Probing the Long Tail of the Magnetosphere

The most prolonged forays ever into the deep geomagnetic tail have found evidence of great blobs of plasma whose formation helps drive the aurora

The nighttime polar skies with their dancing auroral lights have been compared to a television screen that fascinates the viewer but betrays little about the machinery hidden behind it that makes it work. Scientists curious about what flings charged particles against the upper atmosphere to produce the aurora—the way the television tube's electron gun shoots at the screen—have reached higher and higher with rockets and now progressively higher flying satellites, looking for the solar-powered machine that accelerates charged particles Earthward.

A lone spacecraft looping as much as 1.4 million kilometers down the tail of Earth's magnetosphere has found the magnetotail flapping in the solar wind but still intact. This new distant perspective has convinced many researchers that a pinching off of part of the magnetotail sends great blobs of charged particles rushing down the tail while accelerating another mass of plasma toward Earth to drive the aurora. According to this view, the magnetotail stores energy and particles skimmed from the passing solar wind and then releases them suddenly, much of the plasma escaping down the tail without ever affecting Earth.

The recent probing of the deep magnetotail was something of an afterthought. For 4 years the International Sun-Earth Explorer-3 spacecraft (ISEE-3) had been lazily circling a point 1.5 million kilometers (240 Earth radii) sunward of Earth, thanks to a balance between the gravitational pulls of the sun and Earth. Being always between the two bodies, ISEE-3 could report on the electrons, protons, and other charged particles rushing from the sun at hundreds of kilometers per second well before this solar wind and the sun's magnetic field embedded in it encountered Earth's magnetic field.

To send ISEE-3 on the first leg of a jury-rigged mission to intercept the comet Giacobini-Zinner, the satellite's controllers rocketed it out of its halo orbit in the solar wind upstream of Earth and into a carefully choreographed series of orbits under the influence of the gravitational fields of both Earth and the moon. Swinging by Earth, it would sail down the magnetotail, slow to a near standstill for weeks at a time, and then loop back—usually in a figure eight—to swing by the moon and Earth and repeat the process. Its deepest long-duration penetration of the tail reached a distance of 240 Earth radii. That was far beyond the limits of all but a few previous missions, most missions not reaching past the moon's orbit at 60 Earth radii.

ISEE-3's most clear-cut discovery was that there is a recognizable tail to the magnetosphere a million kilometers beyond the moon's orbit. Two earlier spacecraft on their way to more distant targets passed briefly through the tail at about 500 and 1000 Earth radii, but researchers could not agree whether the tail there was intact or shredded into separate filaments by the solar wind. The large amount of data produced by ISEE-3 allowed Bruce Tsurutani of the Jet Propulsion Laboratory, Douglas Jones of Brigham Young University, and David Sibeck of the University of California at Los Angeles to determine the structure of the tail with good statistical reliability.

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According to Tsurutani's group, beyond 200 Earth radii, the magnetotail structure is surprisingly like that of the tail near Earth. It measured about 55 Earth radii from north to south and 45 Earth radii across, despite the expected tendency of the interplanetary magnetic field enveloping it to squash it until it is wider than it is high. The shifting solar wind, the tail's own tendency to twist, and internal disturbances of the tail caused it to flap back and forth only 6 degrees at most. And the internal structure of the tail—the northern and southern tail lobes enveloping a flat, central plasma sheet—is the same as near Earth. The plasma sheet, where most of the solar wind's plasma is trapped, is 9 to 15 Earth radii thick, much as it is near Earth.

The structure of the tail may have been familiar, but some of its behavior was not. In the plasma sheet of the distant tail, ISEE-3 found plasma flowing tailward as fast as 1000 kilometers per second, far faster than the few tens of kilometers per second detected near Earth and at times even faster than the solar wind. An ISEE-3 group at the Los Alamos National Laboratory headed by Samuel Bame has offered an explanation of the high plasma speeds that addresses how the magnetosphere stores and ultimately rids itself of the charged particles and magnetic fields that it picks up from the solar wind.

