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The Sun's Fury In Three Dimensions

The Ulysses spacecraft's unique orbit over the solar poles gives scientists otherwise unattainable insight into the driving forces behind space weather.

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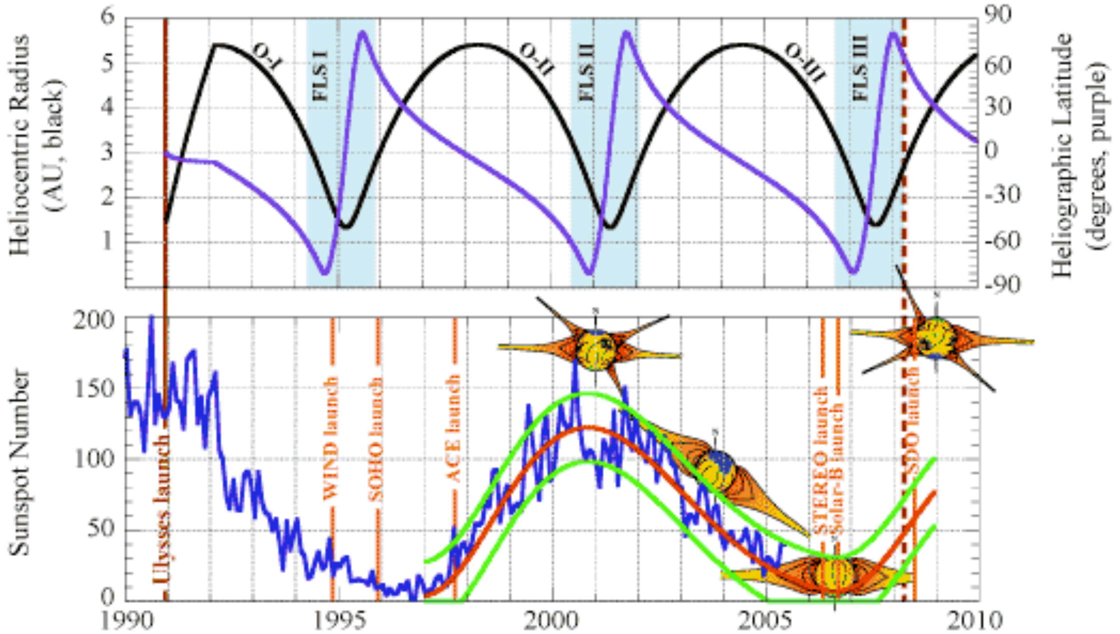
As electrified blobs of the Sun's gaseous outer atmosphere blow past Earth, the resulting geomagnetic storms can disable wireless telephone calls, satellite communications and electric power grids. Predicting when such detrimental solar activity will strike is a fundamental goal of space weather research. Yet computer models that make such forecasts have been long handicapped by a limited perspective.

Until recently, scientists got good looks at our parent star only near a thin plane that intersects its mid-section; most spacecraft, like Earth and the other planets, circle the sun near its equator. This partial, two-dimensional knowledge is not sufficient to build practical space weather forecasting models, notes Louis J. Lanzerotti, a physicist with Lucent Technologies' Bell Labs and the New Jersey Institute of Technology, and the editor of this journal.

That situation changed for the better in 1990, when the space shuttle Discovery launched Ulysses, a joint mission of NASA and the European Space Agency. The first and only spacecraft to fly an unusual orbit that takes it over the Sun's polar regions, Ulysses soars 80 degrees north and south of the solar equator, roughly analogous to the northern tip of Greenland and the coastline of Antarctica on Earth. Now scientists are getting clear, high-latitude views of the Sun as it passes through its full range of activity levels, and many of these observations have forced fundamental changes in the way scientists think about space weather.

Ulysses' first polar orbit from 1992 to 1998—glimpsed the Sun's poles during its periodic relatively calm phase, called the solar minimum. More discoveries came to light as scientists compared those initial measurements with others taken along the spacecraft's second, six-year orbit, when the polar passages in 2000 and 2001coincided with the start of the Sun's most turbulent period, known as solar maximum. Ulysses is now just beginning its third orbit, which will finish in March 2008 if NASA agrees to extend the mission (Figure 1).



