

resolution technique to two types of structures: rat secretory granules, which are more or less spherical, and meshes of microtubules. In both cases the CARE network revealed substructures that had remained imperceptible after they were enhanced with a traditional deconvolution method of image restoration. For the microtubule sample, the CARE network resolved structures as effectively as a state-of-the-art superresolution technique but did the job 20 times as fast because it required fewer images.

Verifying the results

Although their performance is impressive, CARE networks are only useful to the extent that their output is reliable. “For the scientific utility of the network, it is very important to know not only what is predicted but how accurate it is,” says Royer. To that end, the researchers changed the last step of the CARE net-

work so that instead of just reporting a pixel value, it gave a probability distribution for each pixel whose mean was the predicted pixel value and whose width indicated the uncertainty in that prediction.

The consistency of the CARE networks also factored into their reliability measure. Instead of relying on a single network, the researchers trained an ensemble of networks; based on the restorations produced by each network, they calculated an ensemble disagreement value that quantified the networks’ confidence in the predicted pixel value, as shown in figure 3. The networks often—but not always—agreed on pixel values and had a low ensemble disagreement. The ability to identify areas of disagreement is crucial to CARE’s utility because those areas alert researchers to places where an image restoration may not be reliable.

CARE networks have thus far outperformed other currently available image restoration methods for all tasks to which they have been applied. But Royer acknowledges that there is still room for progress: “There are scenarios where more research is needed to get a really secure, really robust estimate of where and when to trust the networks.”

Christine Middleton

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Satellites glimpse the microphysics of magnetic reconnection

In situ measurements capture a nonturbulent, efficient reconnection event on Earth’s nightside.

Because of Earth’s magnetic field, the stream of electrons and ions that constantly blows from the Sun gets diverted around the planet. The particles mostly travel with the solar-wind magnetic field lines on their way past Earth, but sometimes they breach the magnetosphere, the region of space where the dominant magnetic field is that of Earth. Such breaches eventually manifest themselves as auroras and geomagnetic storms. Driving the large-scale bursts of energy released in those space weather events are electron interactions that may be an important mechanism for energy conversion throughout the solar system.

When oppositely directed magnetic field lines approach each other in astrophysical plasmas, they can break and reconnect in a lower-energy configuration (see the article by Forrest Mozer and Philip Pritchett, *PHYSICS TODAY*, June 2010, page 34). Bent tightly at first, the field lines abruptly straighten, which sends charged particles streaming away

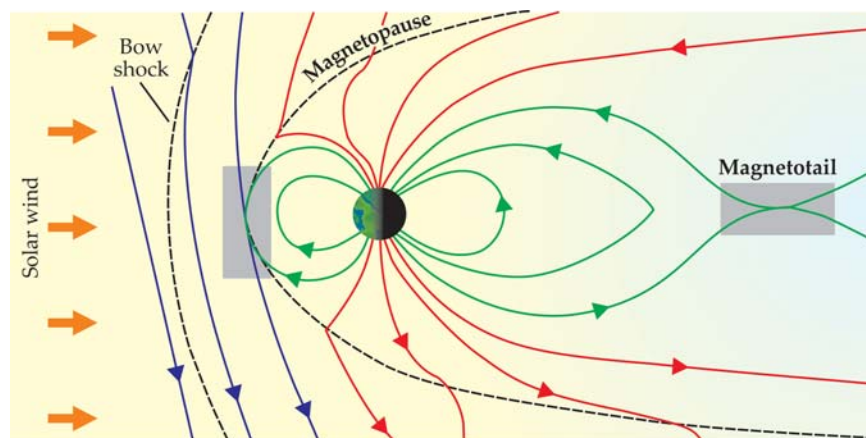


FIGURE 1. MAGNETIC RECONNECTION can occur in two parts (gray boxes) of Earth’s magnetosphere. In the magnetopause, the Sun’s magnetic field (blue) points southward and reconnects with Earth’s closed field (green). In the magnetotail, reconnection occurs when Earth’s open field (red) is squeezed together. (Adapted from ref. 2.)

from the reconnection locus. So far, only with laboratory experiments and computer simulations have researchers been able to probe the details of the process at such scales that they can determine how efficiently energy is converted from magnetic to kinetic. However, reconnection in laboratory plasmas proceeds much too slowly, so researchers have not been able to explain geomagnetic storms and other explosive phenomena observed in space.

