

The dephasing and rephasing both occur when the (1,1) charge state is strongly favored—that is, when $\varepsilon \ll 0$. Inversion, which corresponds to a rotation in the Bloch sphere, occurs when ε is raised just long enough to let the electrons tunnel between dots and complete an odd number of Heisenberg spin exchanges.

That exchange time, τ_E , is given by $J(\varepsilon)\tau_E/\hbar = \pi, 3\pi, 5\pi, \dots$, where $J(\varepsilon)$ is the energy cost of doing the exchange. In figure 3, $J(\varepsilon)$ corresponds to the difference in height between the S and T_0 curves. The Harvard collaboration derived $J(\varepsilon)$ from the behavior of P_S at the degeneracy between S and T_+ .

Figure 4 illustrates how spin echo can prolong the qubit's coherence. When the dephasing and rephasing times are the same and τ_E is appropriately tuned, P_S decays with a best-fitting timescale of 1.2 μs . When the dephasing and rephasing times are different, P_S decays on a best-fitting timescale of 9 ns, which is consistent with not doing any spin echo, as before.

What could be responsible for the 1- μm decoherence time? One possibility is the virtual flipping of the nuclear spins. The electron's wavefunction spreads over many lattice sites. Even if the mean value of B_{nuc} is steady, the random, virtual flip-flopping of nuclear spins creates a torque on the electron's spin whose strength depends on where each flip

occurs in relation to the peak of the electron's wavefunction. To pin down the cause, Petta and coworkers are already investigating its dependence on B and other quantities.

Toward a quantum computer

To quantum compute, one needs, among other things, to rotate one qubit state into another. The nuclear spins can rotate S into T_0 and vice versa, but not by a predictable amount. Given that exchange can control the mix of $|\downarrow\uparrow\rangle$ and $|\uparrow\downarrow\rangle$, can those states be used as a possible basis for a qubit's 0 and 1?

Yes, according to the Harvard collaboration, provided the electron pair, just before rotation, is in $|\downarrow\uparrow\rangle$ or $|\uparrow\downarrow\rangle$, rather than S or T_0 . Consider the case when $|\downarrow\uparrow\rangle$ happens to be lower in energy than $|\uparrow\downarrow\rangle$. If the spins are separated adiabatically—that is, slowly enough to let B_{nuc} torque the spins—they'll settle into their ground state $|\downarrow\uparrow\rangle$. From there, exchange can be turned on to make one or more complete inversions, thereby converting $|\downarrow\uparrow\rangle$ to $|\uparrow\downarrow\rangle$. Rejoining the spins adiabatically turns $|\uparrow\downarrow\rangle$ into T_0 ; plotting the singlet survivability P_S as a function of τ_E results in oscillations whose minima occur when $J(\varepsilon)\tau_E/\hbar = \pi, 3\pi, 5\pi$, and so on—which is what the Harvard collaboration observed.

What's more, by using the same scheme but with half the value of ex-

change (that is, $\pi/2, 3\pi/2, 5\pi/2, \dots$), the Harvard collaboration could perform the so-called square-root-of-swap operation. That operation forms the basis for the XOR logic gate in Loss and DiVincenzo's 1998 proposal.

Recruiting the hyperfine splitting to rotate qubits is far from ideal, however, because it depends on the chance and unpredictable value of ΔB_{nuc} . Establishing a constant ΔB_{nuc} would be better. Also needed for quantum computation are two-qubit operations and the ability to initialize and read out single qubits. (Averaging 100 000 measurements with a QPC doesn't count.)

Whether those and other obstacles will ever be overcome remains uncertain. But progress has been surprisingly quick. Says Sankar Das Sarma of the University of Maryland in College Park, "I didn't think anyone would be able to manipulate and decouple single spins until 2010!"

Charles Day

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Enormous Magnetic Reconnection Event Washes over Three Spacecraft Millions of Kilometers Apart

The abrupt reconnection of magnetic flux lines embedded in plasmas is an important mechanism for transferring energy from the magnetic field to the motion of plasma particles. Magnetic reconnection manifests itself spectacularly on diverse scales: solar flares, auroras from the penetration of solar wind into Earth's magnetosphere, and containment failures in laboratory tokamaks. And reconnection is suspected in neutron-star quakes, gamma-ray bursts, and jet formation in black-hole accretion disks.