Steven T. Suess / NASA Marshall Space Flight Center

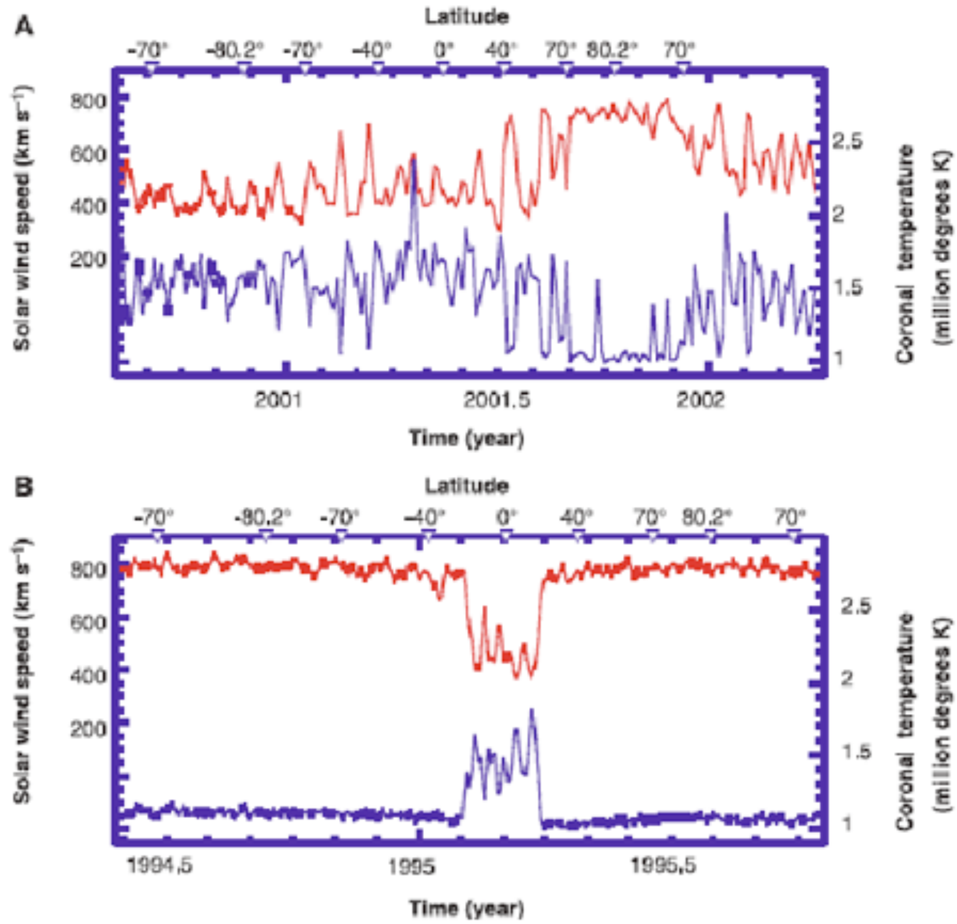
Figure 1. Ulysses' position relative to the Sun (top panel) plotted against average monthly sunspot numbers (bottom panel; larger numbers mean more solar activity) shows how the spacecraft flew nearest the Sun's poles during the minimum (in 1994–95) and maximum (2000–01) of the most recent solar cycle. Ulysses has just begun its third orbit and will next glimpse the solar poles during the next solar minimum (2007–08) if NASA approves a proposed mission extension.

Blown Away

Ulysses scientists began their studies knowing that the degree of space weather disturbances at Earth depends in great part on the speed of the solar wind. Simply put, faster wind causes stronger geomagnetic activity. But before Ulysses, scientists had only a partial view of the fastest wind, which moves at 600 to 900 kilometers per second, because it originates at the Sun's high latitudes—out of sight for Earth-based instruments and spacecraft flying at low latitudes, said Edward J. Smith of NASA's Jet Propulsion Laboratory in Pasadena, Calif. Smith serves as the U.S. project scientist for the Ulysses mission.

Measurements made in the 1970s by astronauts on the space station Skylab revealed that much of this fast wind originates in holes in the Sun's polar regions. These so-called 'coronal holes' are low-density regions that form as the solar wind flows out into space. The wind leaves these coronal holes along "open" magnetic field lines that are attached to the Sun at one end and stretch into space at the other, like streamers blowing outward from an electric fan, explained Smith.