Now a new observational window has

opened. The four formation-flying spacecraft of NASA’s Magnetospheric Multi-scale (MMS) mission have witnessed the electron interactions that drive reconnection events in Earth’s magnetosphere.¹

The magnetosphere offers a local, natural laboratory in which to study two regions that host frequent reconnection events.² On Earth’s dayside, the solar wind abuts Earth’s magnetic field at a region called the magnetopause. On the nightside, Earth’s field lines sweep out into a trailing magnetotail. Both regions

are shown in figure 1. The MMS was launched in 2015 to make the first high-resolution *in situ* measurements of plasma and fields and to map reconnection events on both sides of Earth.

Reconnection reconnaissance

In a plasma in a strong magnetic field, the field lines act like wires: Charged particles tightly orbit the field lines, and the net electric current is guided on fixed paths through the plasma. Since the 1970s plasma physicists have understood that for reconnection to occur, the magnetic field must first become “unfrozen” from the plasma’s electrons and ions in a process called demagnetization.

As magnetized plasmas flow toward each other, field lines get squeezed together from above and below the midplane toward a notional central locus called the X-line, as illustrated in figure 2. When the radius of curvature of the field lines becomes comparable to the radius of gyration of charged particles’ spirals about the field lines, the particles resist that squeezing and break away. Positive ions, with their larger radius of gyration, leave their field lines while electrons stay tied to the magnetic field lines and con-

tinue to stream into a confined region, typically just tens of kilometers across, known as the electron diffusion region. There the electrons finally leave their field lines and set off the reconnection process. As the tightly bent magnetic field lines straighten, the electrons are flung outward in two oppositely directed jets.

Reconnection had never before been observed directly and completely. In 1999 NASA’s *Wind* spacecraft filled in part of the picture, when it detected magnetic fields and electron currents established by inflowing electrons during reconnection (see *PHYSICS TODAY*, October 2001, page 16). Now the MMS is peering inside the electron diffusion region to investigate the processes that unfreeze those electrons and drive reconnection. The mission’s four identical satellites each carry eight electron sensors and travel in an adjustable 10-km-scale tetrahedron to measure the three-dimensional electron distribution and the electric and magnetic fields when the spacecraft fly through the epicenter of a reconnection event.

Efficient reconnection

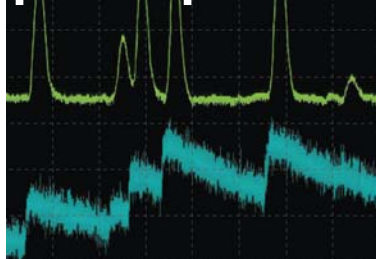
The MMS spent the first part of its mission observing Earth’s dayside where

unequal magnetic fields, that of the solar wind and that of Earth, reconnect in an asymmetric fashion. Since 2017, the satellites have been observing the night-side. On 11 July 2017, the MMS detected jets of ions and electrons streaming toward and away from Earth, providing evidence of an electron diffusion region.

The four spacecraft travelled in a pyramid formation; they were 17 km apart and stayed within 50 km of the most probable region for a reconnection event to occur. During a 10-minute period, the spacecraft moved together from south to north across the magnetotail midplane, 22 Earth radii from Earth. For six seconds, the satellites straddled the electron diffusion region of a reconnection event. Those seconds marked the first *in situ* observation of terrestrial magnetic field lines reconnecting with themselves in a symmetric fashion.

