

Spacecraft Probes the Site of Magnetic Reconnection in Earth's Magnetotail

Even in its quietest moments, the Sun spews forth a hot high-speed wind of ions and electrons. Fortunately for earthly life, the solar wind is diverted around Earth by the planet's magnetic field, which forces the particles to travel along, not across, the field lines. But some charged particles, and the energy they carry, do penetrate Earth's magnetosphere, as the magnetically shielded cavity is known. Magnetic storms that knock out satellites and power grids, the spectacular auroras, the Van Allen belts are all fed and fueled by the solar wind. How are Earth's magnetic defenses breached?

In 1961, James Dungey proposed that the answer lies in magnetic reconnection, an idea that Ronald Giovanelli conceived in 1946 to explain solar flaring. When more or less oppositely pointing field lines approach each other, they can abruptly short-circuit or "reconnect," as shown in figure 1. In the new reconnected configuration, the field lines are bent tightly like the elastic strings of a catapult. When the field lines suddenly straighten, they fling out plasma in opposite directions.

The Sun's magnetic field reverses its overall polarity every 11 years, but the solar wind seethes with a variety of transient structures that change the field's local direction at Earth on much shorter time scales. Where Earth's more stable field abuts the solar field, the conditions for reconnection arise in two zones: at the magnetopause, the Sunward-facing nose of the magnetosphere, and in the magnetotail, its stretched out nightside tail (see figure 2).

Evidence for Dungey's idea has been building steadily. In 1979, the two ISEE spacecraft observed the most dramatic manifestation of reconnection, fast plasma jets, at the magnetopause.¹ And in 1998, the GEOTAIL and Equator-S spacecraft teamed up to catch both jets of the same reconnection event, also at the

For the first time—and quite by chance—a spacecraft has directly encountered one of the most important energy conversion mechanisms in the solar system.

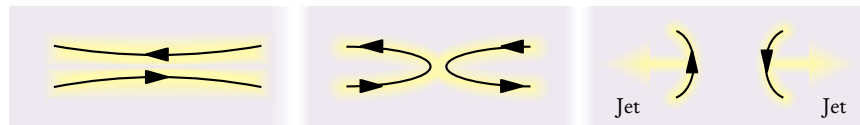


FIGURE 1. BEFORE RECONNECTION occurs (left), neighboring field lines (or field line components) point in opposite directions. Just after reconnection (middle), the newly connected field lines are bent tightly. Later (right), the fields straighten, transferring magnetic energy to oppositely directed particle jets.

magnetopause.² But until now, no spacecraft had actually encountered the zone where reconnection occurs. That's not surprising. Reconnection takes place at an unpredictable rate in small regions whose location from Earth is also unpredictable.

On 1 April 1999, NASA's WIND spacecraft was traveling down the magnetotail on its way to an orbit-changing lunar flyby. Just before 8 AM GMT, it flew through a reconnection

event. Marit Øieroset (University of California, Berkeley) didn't discover this serendipitous prize until she routinely analyzed the day's data five months later. When she did so, she and her colleagues found³ not only the tell-

tale oppositely directed plasma flows of reconnection, but also distinctive magnetic and particle signatures. Although the WIND results don't directly constrain models of jet acceleration, they do provide an unprecedented snapshot of the conditions that lead to reconnection.

X marks the spot

The tenuous plasmas of the magnetosphere are difficult to observe. Unlike the Sun's corona, they don't glow, so measurements have to be made in place. And to get a three-dimensional picture, you need multiple spacecraft. Worse, the plasmas and fields vary over huge spatial and temporal ranges. Of necessity, reconnection mechanisms have been studied more through theory and modeling than through observation.

Before reconnection can occur, the electrons and ions must demagnetize—that is, break away from their original field lines. How they achieve this feat is a key, and still open, question.

Interparticle collisions clearly can't do the job because they're too infrequent in the thin hot plasmas of the magnetosphere. Instead, theorists believe, particle inertia has to play a role. Particles could become scattered through the interaction with wave fields, a mechanism often referred to as anomalous resistivity. Alternatively, recent theoretical and numerical investigations suggest that particles demagnetize by virtue of their orbital motion in regions of low magnetic field or strong gradients.

The WIND data favor the second mechanism and confirm a picture of magnetospheric reconnection first sketched out in 1979 by Bengt Sonnerup of Dartmouth College.⁴ Accord-

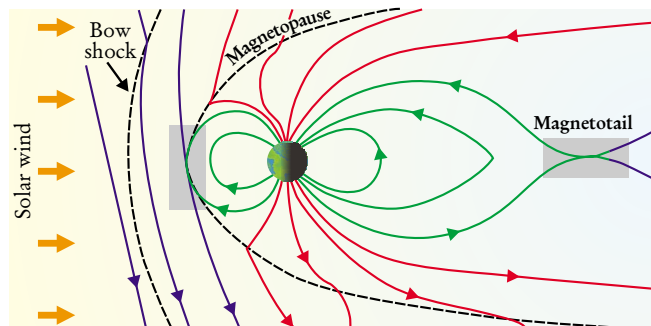


FIGURE 2. MAGNETIC RECONNECTION can occur in the two magnetospheric regions indicated here in gray: at the magnetopause and in the magnetotail. When the Sun's magnetic field (blue) points southward (downward), it can reconnect at the magnetopause with Earth's closed field (green). In the magnetotail, reconnection occurs when Earth's open field (red) is squeezed together. The sketch is not to scale.

ing to this picture, reconnection begins when the solar wind squeezes a part of the magnetotail from above and below the so-called X-line, the notional locus of a reconnection event (see figure 3). Magnetically entrained particles can't be compressed indefinitely. They resist when the region they occupy is about the same size as their radius of gyration about the field lines.

