Three-Spacecraft Team Probes the Magnetosphere

New data tie magnetospheric physics to solar and nuclear physics and astrophysics

Two satellites chasing each other around the magnetosphere have found evidence of a major link between the earth and the sun. Magnetic field lines from the sun appear to merge with some from the earth. The merging of field lines rips open the magnetosphere—idealized as a cocoonlike barrier to the solar wind and cosmic rays—leaving the earth vulnerable to influences by the sun. Such magnetic liaisons are thought to play key roles in many astrophysical phenomena.

The satellites are part of the International Sun-Earth Explorer (ISEE) program, a cooperative venture of the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA).* Project goals include investigating the solar wind, determining how it affects the magnetosphere, and studying the boundaries between different regions of the earth's space environment. As one key achievement, ISEE researchers have perfected a way to sense the position and motion of the outer boundary of the magnetosphere.

In October 1977, NASA's ISEE-1 and ESA's ISEE-2 were launched into nearly identical orbits so that data records from similar instruments on the two satellites could be compared. With the double data set, researchers can distinguish between fluctuations in time and variations in space—an impossible task with data from one spacecraft alone. Having two satellites in one orbit is particularly advantageous for probing the details of magnetospheric boundaries. In the course of 1 year, ISEE-1 and ISEE-2 study all regions and boundaries in the magnetosphere within about 130,000 kilometers of the earth.

In August 1978, NASA launched the third satellite of the ISEE team. Instead of orbiting the earth, ISEE-3 makes tiny circles around a point between the earth and the sun where the gravitational attraction of both are equal. From this vantage point 1.5 million kilometers from the earth, ISEE-3 monitors the solar wind—an agent which has long been recognized to influence our planet. Since ISEE-3 has not been gathering data long, only a few of the planned comparisons have been made between its observations and the records from ISEE-1 and ISEE-2 nearer the earth.

But ISEE-3 alone has made some noteworthy measurements. One reason it was positioned so far from the earth was to ensure that it would monitor only cosmic rays and the solar wind, with no terrestrial influence. To the researchers' surprise, however, particles from the earth's magnetosphere stray far enough upstream against the solar wind to be detected by ISEE-3.

The magnetopause is perhaps the most interesting boundary of the magnetosphere, because "it essentially separates us from the interplanetary medium," according to Keith Ogilvie of NASA's Goddard Space Flight Center in Greenbelt, Maryland, who is project scientist for ISEE-1. Yet it has long been known that the magnetopause does not cut us off completely. Auroras and magnetic storms that play havoc with radio communications are triggered by the solar wind. Recently, Syun Akasofu of the University of Alaska devised a formula for predicting such events from properties of the solar wind. Somehow, particles and energy from the solar wind manage to penetrate the magnetopause and interact with the earth. One mechanism, proposed nearly 20 years ago, is that the magnetosphere may be torn open by the solar wind.

The first solid evidence for this process, known as reconnection, was obtained by ISEE-1 and ISEE-2 in the fall of 1978 and was analyzed last year by Götz Paschmann of the Max-Planck Institute for Physics and Astrophysics in Garching, West Germany, Bengt Sonnerup of Dartmouth College, and co-workers at Los Alamos Scientific Laboratory and the University of California, Los Angeles.† In reconnection a magnetic field line in the rapidly flowing solar wind merges on the sunward side of the magnetopause with the outermost field line in the magnetosphere. The solar wind yanks the connected magnetospheric field line out of position and peels it back toward the night side. There the "tail" of the magnetosphere extends more than 700,000 kilometers into space. At the moment merging occurs, the connected field line is similar to a drawn slingshot—it is sharply bent and quite stretched compared with the way it will be when it has been peeled back into the tail. Particles on the inside of the bend, like rocks in a slingshot, are accelerated as the field line straightens out, explains Paschmann. It is this acceleration of particles—to speeds five to ten times greater than normal—that ISEE detected and the researchers recognized as a signature of reconnection. "Until ISEE," says Christopher Russell, one of the collaborators from the University of California, "there was a large group of people who didn't believe in reconnection."

The confirmation of reconnection "ties magnetospheric physics to solar, astro-, and nuclear physics," says Sonnerup. The process is cursed as a nuisance in nuclear fusion devices, and is invoked to explain the spectacular release of energy in solar flares. The magnetosphere may prove to be a convenient site for studying reconnection under conditions that are common in space, yet impossible to achieve in the laboratory.