When there's magnetic field in a plasma, the cyclotron gyration of electrons and ions effectively binds them to individual flux lines. The result is that the field lines are generally frozen into the plasma, riding along with its bulk motion. For example, in the solar wind—a plasma of electrons and ions (mostly protons) from the Sun—embedded magnetic field lines

How large can reconnection events in plasmas get? Theory provides no easy answer. But the solar wind beyond Earth's cramped magnetosphere is a good place to look.

ride Earthward at several hundred kilometers per second.

Magnetic reconnection is a striking exception to the general plasma picture of frozen-in field with charged particles faithful to individual flux lines. When parts of two lines of roughly opposite sense get close enough to each other under special circumstances not completely understood, the two lines can suddenly reconnect so that charged particles lose old traveling companions and gain new ones (see figure 1a on page 20).

The newly configured flux lines, now sharply bent, act like slingshots, propelling jets of plasma particles before them as they straighten out to lower the energy of the magnetic field. When whole planes of opposing flux

lines come into contact, as in figure 1b, reconnection can occur coherently over large distances. An important question for plasma theorists has been, How large?

Solar flares and distant astrophysical outbursts can be viewed from afar. But not all reconnection events are that showy. And in any case, observers really want to study large-scale reconnection events in situ. For more than 20 years, spacecraft in Earth's magnetosphere and on its boundary—the so-called magnetopause—have been recording manifestations of reconnection (see PHYSICS TODAY, October 2001, page 16).

Compared with length scales of particular interest, however, the magnetosphere is cramped and subject to

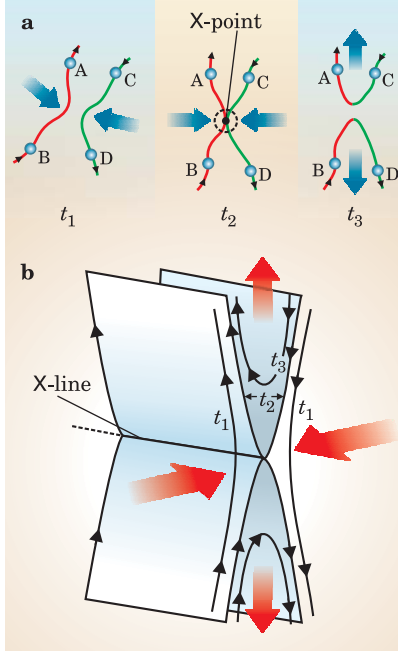


Figure 1. Magnetic reconnection in plasma can occur when magnetic field lines of roughly opposite direction get close enough. **(a)** Before reconnection (at time t_1), charged particles (A–D) are bound to individual lines by cyclotron gyration, thus freezing the flux into the plasma. But when, at t_2 , two lines meet and reconnect (at the X-point), the flux is unfrozen as plasma particles switch traveling companions. At t_3 , the sharply bent reconnected lines act like slingshots to expel plasma from the reconnection region. **(b)** When whole planes of oppositely directed flux meet, the region of reconnection can be quite extended (the X-line). Red arrows indicate plasma being expelled by the reconnected flux and replaced by plasma inflow near the X-line. (Adapted from ref. 4.)

erratically changeable boundary conditions. In the Sunward direction, the magnetopause is only about 10 Earth radii ($R_E = 6.4 \times 10^3$ km) away. Furthermore, reconnection events near the magnetopause are dynamically driven by the impact of magnetic field frozen into the solar wind ramming into the magnetosphere.

A fortuitous encounter

Theorists are especially interested in comparing their models with undriven reconnection events in the solar wind itself on scales much larger than the magnetosphere can accommodate. Therefore the recent report¹ of a 2002 reconnection event in the solar wind recorded in situ by three spacecraft separated by hundreds of Earth radii (see figure 2) is getting considerable attention. Never before had a reconnection event been recorded in such detail over such distances. But it would be three years before Tai Phan of the NASA *Wind* spacecraft team at the University of California, Berkeley, and Jack Gosling from NASA's *ACE* team at the Uni-

versity of Colorado, Boulder, discovered the extraordinary coincidence of the three independent data sets.