The high tailward plasma sheet flows are driven by a process called magnetic reconnection, according to the model advocated by the Los Alamos group and others. Reconnection of magnetic field lines makes the difference between a closed, static magnetosphere and a dynamic, open one. A closed magnetosphere is typified by the magnetic field lines that make closed loops from one pole of a bar magnet to the other in the familiar iron filings experiment. All terrestrial magnetic field lines would have both ends firmly anchored on Earth in a closed magnetosphere. On the upstream side of an open magnetosphere, properly oriented field lines of the solar wind field and the terrestrial field—driven together by the solar wind—would break open. But terrestrial field lines would reconnect with solar wind field lines, which would peel open the upstream side of the terrestrial field like an orange.

Anchored to Earth at only one end now, the reconnected field lines "blow" downwind, drape around the closed field lines of the inner magnetosphere, and form the north and south lobes of the tail. Because reconnection on the upstream side has added magnetic field lines to the tail of the magnetosphere, reconnection must also occur on the downstream side so that magnetic flux does not accumulate there indefinitely. Reconnection occurs where the opposing lobes come together, beyond the end of the plasma sheet. Reconnected field lines Earthward of this magnetic neutral point are closed and become part of the plasma sheet. Downstream of the neutral point, the new field lines are not attached at all to Earth and flow away. Both sets of new field lines carry with them plasma allowed to enter the magnetosphere because of the upstream reconnection. Such reconnection proceeds even during minimal solar activity.

One major question about the magnetic neutral point has been, Exactly where is it? A satellite encounter with the neutral point is unlikely, so researchers have had to infer its position. Somewhere beyond the moon was about as precise as anyone could be until ISEE-3. Ronald Zwickl and his colleagues at Los Alamos believe that the new measurements of plasma flow in the tail beyond the moon place the neutral point typically at about 100 Earth radii, or about 40 Earth radii beyond the moon. Inside of 100 Earth radii, plasma seems to flow away from Earth as often as it flows toward it, but beyond 120 Earth radii the plasma almost always flows away. The neutral point—the reconnection-driven plasma source—presumably lies between these two points.

Although Daniel Baker of the Los Alamos group calls this "rather definitive" evidence, he points out that it has not yet been reconciled with the ISEE-3 observation that the magnetic field is not consistently southward—the direction expected beyond the neutral point—until a distance of about 200 Earth radii. In any case, the neutral point must typically lie in the now explored region between 100 and 200 Earth radii.

The most provocative proposal from the Los Alamos group is that ISEE-3 found strong evidence of a third reconnection site. Such a site had been proposed on the basis of near-Earth observations to explain the sudden brightening and poleward spreading of the aurora called an auroral substorm. Depending on the level of solar activity, substorms lasting an hour or two recur from a few times a day to almost continually. According to the reconnection explanation of substorms, the magnetosphere begins to store energy after enhanced reconnection on the upstream side couples additional solar wind to the tail. As the stored energy grows, the tail lobes swell, squeeze the central plasma sheet, and, after an hour or so, pinch it in two at a distance of about 10 to 20 Earth radii. Earthward of the new neutral point, the new closed field lines (which are attached to Earth) spring inward, accelerating the enclosed plasma toward the upper atmosphere and creating an auroral substorm.