Keeping an eye on the elusive wind emanating from the coronal holes led to a few of the mission's first big surprises. Early on, it became clear that the speed of the fast wind varies inversely with the electron temperature of the corona—exactly the opposite of what prior models of the Sun predicted. Those previous models, which relied on pressure gradients to create the solar wind, implied that higher temperatures should lead to faster, not slower, gales (Figure 2).

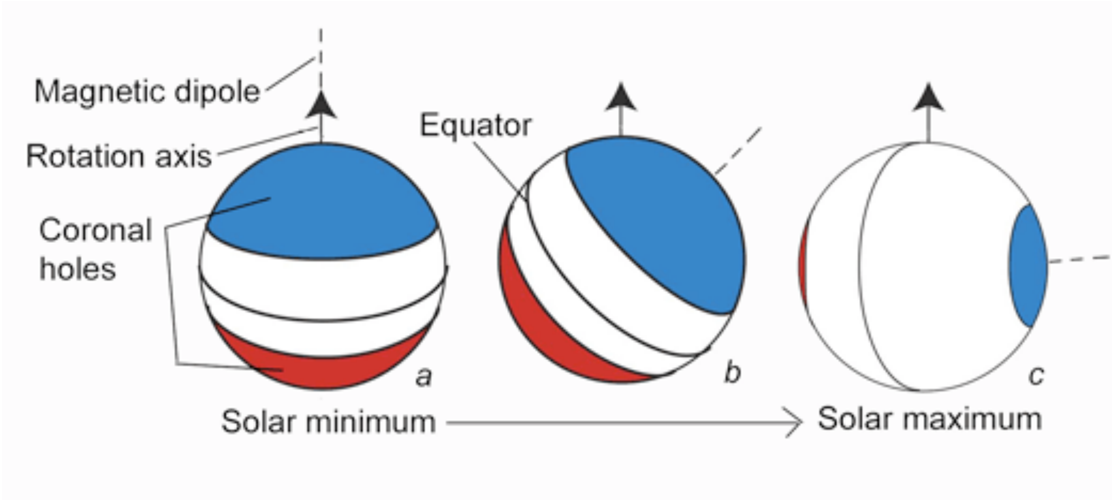


George Gloeckler and SWICS (Solar Wind Ion Composition Spectrometer) Ulysses instrument team.

Figure 2. One of Ulysses' many surprising observations is that the speed of the fast solar wind varies inversely with coronal temperature—the opposite of what most models of the Sun predicted previously.

Other revelations came about as Ulysses watched the fast wind change through a complete solar cycle. Observations of the close relationship between the wind, the Sun's magnetic field, and the position and size of the coronal holes clarified how and when the high speed solar gale reaches solar latitudes low enough to sweep past Earth, Smith explained.

Scientists have long understood that the coronal holes form at the two ends of the Sun's magnetic dipole, which is analogous to a bar magnet. At solar minimum, the dipole axis nearly coincides with the Sun's axis of rotation (similar to Earth's dipole), which means the fast wind is unable to reach low latitudes. But Ulysses observed that angle between the magnetic dipole and the rotation axis changes dramatically approaching solar maximum: the dipole falls sideways, becoming nearly parallel to the Sun's equator (Figure 3).



Steven T. Suess / NASA Marshall Space Flight Center

Figure 3. Fast solar wind emanating from holes in the Sun's corona can kick up space weather at Earth when it leaves the Sun near its equator. Fast wind is rarely seen at the equator at solar minimum, when the magnetic dipole is aligned with the rotation axis (a). Then, as the dipole begins to tilt, the Sun's rotation means alternating fast and slow wind head toward Earth as the edges of the coronal holes rotate around the low latitudes (b). At solar maximum, the dipole lies nearly parallel with the equator, but fast wind lessens because the coronal holes are smaller (c).

As solar activity begins to decrease once again, the magnetic dipole begins a gradual excursion toward a more north-south orientation. For a time during this phase, the tilt of the dipole and the large area of the polar holes cause a segment of the fast wind to cross low latitudes as the Sun rotates. In other words, every 27 days the edge of one or the other of the coronal holes points outward from the equator and hurls its fast wind earthward like the revolving beam of a lighthouse.