On 2 February 2002, *Wind* happened to be about as far from the Earth–Sun line as it ever gets, and the European Space Agency's *Cluster* (actually a tight ensemble of four craft) was making one of its occasional forays outside the magnetosphere. The *ACE* spacecraft was more than $200R_E$ upwind of *Cluster*. All three craft were, more or less, in the ecliptic

plane of Earth's orbit. Compared to the 340-km/s Earthward velocity of the solar wind, their own velocities were negligible.

At about 1:30 Coordinated Universal Time, magnetometers and plasma detectors aboard *ACE* recorded the telltale signal of a reconnection event passing through: an abrupt reversal of one component of the magnetic field, accompanied by a jet of plasma flowing in the direction of the reversing field component and sharply confined

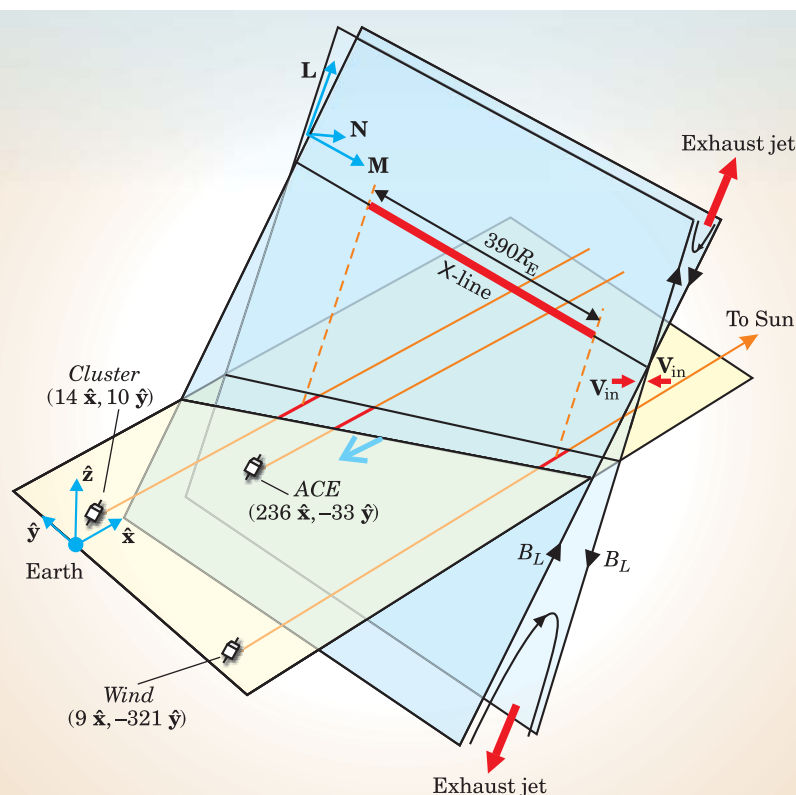


Figure 2. Reconnection event of 2 February 2002 in the solar wind. Coordinates in the ecliptic plane (yellow) of the three spacecraft that recorded the event are in Earth radii R_E . The x-axis points from Earth to the Sun. The bifurcated current sheet (blue) is reconstructed from the spacecraft data. Frozen into the solar wind blowing Earthward at 340 km/s, the sheet overtook the three craft in sequence in a few hours. The 4° bifurcation angle (exaggerated for clarity) results from plasma exhaust expelled by magnetic reconnection over at least $390 R_E$ along the X-line, near which slower plasma inflow replaces the expelled material. In the L, M, N rectangular coordinate system deduced for the current sheet, it was the B_L component of the magnetic field that reversed direction from one branch of the sheet to the other. The sheet current required for that reversal flowed in the M direction parallel to the X-line. (Adapted from ref. 1.)

to the reversal region (see figure 3 on page 22). The event lasted only eight minutes. But an hour later, *Cluster* recorded almost exactly the same transient signal. And then, after another hour and a half, it was *Wind*'s turn.