New discoveries such as the evidence for reconnection are made possible by the pair of satellites. Paschmann notes that "Previously when we saw a strange event, we tended to ignore it. But when the same thing shows up on records from identical instruments on two spacecraft, we have a lot more confidence that it is real." And often strange little events provide important clues to the physics of the magnetosphere. "You look at the data from one instrument on ISEE-1 and

*See K. W. Ogilvie, T. von Rosenvinge, A. C. Durney, "International sun-earth explorer: A three spacecraft program," *Science* **198**, 131 (1977).

†G. Paschmann, B. U. Ö. Sonnerup, I. Papamastorakis, N. Sckopke, G. Haerendel, S. J. Bame, J. R. Asbridge, J. T. Gosling, C. T. Russell, R. C. Elphic, *Nature (London)* **282**, 243 (1979).

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get one idea. Then you look at the data from the same instrument on ISEE-2, and the whole picture becomes clearer," says Alastair Durney of ESA, project scientist for ISEE-2.

But there are clues to reconnection that can be obtained with just one satellite. According to Forrest Mozer of the University of California, Berkeley, the most definitive clue is that a large amount of electrical energy is dissipated at the magnetopause during reconnection. Based on measurements of electric fields alone, Mozer claims to identify reconnection events readily. To date, his classifications have been "100 percent confirmed" by other data, he says.

Mozer explains that electric energy must be dissipated during reconnection, because at that time near the magnetopause the electric field is aligned with electric currents. Reconnection can occur at the magnetopause on the sunward side of the earth when the outside interplanetary magnetic field is directed southward, and the inside field, controlled by the earth's magnetic dipole, is directed northward. This abrupt change in magnetic field direction at the magnetopause is associated with an electric current flowing in the magnetopause. The current flows around the earth in the direction from dawn to dusk.

Moreover, during reconnection the magnetopause is open. Positively and negatively charged particles, called plasma, flow toward the opening from both sides. Thus, the electric field, which according to Maxwell's equations must be perpendicular to both the plasma flow and the magnetic field, is also directed from dawn to dusk in the magnetopause. This configuration, with electric field and current aligned, maximizes electric energy dissipation.

Electric energy dissipated at the site of reconnection can accelerate particles, produce heat, or both. "ISEE supports the idea that at a reconnection event there is enhanced heat flow," says Jack Scudder of Goddard. He and Ogilvie frequently observe heat flowing from the magnetopause toward the outside, but not the inside, during reconnection. They surmise that outside, where the density of plasma is high, the conductivity for heat is likewise high. Consequently, heat flows easily there. Inside the magnetosphere, however, the particle density and heat conductivity are too low to carry the heat. Since the heat flow toward the inside is stifled by the low conductivity, particles there are accelerated.

Ogilvie and Scudder think that heat flow may be a useful clue to reconnection when the spacecraft is outside the magnetopause and perhaps not in a good position to detect other signatures of the process. The heat that may flow out from the boundary during reconnection flows along the interplanetary magnetic field lines that make the connection. When the satellite is on such field lines, it may detect the heat flowing away from the magnetopause.

Both the heat flow determination and the electric field measurement are considered to be among ISEE's greatest achievements. "I would have bet any amount of money that the heat flow measurement could not have been made," says Mozer. Even Ogilvie is "surprised that the measurement can be made so consistently."

Mozer's unprecedented electric field measurements have proved to be a valuable clue to reconnection. In spite of this, some researchers question the accuracy of Mozer's data, which occasionally seem at odds with other indications of electric field strength. Moreover, many ISEE researchers curse Mozer's detector at times. Typically, on one orbit in four the satellite operates in what is known as "Mozer's preferred mode"—a mode not preferred by the others. This came about because in the design of Mozer's instrument, there was a slight error, which makes the electric field measurements difficult to interpret. By putting a small charge on the spacecraft the design flaw can be overcome. But the cure has complications. A charged spacecraft influences the nearby charged particles; thus the scientists studying particles cannot trust their data when "Mozer is in his preferred mode."

In addition to catching a breach in the magnetopause, ISEE researchers are the first to be able to locate the boundary and gauge its motions when the satellite is several hundred kilometers away. Previously the magnetopause position was known only when a satellite was crossing it and detected the characteristic abrupt change in magnetic field strength and direction. It was nearly impossible to guess the position at other times.

