Earth's in a kind of magnetic handshake, opening a route for particles and energy into the magnetosphere.

The findings about the solar wind gusts explained what perturbed Earth's magnetic field, but they did not shed any light on the question of what had disturbed the solar wind in the first place. For solar physicists, the brilliant solar flares were the obvious answer. For decades investigators had been marveling at the flares, which occur when an instability in the sun's magnetic field causes its surface to brighten many thousandfold and give off prodigious amounts of radiation and energetic particles. As space physicist David Rust of Johns Hopkins University explains: "It was a simple picture to say: 'Here's an explosion—a flare—and this shock wave goes through the corona [the sun's atmosphere].'" What's more, the flares often show up in solar telescopes a day or two before severe magnetic storms strike. Magnetic storms, it seemed, were the distant echoes of these solar explosions.

And that's where things stood when Skylab flew in 1973 and 1974 and made the first extensive observations of the sun's corona from space. They revealed what looked like a more direct trigger—coronal mass ejections. Every few days, recalls space physicist Jack Gosling of the Los Alamos National Laboratory, Skylab's coronagraph (a telescope equipped to block out the visible disk of the sun and reveal its outer atmosphere) showed vast, glowing bubbles of plasma escaping from the sun. From the size of these mass ejections—some of them were nearly as wide as the sun itself—and their density, Gosling and his colleagues estimated that they carried as much as 10 million metric tons of material. The fastest of them traveled at speeds of more than 1200 kilometers a second, more than three times as fast as the normal solar wind, and fast enough to slam into Earth's magnetosphere in less than 2 days. "When we started observing these coronal mass ejections," says Gosling, "we thought that these had to be the cause of magnetic storms."

That suspicion came to be shared widely

by space physicists. But confirming it has not been easy. The problem, says Gosling, has been that although mass ejections are easy enough to see at the edge of the sun, where they are silhouetted against the blackness of space, "what you can't see are the ones coming at you." And, as solar physicist Art Hundhausen of the National Center for Atmospheric Research's High Altitude Observatory in Boulder puts it: "That's where Gosling has made an advance."

Even by the mid-1980s, Gosling and his Los Alamos colleagues had started to make progress. They were looking over data collected by a remarkable probe, International Sun-Earth Explorer-3 (ISEE-3). ISEE-3 had spent the last solar-cycle maximum, from its launch in 1978 through 1982, circling the so-called L1 point, about a million kilometers sunward of Earth, where the sun's gravitational pull just balances Earth's. Occupying a kind of lookout post in the solar wind, ISEE-3 presumably lay right in the path of mass ejections headed toward Earth. And Gosling and his colleagues noticed an unusual signature in the data collected by its instruments: Waves of electrons were shuttling in both directions along magnetic field lines.

These "counterstreaming" electrons were a puzzle, because high-energy electrons from the sun normally take a one-way trip outward along the solar wind's open magnetic field lines. What the investigators were seeing, they soon realized, was the signature of coronal mass ejections sweeping past the probe. Gosling and his colleagues reasoned that mass ejections ought to drag closed magnetic loops out into space from the sun, stretching the field lines like taffy. That field configuration could account for the counterstreaming electrons. As Gosling explains: "When you get a loop of magnetic field coming out of the sun, electrons run both ways, because both ends are connected to a hot object, the sun."

That was a crucial recognition: It meant that Gosling and his colleagues could pin down the role of mass ejections in magnetic storms by determining if severe storms correlated with the episodes of counterstreaming electrons that showed up in 4 years of data from ISEE-3.

Their results, published last year in the 1 May issue of the *Journal of Geophysical Research*, leave little doubt about the role of mass ejections in the largest and most damaging storms. Of the 14 most severe magnetic storms in the 4-year period, all but one began about the time a wave of counterstreaming electrons swept over ISEE-3. And even the one exception may still have been triggered by a mass ejection. Though the probe didn't see the electron signature, it did record a shock—the broad bow wave, Gosling suggests, of a mass ejection that just missed the spacecraft. Other space physicists seem to have accepted the idea. "In my picture, 80% of large storms are caused by magnetic clouds [a form of mass ejection] and coronal mass ejections," says Len Burlaga, a space physicist at the Goddard Space Flight Center in Greenbelt, Maryland, "and most people would agree with that."