When Roy Torbert (University of New Hampshire) and colleagues looked at the 2017 data, they found an electron velocity that exceeded 15 000 km/s. The high-speed jets carried a strong current away from the X-line, at speeds near the theoretical limits expected for highly efficient conversion of magnetic to kinetic

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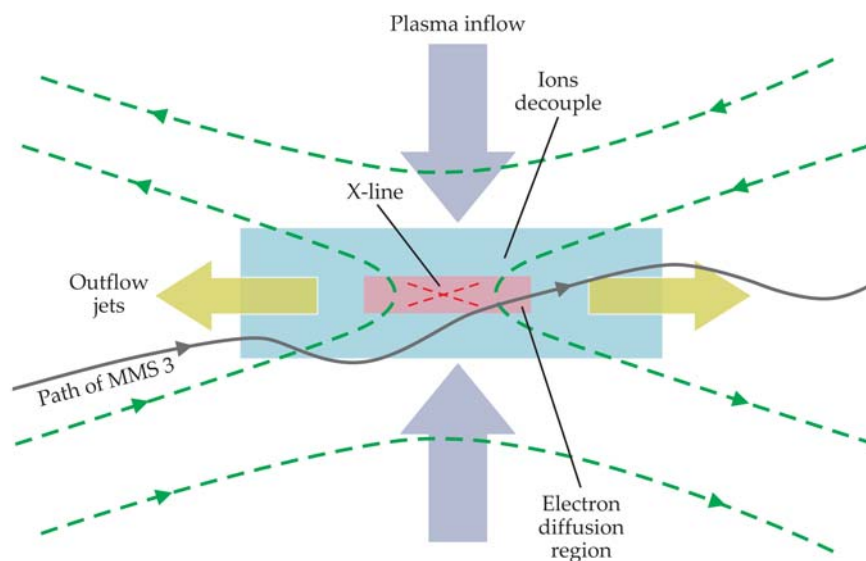


FIGURE 2. THE FOUR SATELLITES IN NASA'S MAGNETOSPHERIC MULTISCALE (MMS) mission flow through the electron diffusion region of a reconnection event in Earth's magnetotail. Here, magnetic field lines (dashed green lines) are compressed from above and below the conceptual X-line, indicated by dashed red lines. Positive ions decouple from the bent field lines, followed by electrons. During reconnection, magnetic energy is sent to oppositely directed particle jets (yellow). The path of one of the satellites, MMS 3, is traced in gray. (Adapted from ref. 1.)

and thermal energy. Figure 3a shows observations from the MMS magnetotail encounter.¹

One of the MMS's goals was to determine the reconnection rate in the electron diffusion region or, as Torbert's coauthor James Burch (Southwest Research Institute) says, "what fraction of the lines reconnect when the plasmas are squished together." The aspect ratio of the electron diffusion region represents the ratio of plasma outflow to inflow and is considered an indicator of the reconnection rate. If the sides and the ends of the diffusion region were of equal length, then the outflow rate would equal the inflow rate. Since all the plasma flowing in to the diffusion region must flow out the ends, the outflow region acts like a pair of nozzles that regulate the inflow rate. Measurements taken as the MMS probes transited revealed an aspect ratio of 0.1 to 0.2, which is consistent with simulations of fast reconnection.³

Curious crescents

In the 1990s Michael Hesse and colleagues at NASA's Goddard Space Flight Center had proposed a laminar mechanism for dissipating magnetic energy, in which thermally mobile electrons rapidly transit through and carry energy away from the electron diffusion region. From their

dayside work three years ago, Burch, Torbert, and colleagues reported MMS observations of electron demagnetization and acceleration.⁴ The results included identification of a crescent-shaped feature in the velocity distributions of electrons at the reconnection site, such as the ones shown in figure 3b. The crescent feature was predicted to be a result of electrons whose orbits meander across a boundary between oppositely directed magnetic fields. The meandering is part of the demagnetization of electrons.⁵

Torbert and colleagues now report multiple discrete structures in electron velocity distributions during reconnection in the magnetotail. As shown in figure 3b, the structures appear crescent shaped in a 2D plot of two velocity components. The velocity distributions from the MMS vindicated predictions that laminar flow, rather than turbulence, dominates the electron dynamics during reconnection.