The X-shaped double plane intersecting the ecliptic in figure 2 is called a bifurcated current sheet. Even in the absence of reconnection, when plasma regions of magnetic flux **B** pointed more or less in opposite directions are closely juxtaposed, the quasistatic Maxwell equation $\nabla \times \mathbf{B} = \mathbf{j}$ requires that a sheet of current flow normal to **B** in the boundary layer between the opposing flux regions. Such unbifurcated current sheets are quite common in the solar wind, because regions of oppositely directed magnetic flux on the Sun's surface frequently launch magnetic field into the wind with abrupt flux-direction boundaries. The bifurcation happens when the sheet is split in two by jets of plasma expelled up and down by reconnection taking place along a limited juxtaposition region—the so-called X-line in figures 1 and 2.

The event reconstructed

Figure 2 shows the bifurcated current sheet of 2 February 2002 impressively reconstructed from the observations recorded by the three spacecraft. (The bifurcation angle, only about 4°, is exaggerated for clarity.) Embedded in the solar wind, the sheet sailed steadily Earthward at about 340 km/s along the *x*-axis, which is defined by the Earth–Sun line. The sheet's normal (**N**), however, was found to be inclined about 45° from the *x* direction.

The most striking result of the reconstruction is the inferred length of the X-line, far north of the ecliptic plane, where the bifurcated current sheet joins up and the magnetic reconnection is actually taking place. Anchored in the east by the *Wind* data and in the west by *Cluster*, the line along which magnetic flux was steadily reconnecting for at least two and a half hours was at least $390R_E$ long!

Why is that so impressive? The obvious length to which one compares the X-line is the so-called ion inertial length λ_i , the characteristic distance at which protons decouple from flux lines about to reconnect. Effectively, it's the thickness of the X-line in the direction normal to the current sheet. Given the local plasma density (about 10 protons per cubic centimeter), λ_i was roughly 60 km.

"This result shows us, up close for the first time, that reconnection events can span huge distances," says

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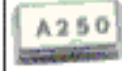


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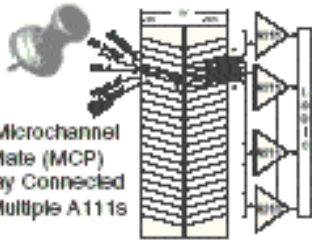



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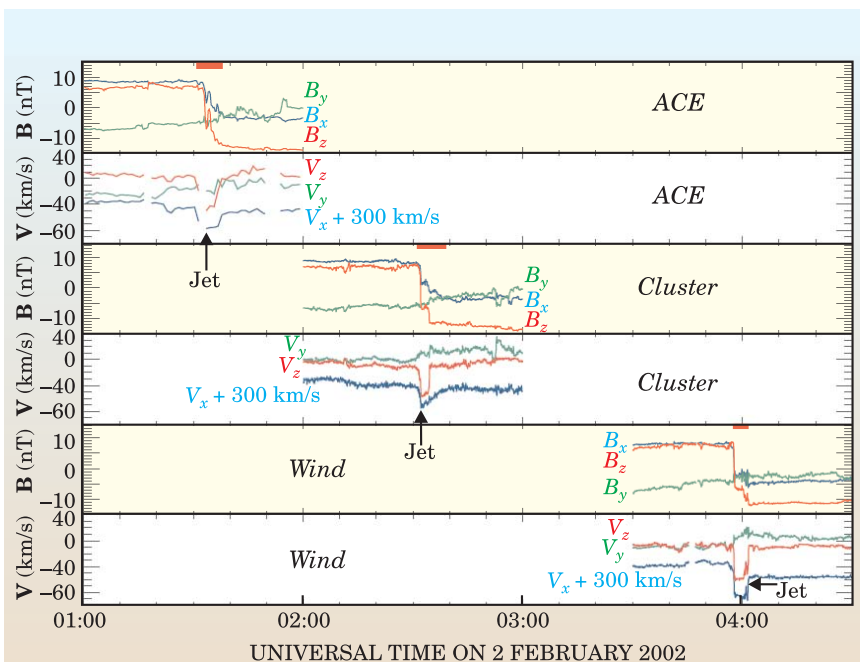