First to push back and demagnetize are the positively charged ions (mostly protons), whose gyroradius in the magnetotail is about 700 km. The electrons, meanwhile, continue inward, moving past the more or less stationary ions until they reach their much smaller gyroradius of about 20 km. It is in this small region, known as the electron diffusion region, that the electrons demagnetize and set off reconnection.

The drift of electrons relative to the ions creates a system of currents and magnetic fields akin to the classical Hall effect (see figure 3). Characteristically, the Hall fields are directed across, not along, the magnetotail and can exist well above the midplane of the magnetotail. In its chance encounter with the 1 April 1999 reconnection event, WIND detected both the Hall current and magnetic field. GEOTAIL, too, has observed Hall signatures,⁵ which would not be seen if

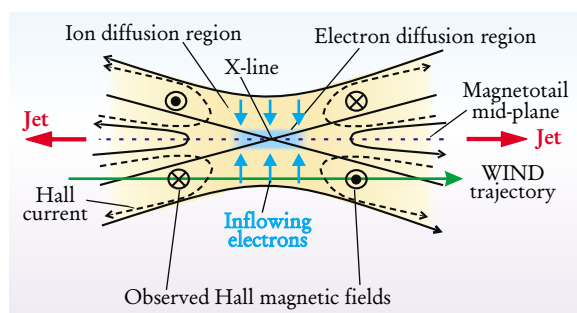


FIGURE 3. THE WIND SPACECRAFT flew through a reconnection event on 1 April 1999. Its trajectory, shown in green, took it through the Hall-like system of magnetic fields and electric currents established by inflowing electrons during reconnection. (Adapted from ref. 3.)

reconnection were mediated by anomalous resistivity.

Paradoxically, although WIND missed the electron diffusion region, the spacecraft's chance encounter underscores the importance of probing the region where electrons demagnetize. Pulling the electrons off their field lines requires an electric field, but reconnection, at least at the X-line, implies zero magnetic field and, with it, the possibility that electrons could short-circuit the electric field. Some kind of plasma instability might maintain the electric field, but simulations show that electrons tend to be kicked away from the X-line by the

Lorentz force, so an instability might not be needed.

Observing the electron diffusion region is one of the goals of NASA's Magnetospheric Multi-scale mission (MMS). Scheduled for launch in 2006, MMS consists of four identical spacecraft that will fly in a tetrahedral formation with a minimum separation of 10 km—fine enough, space physicists hope, to measure what they call the microphysics of reconnection in three dimensions. Meanwhile, another formation flyer, the European Space Agency's Cluster 2 mission, has been gleaned data in the magnetosphere since its launch last year.

WIND, however, might not witness another reconnection event. To save money, NASA plans to mothball the seven-year-old spacecraft.

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References

1. G. Paschmann et al., *Nature* **282**, 243 (1979).
2. T. D. Phan et al., *Nature* **404**, 848 (2000).
3. M. Øieroset, T. D. Phan, M. Fujimoto, R. P. Lin, R. P. Lepping, *Nature* **412**, 414 (2001).
4. B. U. Ö. Sonnerup, in *Solar System Plasma Physics*, vol. III, L. T. Lanzerotti, C. F. Kennel, E. N. Parker, eds., North-Holland, New York (1979), p.45.
5. T. Nagai et al., *J. Geophys. Res.* (in press).

Spectra of the Most Distant Quasars Elucidate the Reionization of the Cosmos

In 1965, just two years after quasars were first identified as cosmologically distant objects, James Gunn and Bruce Peterson at Caltech called attention to a peculiar spectroscopic aspect of these high-redshift beacons. Looking at the spectrum of a quasar with a redshift z of about 2, they pointed out that it did not exhibit a trough of total absorption on the blueward side of its prominent Lyman- α hydrogen emission peak. But if, as was generally supposed, the intergalactic medium between us and the quasar had lots of neutral atomic hydrogen, there would have to be such an absorption trough.

The absence of a "Gunn-Peterson trough" in any of the quasar spectra measured in the ensuing 35 years is the primary evidence we have that the intergalactic hydrogen is *not* neutral. It is, in fact, overwhelmingly ionized.

As cosmological epochs are reckoned, this ionized intergalactic medi-

Half a million years after the Big Bang, almost all the hydrogen in the cosmos was neutral. When and how did it all get reionized?

um has to be a rather recent state of affairs. The cosmic microwave background teaches us that, some 400 000 years after the Big Bang, the universe finally became cool enough for neutral hydrogen atoms to survive (see PHYSICS TODAY, July 2001, page 16). Astrophysicists have been striving for decades to pinpoint the time of the subsequent cosmic "reionization" phase transition—perhaps a billion years later—by looking at the spectra of ever more distant, higher-redshift quasars in search of one early enough to exhibit a Gunn-Peterson trough. The reionization time is an important parameter for models of the evolution of structure in the cosmos.

For the past year or two, this task

has been greatly aided by a byproduct of the prodigious Sloan Digital Sky Survey. Gunn, who has been at Princeton since 1968, is the Sloan survey's project scientist. The survey's principal task is to measure the redshifts—and hence the distances—of a million galaxies. But in the process, the survey has been identifying handfuls of the most distant quasars ever seen.¹

The trough, at last

Now we have a paper from the Sloan team reporting that their most distant quasar, with a z of 6.28, shows the first "clear detection of a complete Gunn-Peterson trough."² In a related paper,³ George Djorgovski and colleagues at Caltech, having taken a high-resolution look at the spectrum of a $z = 5.73$ quasar discovered by the Sloan survey last year, argue that residual dark patches in that spectrum are a signature of the final moments of the reionization transition.