The crescent structures remained unperturbed during rapid fluctuations in the electromagnetic fields during reconnection. That stability implies that turbulent effects, which would scatter electrons and hence eliminate distinct features like crescents, do not dominate the particle dynamics in the electron diffusion region during reconnection. Rather, the recon-

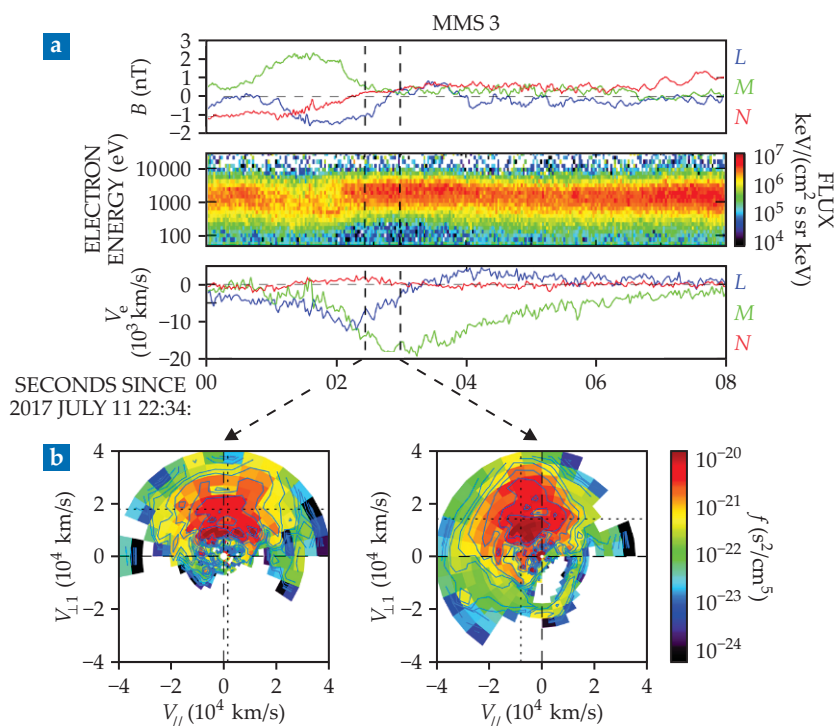


FIGURE 3. A CAPTURED RECONNECTION EVENT. Observations by the Magnetospheric Multiscale mission include (a) the magnetic field B (top), electron spectrogram (middle), and electron velocity V_e (bottom) in the electron diffusion region of a magnetic reconnection event on 11 July 2017. Velocity and field vectors are separated into orthogonal components L , M , and N . During reconnection, the magnetic field vanished and the electron bulk velocity peaked at 15 000 km/s. (b) Crescent-shaped structures persisted in the electron velocity distribution during reconnection. The plots show phase-space density f as a function of velocity components $V_{\perp}$, in the direction perpendicular to the magnetic field, and $V_{\parallel}$, parallel to the magnetic field. (Adapted from ref. 1.)

necting field can continuously accelerate the electrons and drive them into high-speed jets, possibly as a consequence of confinement in the symmetric magnetic structure.

Surprises and predictions

The observations provide the first evidence of how reconnection works at the electron scale, and they confirm that reconnection releases magnetic energy efficiently. MMS scientists hope that more data from Earth's magnetosphere will help explain just how much energy is dissipated by magnetic reconnection throughout the universe and what conditions determine when reconnection begins and ceases.

Torbert's colleague Tai Phan (University of California, Berkeley) has already found one surprise in data transmitted from the MMS while it transited Earth's turbulent magnetosheath, the region between the magnetosphere and the bow shock produced when the solar wind

speed decreases as it approaches the magnetopause (see figure 1). There, diverging electron jets provided the telltale sign of reconnection. But in contrast to standard reconnection, ions were bystanders. Phan concluded that reconnection driven by electron interactions alone can facilitate energy transfer in a turbulent plasma.⁶

By studying reconnection on both sides of Earth, the MMS also helps astronomers understand reconnection elsewhere, such as in the atmospheres of stars, near black holes and neutron stars, and at the boundary between our solar system's heliosphere and interstellar space.

Rachel Berkowitz

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