Figure 3. Three widely separated spacecraft in the solar wind recorded the passage of the 2 February 2002 reconnection event with almost identical magnetic-field (**B**) and plasma velocity (**V**) signals as the bifurcated current sheet passed over them in turn. Each traversal time is indicated by a red bar. The geocentric solar-ecliptic *x*, *y*, *z* coordinates are the same as in figure 2. The telltale indicator of the reconnection going on far above the ecliptic plane is the abrupt reversal of magnetic field direction accompanied by a sharply constrained jet of high-speed plasma exhaust flowing downward in the direction parallel to the reversing field component. (Adapted from ref. 1.)

University of Maryland theorist James Drake. “This was a quasi-steady-state process lasting hours and covering at least $4 \times 10^4 \lambda_i$.” In the much denser plasma near the Sun, where λ_i is only about 10 meters, reconnection flares extend over $10^6 \lambda_i$. And solar flares are certainly not quasi-steady-state events. “But there we can’t hope to get close enough to study the microphysics of reconnection,” says Drake.

Two years ago, Gosling and company discovered solar-wind reconnection events in their archival *ACE* data. Those were the first in situ identifications of reconnection outside the magnetosphere. But with data from only a single craft, one couldn’t determine spatial extent. So the *ACE* and *Wind* teams joined forces to comb their archives in search of events both craft had recorded. The paper by Phan and company is the report of that search, which was expanded to include data from *Cluster* when it was outside the magnetosphere. The three-craft February 2002 event is the

collaboration’s crown jewel. But the paper also reports 27 two-craft sightings. “There were no events seen by only one of the craft,” says Phan, “which implies that, unlike the small, patchy reconnection events we find in the magnetosphere, events in the solar wind typically extend over more than a hundred R_E .”

Confronting theory

The prevailing theory of reconnection in low-density plasmas was introduced by Harry Petschek in the 1960s and elaborated in recent years by Drake, Joachim Birn, and others. Petschek incorporated the acceleration of exhaust by Alfvén waves into an earlier theory by Eugene Parker that could not account for the high speed with which reconnection is seen to occur in solar flares. Alfvén waves are transverse disturbances that propagate in plasma. The exhaust velocity observed in the February 2002 event was, as expected from Petschek’s theory, the Alfvén wave velocity—about 70 km/s in this case.

And the theory reproduces well the observed increase of plasma density and temperature in the exhaust jet.

But attempts to replicate the observed rates of so-called fast reconnection by computer simulation based on the unadorned Petschek theory have failed. Birn, Drake, and coworkers appear to have succeeded by adding the usually neglected Hall effect to the magnetohydrodynamic equations.² The Hall effect, they argue, speeds reconnection by facilitating the requisite decoupling of ions from the flux lines and their still attached electrons. Freed from the ponderous ions, the electrons can drag the lines laterally at high speed into the reconnection region.

Whether or not Hall-assisted Petschek reconnection can sustain quasi-steady-state reconnection over $10^4 \lambda_i$ is a matter of some dispute among theorists.³ And because of the enormous disparity between the relevant small and large scales, it’s difficult to draw unambiguous conclusions from numerical simulations. So observations are crucial.

The rate at which plasma is expelled in the reconnection exhaust jets has to be balanced by plasma flowing transversely into the X-line and nearby exhaust regions. For the February 2002 event, the data yielded inflow velocities (in the bifurcated sheet’s rest frame) of about 3% of the Alfvén velocity. “We assume that this inflow rate reflects augmentation by the Hall effect,” says Drake, “but we can’t be sure yet.” The present fleet of spacecraft, he expects, will soon provide enough data to determine whether or not the microphysics of large-scale solar-wind events really is Hall-assisted Petschek reconnection.

How large can reconnection events get in the solar wind? NASA’s *STEREO* mission, a pair of spacecraft scheduled for launch this summer, are to be injected into orbits about the Sun that track Earth’s orbit in opposite directions. In little more than a year, they’ll be farther from each other than they are from the Sun. If reconnection events get that big, *STEREO* should find them.

Bertram Schwarzschild

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