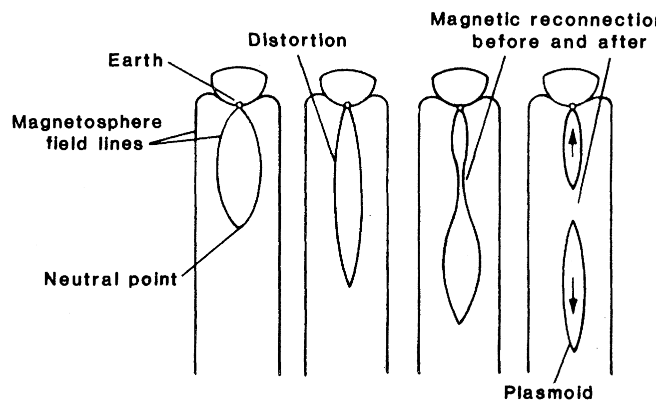
Tailward of the new neutral point, the field lines would also be closed but they would not be anchored. Between the new and the more distant neutral point, the field lines would enclose a blob of plasma called a plasmoid. Unanchored, a plasmoid would rush downstream, carrying much of the energy picked up from the solar wind. The whole system resembles a dripping faucet—droplets or plasmoids split off and fall away when the strain becomes too great while the remaining water or plasma momentarily springs back. It was rapidly departing plasmoids that ISEE-3 encountered beyond the moon's orbit, the Los Alamos group suggests, so that the activity detected by near-Earth spacecraft that so confused earlier analyses must have been the turbulent result of nearby reconnections.

The Los Alamos group cites several lines of evidence supporting the reconnection model of substorms. At a distance of about 220 Earth radii, things are relatively quiet until about half an hour after the beginning of a substorm back at Earth, when a denser, more energetic, higher speed plasma appears. One-half an hour is enough time for this plasma to have traveled from the near-Earth reconnection point at its speed of up to 1000 kilometers per second. At the same time, the tail's magnetic field swings to the north and then back toward the south. That is the sequence expected from the passage of a plasmoid. And the energetic plasma particles seem to be moving at this time as if they are trapped within closed magnetic field lines rather than free to stream away along open field lines.

Most researchers now agree that plasmoids probably do form, or at least that the ISEE-3 observations are consistent with the model. However, some researchers have reservations. A common complaint is that the use of a single spacecraft prevents a truly objective distinction between changes due to the spacecraft moving through the tail and those caused by the tail moving across the spacecraft. As a result of such limitations, some ISEE-3 data remain open to multiple interpretations. For example, Tsurutani notes that although the reorientations of the magnetic field do correlate with substorms—supporting the plasmoid interpretation rather than a flapping of the tail across the spacecraft—the character of magnetically trapped particles could be mimicked by the high turbulence in the tail.

There is also a competing philosophy, if not a specific alternative, that is challenging the reconnection model. Reconnection and plasmoid formation may or may not occur, argue some skeptics such as Louis Frank and Timothy Eastman of the University of Iowa, but, even if they do occur, do they dominate all the other processes in the magnetosphere that can accelerate charged particles? Frank and Eastman suggest that there are other candidate processes, in particular, those connected with the outer boundaries of the magnetosphere and the plasma sheet. Although these boundary layers constitute less than 5 percent of the volume of the outer magnetosphere, Eastman and Frank say, they carry more than 50 percent of the plasma and energy. A relatively small effect in the boundary layers, whose more complex physics makes quantitative calculation difficult, could be crucial to understanding the operation of the entire magnetosphere, they say.

As the new ISEE-3 observations become more widely disseminated, the existence of near-Earth reconnections may become even more generally accepted, but the vocal skeptics and those with less public reservations will expect a great deal more work to be done. Some even see an eventual merging of reconnection and boundary-layer models as the most likely outcome.—**RICHARD A. KERR**



The dripping-faucet model

With the solar wind blowing from the top, the plasma sheet of the inner magnetosphere is drawn out and then pinched off to form a plasmoid, much the way a drop of water falls away from a dripping faucet. [Los Alamos National Laboratory]

Additional Readings

1. T. E. Eastman and L. A. Frank, in *Magnetic Reconnection in Space and Laboratory Plasmas* (American Geophysical Union, Washington, D.C., 1984), pp. 249–262.
2. J. T. Gosling, D. N. Baker, E. W. Hones, Jr., *Los Alamos Sci.* (No. 10) (spring 1984), p. 32.
3. B. T. Tsurutani and T. T. von Rosenvinge, Ed., special "ISEE-3 Distant Geotail Results" issue, *Geophys. Res. Lett.* **11**, 1027 (1984).