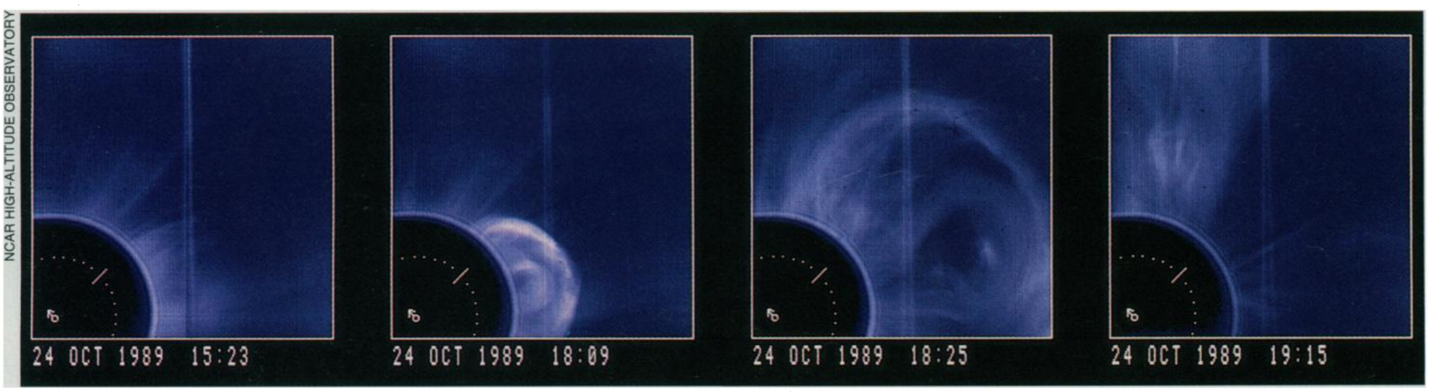
So now the challenge is to turn that understanding into better ways to predict magnetic storms. "I'm trying to convince people who are interested in prediction that it can be done," says Gosling. But the effort faces some hurdles, one of which is the lingering specter of flares. Hundhausen says some researchers have continued to argue that even if flares aren't the direct cause of magnetic storms, they may still trigger them indirectly—by unleashing coronal mass ejections. That would mean that flare observations might still be the key to reliable storm warnings several days in advance. Not so, says Hundhausen. "What we see is that mass ejections often occur without any flare, or with a flare occurring only afterward."

Hundhausen and other researchers, including Richard Harrison of Britain's Rutherford-Appleton Laboratory, came to that conclusion after 3 years of scrutinizing both space- and ground-based observations of the corona. The observations show, Hundhausen says, that mass ejections develop from vast, domelike eruptions of ionized gas called helmet streamers. The streamers' appearance suggests that they are tethered to the sun's surface by magnetic field lines. But the fields shift continuously, and "when the roots of the closed field lines move apart, the streamer gets bigger," says Hundhausen. "Eventually the field evolves to where it can no longer hold the plasma down," and the plasma is unloosed as a mass ejection. Afterward, the underlying magnetic field reorganizes itself—a process that sometimes, but not always, generates a flare within 20 to 30 minutes of the mass ejection's lift-off. In that picture, flares are, at best, "a sort of side effect of the mass ejection," Hundhausen says.

As a result, he maintains, scientists trying to predict magnetic storms would do better not to focus on flares but on other markers more directly linked to mass ejections. One possibility: The tongues of cool gas called prominences, which are visible on the face of the sun. "When you see a prominence lift off, you know something has blown out," says Hundhausen. If it's a big prominence and it lifts off fast, he continues, you might infer that a major mass ejection is on its way to Earth. But he cautions that there is no good way of clocking the erupting prominence's final speed to learn whether it heralds a large mass ejection.

Still, Joselyn says that NOAA's Space Environment Laboratory is already taking these new developments to heart in making its 3-day storm forecasts, which are based largely on images from solar telescopes. Instead of watching for isolated flares, she and her colleagues are now alert to erupting prominences and to large clusters of flares that might have been triggered by a mass ejection. "We're looking at the forest instead of that one big tree [the flare]." And though predicting storms is still highly inexact, she says, "we're doing better on false alarms and on hitting storms."

Further improvement, researchers agree,



NCAR HIGH-ALTITUDE OBSERVATORY

Up, up, and away. *Millions of tons of ionized gas erupt from the sun's atmosphere in a coronal mass ejection, captured by the Solar Max satellite in 1989 in a 3-hour sequence. The event could trigger a magnetic storm if it were headed toward Earth.*

will require some way to detect mass ejections directly. Ernest Hildner, director of the Space Environment Laboratory, raises one possibility: the radio-frequency twinkling, called interplanetary scintillation, that a mass of oncoming plasma would create. Like a dust cloud growing on the horizon, the twinkling would warn that a mass ejection is on the way. Other researchers speak of powerful radar that could clock the onrushing plasma like a traffic officer's radar gun. Still others, including Gosling, dream of a satellite that would trace out the same orbit as Earth, but offset by a quarter of a revolution, so it could watch the edge of the sun for mass ejections that are headed toward Earth.

Even those schemes won't yield foolproof warnings, however, until some remaining scientific issues are cleared up. Bruce Tsurutani of the Jet Propulsion Laboratory and Walter Gonzalez of the National Institute of Space Research in São Jose dos Campos, Brazil, have found that only about one mass ejection in six is accompanied by a southward magnetic field strong enough to cause a large storm. Just why is still not known. One factor may be how fast the mass ejection plows through the solar wind, compressing and intensifying the fields ahead of it. Large storms may also be favored by episodes of southward field on the sun or in the solar wind—and investigators are still unsure what causes those episodes, or how to predict them.