Donald Williams of the National Oceanic and Atmospheric Administration's Environmental Research Laboratory, Boulder, uses the trajectories of protons to measure the distance from ISEE-1 to the magnetopause. Protons inside the magnetosphere tend to be trapped and gyrate around field lines. The radius of gyration depends on the energy of the proton and the strength of the magnetic field. For protons near the magnetopause, the radius ranges between a few tens and several hundreds of kilometers. A proton spiraling around a field line is lost if it goes outside the magnetopause, where the earth's dipole no longer controls the field.

By looking at the trajectories of protons of different energies, Williams determines in what directions and at what energies protons are lost. From the radius of gyration of the lost protons, he can calculate the distance to the magnetopause. This method is not new, but it did not work until ISEE because earlier data were not good enough. "The amazing thing is that from the standpoint of the trapped particles, the boundary really is a simple transition between ordered magnetosphere fields and disordered fields outside," says Williams. So far, he claims, the boundary he picks is the same one that would be recognized from magnetic field data taken by a satellite crossing the boundary.

In addition to determining the distance to the magnetopause, Williams can gauge the orientation of the boundary and detect undulations in it. "I always see waves on the boundary," he says.

Other researchers are so enthusiastic about Williams' calculations that they would like to see the magnetopause position calculated routinely. They feel that for a satellite in the outer magnetosphere the distance to the magnetopause is a more meaningful reference than the distance to the surface of the earth—the standard reference datum. Unfortunately, such calculations cannot be made for ISEE-1 after early 1979 because, says Williams, data collection from the proton detector came to a sad, untimely, and mysterious end.

However, Williams' colleague Theodore Fritz very recently adapted the method for a similar instrument on ISEE-2. Although the spatial resolution of the proton detector on ISEE-2 is not as fine as it was on the ill-fated ISEE-1 instrument, the adapted technique seems to work well. What is lost in spatial resolution is gained in time: ISEE-2 data can be used to estimate the magnetopause position every 3 seconds, whereas with ISEE-1 it took about ten times longer to gather enough data. For such a mobile boundary—Fritz has clocked the magnetopause moving in and out at up to 90 kilometers per second—there are advantages to frequent measurements.

ISEE's many instruments (there are 13 on ISEE-1 and seven on ISEE-2) collect data so fast that it is possible to get a detailed look at the magnetopause. It now appears that the boundary, which can be as thin as 100 or as thick as 2000 kilometers, really has two layers. Confusingly, the term magnetopause is reused to refer to the outer layer, because it is there that the strength and direction of the magnetic field changes markedly—typically the field is half as strong on the outside. The current described by Mozer flows in this layer and can be used to help identify it.

Just inside the magnetopause is a region of fluctuating magnetic field, known as the plasma boundary layer. Donald Gurnett of the University of Iowa has observed that this boundary layer is an incredibly turbulent sheet where the particle density changes from its low inside value to a much higher outside value. The relative thicknesses of the boundary layer and the magnetopause are disputed. In one case, Fritz has estimated that both have a scale thickness of 40 kilometers. "As far as I can tell, in this case the boundary layer may be identical with the magnetospheric current layer [magnetopause]," he concludes.

Edward Hones of Los Alamos Scientific Laboratory suggests that the boundary layer may be a narrow channel linking the outer edge of the magnetosphere with the upper region of the atmosphere—the ionosphere—where auroras and magnetic storms occur.

Recent ISEE data appear to be supporting Hones's idea, a popular one among magnetospheric physicists. George Parks of the University of Washington points out that one signature of the boundary layer—a shoulder of intermediate particle density on the data records—is also seen by ISEE at the edge of a region in the tail of the magnetosphere. This tail region is thought to play a major, although not well understood, role in magnetic storms and auroras. On ISEE records, Louis Frank of the University of Iowa has seen the first convincing evidence that electric current flows along magnetic field lines in this region of the tail. The current is due to charged particles streaming toward or away from the earth. Frank's data support the idea that plasma boundary layers may connect the earth with the outer fringes of its space environment.