Sudden Storms

Just as sudden thunderstorms, tornadoes, and hurricanes on Earth can make already bad weather worse, the Sun can whip up sudden storms that cause havoc beyond what the solar wind dishes out. Based in significant part on Ulysses observations, space scientists now widely recognize large solar eruptions called coronal mass ejections (CMEs)—billions of tons of the Sun's atmosphere traveling in a self-contained cloud of magnetized plasma&m-dash;as the cause of much of the most threatening space weather, said Jack Gosling of the Laboratory for Atmospheric and Space Physics at the University of Colorado.

By providing the first observations of CMEs ever at high solar latitudes and the first good observations of CMEs beyond Earth's orbit, Ulysses observations revealed much of the basic nature of these phenomena that experts now treat as common knowledge. In the early 1990s, for instance, Ulysses-related research helped overthrow the notion that CMEs are the result of solar flares and demonstrated that they can speed up or slow down dramatically as they interact with the surrounding solar wind, Gosling explained.

Gosling said the biggest surprise was the discovery of a new type of CME-driven upheaval at high latitudes —so-called 'over-expanding CMEs.' "This type of disturbance was found to be relatively common at high latitudes but had never been observed in the ecliptic plane," he said. Such insights about tumultuous activity outside of the immediate line of sight between the Sun and Earth is critical for making accurate forecasts of the space weather astronauts might encounter on their way to Mars or elsewhere in the solar system.

Similarly, Ulysses measurements were the first to reveal the true three dimensional nature of an entirely different type of far-reaching solar wind disturbance that can encumber interplanetary travelers and earthbound systems alike, Gosling said. These disturbances, known as corotating interaction regions (CIRs), are produced when streams of high-speed wind overtake the slow solar wind blowing ahead of it.

The collision between the fast and slow wind masses creates a region of denser magnetic fields and higher pressures that accelerate the solar wind both ahead and behind it. Because both wind flows rotate with the Sun, CIRs return every 27 days, causing recurrent geomagnetic disturbances quite different from the singular events that CMEs stir up. What is more, a single CIR-initiated geomagnetic storm at Earth can last for several days at a time, rather than only a day or less.

Problematic Particles

Gusts of solar wind and magnetized clouds of plasma are not the only sources of space weather. Whizzing around the solar system are two types of particles that can also cause trouble: galactic cosmic rays and solar energetic particles. Both kinds of particles have extraordinary penetrating power and can disrupt anything from microelectronics in spacecraft to DNA (?) in human cells.

Galactic cosmic rays enter the solar system from interstellar space. With its unique ability to monitor these particles throughout the heliosphere, Ulysses has confirmed that their history strongly determines their behavior and characteristics near Earth. For instance, scientists knew that the Sun's extended magnetic field holds off 30 percent more cosmic rays at its maximum activity level than at its minimum, said J. Randy Jokipii, a space physicist at the University of Arizona in Tucson. But Ulysses observed the unexpected result that this reduction of cosmic rays is similar at all heliolatitudes, he added.

Ulysses also uncovered significant surprises regarding solar energetic particles that originate at the Sun, primarily in dark patches of extreme activity known as sunspots or in groups of sunspots called solar active regions. Solar activity in a new solar cycle begins at mid-to-high solar latitudes and then slowly migrates toward the equator. Before Ulysses, scientists could not see what was happening with the particles when these regions were at high latitudes, but they generally assumed that hazardous particles emanating from these regions would be delayed in reaching earth.

But around solar maximum, when the sunspots were at the equator, Ulysses measured these particles at high latitudes a very short time after activity at the equator, implying that the particles had moved across latitudes much more quickly than thought possible. "If they can move from the equator to the poles, the converse can be true as well," Lanzerotti said. "That means solar particles produced almost anywhere could affect the Earth."

Anchors Away

Realizing that solar particles were so unexpectedly mobile had even more profound implications for the basic nature of the Sun's magnetic field "and provided key insights into the way the solar wind is generated, said Lennard A. Fisk of the University of Michigan.