But another plan might give reliable—albeit very short-term—warnings even before those issues are resolved. The idea, as Hildner describes it, would be to recreate the success of ISEE-3 by stationing a monitor upwind of Earth at the L1 point. By recording both mass ejections and the accompanying magnetic fields, such a solar wind sensor "could give an hour's warning [of a magnetic storm] with almost 100% certainty," he says. "That way, you'd know when the dam had burst and the flood had started toward you." An hour may not sound like much time, but Hildner says it would be enough for utilities, satellite operators, and communications networks to prepare for magnetic havoc.

The Department of Energy and the Air Force are cheering NOAA on in its campaign for a solar wind monitor, Hildner says, and several private space companies are interested in launching and operating the probe and selling the data to NOAA. The worst magnetic storms of this solar maximum may have come and gone before any such warning system gets off the ground. But before the solar cycle peaks again, bringing a new season of magnetic storms, the deep space weather station may be on site.

■ TIM APPENZELLER

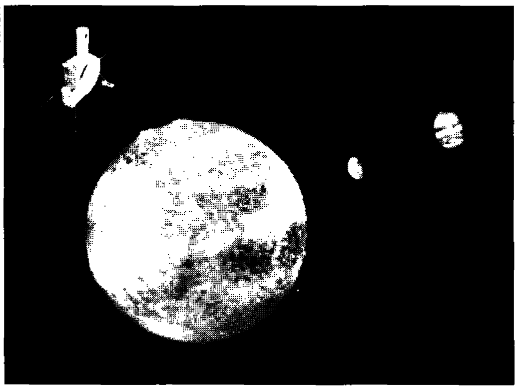
Boom and Bust at Jupiter

When the Ulysses spacecraft swung by Jupiter early this month on its way to study the sun's polar regions, the U.S. and European scientists monitoring its transmissions got a big surprise. Since Jupiter was last visited, by the two Voyager spacecraft in 1979 and 1980, the planet's enveloping magnetosphere has swollen to twice its former size. Now scientists are wondering what periodically pumps up the magnetosphere—a teardrop-shaped region of ionized gas, or plasma, trapped by the planet's magnetic field. A likely candidate: the erupting volcanoes of the Jovian moon Io.

In retrospect, Ulysses scientists say, they might not have been so surprised by the size of the magnetosphere if they had taken full account of some earlier observations. The Voyager encounters had led them to predict that Ulysses would not reach the bow shock—where the plasma wind that streams out from the sun slams into the magnetosphere—until the spacecraft came within about 4 million kilometers of the planet. But the two Pioneer spacecraft, which visited Jupiter in 1973 and 1974, had sometimes encountered the bow shock at 8 million kilometers out, notes space physicist Edward Smith of the Jet Propulsion Laboratory, who is NASA's project scientist for Ulysses. And as it happened, that's just where Ulysses' bow shock crossing came.

The big question now is what is driving these changes in the size of Jupiter's magnetosphere. Part of the answer undoubtedly lies in changes in the solar wind, says Smith. The greater its speed and density, the more it will compress the leading edge of the teardrop magnetosphere toward the planet. When Ulysses approached Jupiter, Smith notes, the solar wind pressure was down, so an expanded magnetosphere might have been expected.

NASA



Farewell to Jupiter. *Ulysses reaches the sun.*

But Smith suspects the solar wind is not alone in shaping Jupiter's magnetosphere. And that's where Jupiter's satellite Io comes in, because it has a clear influence on the magnetospheric plasma. Orbiting 0.4 million kilometers from the planet, Io has active volcanoes that spew towering plumes of sulfur dioxide. Indeed, a ton of that sulfur dioxide escapes from the satellite's gravity every second to be dispersed as plasma throughout the Jovian magnetosphere. Like air blown into a balloon, the Io plasma could be inflating the magnetosphere, Smith says.

But too much added plasma could make the magnetosphere go bust. Load the magnetic field lines with Io plasma, as might happen at times of heightened volcanic activity, and they might collapse into a more compact arrangement, shrinking the magnetosphere. Io has been relatively quiet in the past year, but it was quite active a decade ago, when the Voyagers saw a shrunken magnetosphere.

The realization that Io may be inflating and collapsing the parent planet's magnetosphere wasn't the only surprise to emerge from Ulysses' brief Jupiter encounter. The Jovian magnetosphere has also changed in character since it was last studied. The smaller magnetosphere charted by Voyager had a simple configuration. What Ulysses found in the outer reaches of the swollen magnetosphere was quite different: an unruly jumble of changing fields and plasma flows. Deeper within the magnetosphere lay another striking change: The equatorial disk of dense plasma, which may be fed by Io, was far larger than it was before. Team member Andre Balogh of Imperial College, London, thinks that blobs of plasma flung off the edge of this disk may be contributing to the commotion in the outer magnetosphere.

Researchers don't know exactly how the tug of war between Io and the solar wind might be producing this Jekyll and Hyde magnetosphere. And because Ulysses will never return to Jupiter, magnetospheric researchers eager to learn more have to wait at least until 1995, when the Galileo probe will make its rendezvous with Jupiter. The wait will be even longer, of course, if JPL's engineers don't succeed in straightening out Galileo's crippled main antenna before then.

■ RICHARD A. KERR