While the magnetopause shields the earth from the solar wind, albeit incompletely, the bow shock communicates the earth's presence to the solar wind. To date, ISEE's studies of the bow shock have been more exploratory than explanatory. "The time resolution of ISEE is enough to get a few observations in the shock itself," says Ogilvie. Physicists and astrophysicists are interested in the structure of the bow shock because it is a "collisionless shock"—the density of particles is so low that they virtually never collide. Similar shocks in outer space are thought to be the source of many cosmic rays. Heat is produced and particles are accelerated in the earth's bow shock. "You can get 1 million-electron-volt particles out of the bow shock," Ogilvie says, and "something has to act as an ejector."

"Almost immediately, using two satellites, we could measure the thickness of the bow shock," says Russell. Typically it is about 30 kilometers thick—thinner than the magnetopause. Although the shock moves more than the magnetopause, its motions appear to be less erratic.

The physicists were surprised that all three ISEE satellites see evidence of the earth upstream of the bow shock. According to Russell, "the bow shock is supposed to be where the solar wind first finds out about the earth." Yet there are earth-induced waves upstream. Some of the waves propagate upstream, but others are too slow to travel against the solar wind, which flows at 400 kilometers per second. Researchers surmise that newly discovered beams of ions and electrons head upwind and stimulate these latter waves by interacting with the solar wind.

Many particles coming from the bow shock are detected at ISEE-3, according to Manfred Scholer of Max-Planck Institute, Garching. Furthermore, he says, "at ISEE-3 the particles arrive highly collimated from the bow shock," when the satellite is on a magnetic field line joined with the shock. Particles nearer the bow shock are not as well collimated. Those observed by ISEE-1 tend to head every which way. Scholer suspects that these latter particles are scattered by waves and turbulence near the shock. Ions that start heading out along magnetic field lines, however, just keep on going—as far as and farther than ISEE-3.

Some of the upstream particles seen at ISEE-3 may be escapees from the magnetosphere. But others appear to be solar wind particles energized and reflected at the bow shock. Paschmann and Norbert Sckopke of Max-Planck Institute, Garching, observe particles bouncing off the bow shock with up to 30 times as much energy as they had when they hit. They say that their observations convincingly support a simple model proposed a decade ago by Sonnerup to explain how particles might be accelerated when they hit a shock.

ISEE-3 also investigates the solar wind, and it is primarily in this capacity that it aids researchers interpreting data recorded by ISEE-1 and ISEE-2. The composition, velocity, and magnetic field of the solar wind provide clues to processes occurring on the sun. An hour after it passes ISEE-3, the solar wind reaches the magnetopause. There it transfers energy and some particles to the magnetosphere. The magnetosphere responds to the influx, and its reaction is monitored, admittedly sketchily, by ISEE-1, ISEE-2, other satellites, and instruments on the ground. Extensive cross-satellite comparisons of data have not been completed yet, but they are in the works and promise to help unravel details of the sun-earth connection.

Since the solar wind controls the magnetosphere to a great extent, ISEE-3 data could be a key to understanding and predicting changes in the magnetosphere, such as show up as magnetic storms and auroras. Currently NASA is arranging to make ISEE-3 data accessible to researchers in "real time." With ISEE-3 data and Akasofu's formula, it may be possible to forecast auroras and magnetic storms. Then researchers studying those processes will know when to set up their instruments or launch them into the ionosphere on rockets or balloons. Later this year the data system should be operating.

A year ago magnetospheric physicists added a new weapon to their data analysis arsenal—so-called Coordinated Data Analysis Workshops (CDAW's). Researchers from around the world gather at a CDAW to pool their expertise and analyze selected data. Juan Roederer of the University of Alaska, past chairman of the 3-year International Magnetospheric Study (1976 to 1979), the umbrella program that includes ISEE, says that a "workshop is like a computer-assisted tomography of space." Typically, at the close of a 3-day workshop participants have results that are ready for publication—results that might have been a long time coming without the workshop serving as midwife.

James Vette of Goddard, director of World Space Science Data Center A, which prepares the workshops, sees in the CDAW's a glimmer of data analysis of the future. He envisions that eventually all magnetospheric data will be stored in a central computer. Researchers will be able to call and manipulate the data from private terminals in their own offices, whether those offices are at the data center or elsewhere in the world.

ISEE data, along with improvements in theory and data handling, have helped reveal details of the structure and variations of the magnetosphere. Nonetheless, the complicated interactions among the magnetospheric regions and between the sun and the earth are a long way from being understood.

—BEVERLY KARPLUS HARTLINE