"We didn't think the field moved systematically on the Sun," said Fisk, who was NASA's associate administrator for space science and applications before joining the University of Michigan faculty in 1993. Since the late1950s, based on a theory known as the Parker spiral, many solar physicists would have accepted that magnetic field lines are effectively anchored into the photosphere of the Sun, like hairs are rooted in your head, Fisk explained. In contrast to this theory, the mobility of the charged solar particles may imply that the origins of the magnetic field lines themselves can migrate over long distances.

Fisk and other researchers have different interpretations about how the field moves, but the bottom line is the same: "We can argue about the details, but there's got to be motions of the field lines back at the Sun," he said.

If the magnetic field is in motion that could mean that the generation of solar wind might well be embedded in the behavior of the magnetic field, Fisk says. "If you're moving a magnetic field around on the Sun, especially a tangle, the magnetic field is going to do work on the corona," he explains. "It's like frictional resistance. The heat generated could be enough to accelerate the particles that make up the solar wind."

If true, it could be much easier to model the origins of space weather than anyone ever thought, mostly because people thus far have been treating the solar wind and magnetic field separately. "What we need is one model for both the magnetic field and the solar wind," Fisk says. "If we can couple those things we'll be much closer to the 'real' model."

The Future in 3-D

Tackling lingering controversies over the behavior of the Sun's magnetic field is one of the major motivations behind extending the Ulysses mission, which could otherwise end early next year. Viewing the Sun through a complete 22-year cycle of its magnetic field—in other words, two complete polarity reversals—would help fill in the gaps, said Ulysses associate project scientist Steven T. Suess, who is based at NASA's Marshall Space Flight Center in Huntsville, Ala.

Other invaluable benefits stem from Ulysses' partnerships with other spacecraft that sample the Sun's fury from the ecliptic, Suess pointed out. In these cases, Ulysses' existence makes it possible to produce three-dimensional observations of single space weather events, he says. For instance, Ulysses often catches the full brunt of solar explosions that the Solar and Heliospheric Observatory (SOHO) sees from the side. Together, Ulysses and SOHO can produce a stereoscopic snapshot of the goings-on, the way the space between human eyes facilitates depth perception.

Using joint Ulysses—SOHO studies, scientists learned how to maximize 3-D views of CMEs and other space weather-inducing disturbances in the solar wind in time to benefit the Solar Terrestrial Relations Observatory (STEREO) mission, Suess says. Scheduled for launch in 2006, this pair of spacecraft will fly facing the Sun just above the ecliptic, with the Earth's orbit between them.

Despite SOHO, STEREO and other members of the world's fleet of Sun- and earth-observing spacecraft, none can replace the heliosphere coverage of Ulysses. "Now the question is how long we can keep Ulysses running," Fisk said. "What worries me is that we'll revert back to our two-dimensional ignorance just when we're ready to make dramatic advances."

More information on the Ulysses mission is available at http://ulysses.jpl.nasa.gov/ and at http://helio.estec.esa.nl/ulysses/welcome.html.

Sarah Simpson is a freelance writer and contributing editor for Scientific American.

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Sidebar

1. **The Sun's Fury in Three Dimensions**
   [Bold*]Ulysses Highlights[*Bold]

   Without the unique, polar view of the Sun that Ulysses has provided for the past 15 years, dozens of observations critical to making accurate space weather predictions would remain unknown or poorly understood. Here are a just a few of them:

   • The speed of the fast solar wind originating in coronals holes varies inversely with electron coronal temperature&m-dash;the opposite of what most models of the Sun predicted previously.

• Dramatic tilting of the Sun's dipole axis, from vertical during solar minimum to nearly parallel to the equator approaching solar maximum, determines for a time whether the fast solar wind blows by Earth.

• Unique looks at the three-dimensional structure of the solar wind, particularly coronal mass ejections and corotating interaction regions, provided several key insights important for predicting space weather problems at Earth and for astronauts and instruments in space.

• At solar maximum, the flux of dangerous galactic cosmic rays is reduced approximately symmetrically at all heliolatitudes.

• Rapid distribution of solar energetic particles across solar latitudes means extra danger in the early part of a solar cycle and implies that the Sun's magnetic field is in motion.