Reconnecting Magnetic Fields

The huge amounts of energy released from the relinking of magnetic fields in outer space are both mysterious and potentially destructive

James L. Burch and James F. Drake

The universe is wonderfully and intrinsically dynamic on many scales, especially when it comes to the forms of energy that it creates and uses. The gravitational attraction of matter with itself leads to clumping and eventually to the formation of stars, fueled by the release of nuclear energy of burning hydrogen at their cores. When high-mass stars run out of the nuclear fuel, their pressure is insufficient to balance the gravitational forces and they collapse in catastrophic supernova explosions, sending supersonic blast waves across the cosmos.

Although such gravitational and nuclear phenomena are the dominant sources of energy in the universe (along with, perhaps, dark energy), the swirling of matter as it moves in response to these sources generates another form of energy: the magnetic field. The twisting and turning of material in the core of the Earth, near the surface of the Sun and other stars, and in galaxies across the universe, amplifies magnetic fields in a process known as the dynamo. The strength of magnetic fields, measured in units of gauss, ranges from around a microgauss out in the empty expanses of our Milky Way galaxy, to 0.5 gauss at the surface of the Earth, to 1,000 gauss at the surface of the Sun. A typical refrigerator magnet is about 10 gauss. The highest magnetic fields in the universe, around 10^{15} gauss, are believed to exist around high-magnetic-field neutron stars, called magnetars because of their enormous fields. The power associated with such a magnetic field is tremendous—the energy in one gallon of magnetar magnetic field corresponds to that in 10^{18} gallons of gasoline.

Given that magnetic fields and their associated energy exist throughout the universe, it is not surprising that this energy is occasionally released, typically in the form of magnetically driven explosions. Storms in the near-Earth space environment and flares in the corona of our Sun and other stars are examples of explosions driven by the release of magnetic energy. The rates of energy release from magnetar flares dwarf those of the largest supernova explosions.

A fundamental question is, therefore, why and how do these explosions take place? The query is unfortunately not just of academic interest, as these explosions can have serious consequences for our technological society. A large fraction of the magnetic energy from solar flares is released as very high-energy particles; exposure to such particles could sicken astronauts and, in rare extreme solar events, could even prove fatal to them. It can also at least temporarily impair the instruments of spacecraft, manned and unmanned. As the Earth's own magnetic fields are buffeted by storms from the Sun, large numbers of energetic particles are injected into the Earth's radiation belts, creating an environment that can disrupt the operations of communications and other satellites, and in rare cases, even cause disruptions in electrical grids on the ground.

How magnetic fields drive these explosions is on the one hand simple and on the other hand very complex and interesting. The simple answer is that adjacent magnetic fields pointing in opposite directions tend to annihilate each other, releasing their magnetic energy and heating the charged particles in the surrounding environment. *(See "A Four-Part Mystery" on page 394.)* The challenge comes about because simple estimates of the time required for oppositely directed magnetic fields to annihilate one another are long—10,000 years in the case of the Sun's corona—whereas observed energy release times from such magnetic explosions are tens to hundreds of seconds.

We now know that the mechanism for the fast release of magnetic energy requires that oppositely pointing magnetic fields be torn apart and reattached to their neighbors in a process called *magnetic reconnection*. This idea was proposed back in the 1950s but remains to date only partially understood, despite intense efforts of many scientists. In the following sections we discuss some of the history of magnetic reconnection, explain the basic concept, explain why the problem has been so challenging and discuss plans for addressing some of the outstanding issues with computer simulations, laboratory experiments, and both remote sensing and in situ measurements in space. The past decade and a half has witnessed noteworthy advances in our understanding, but a breakthrough requires a highly sophisticated space experiment, the NASA Magnetospheric Multiscale mission, which is now in the implementation phase and currently scheduled for launch in 2014.

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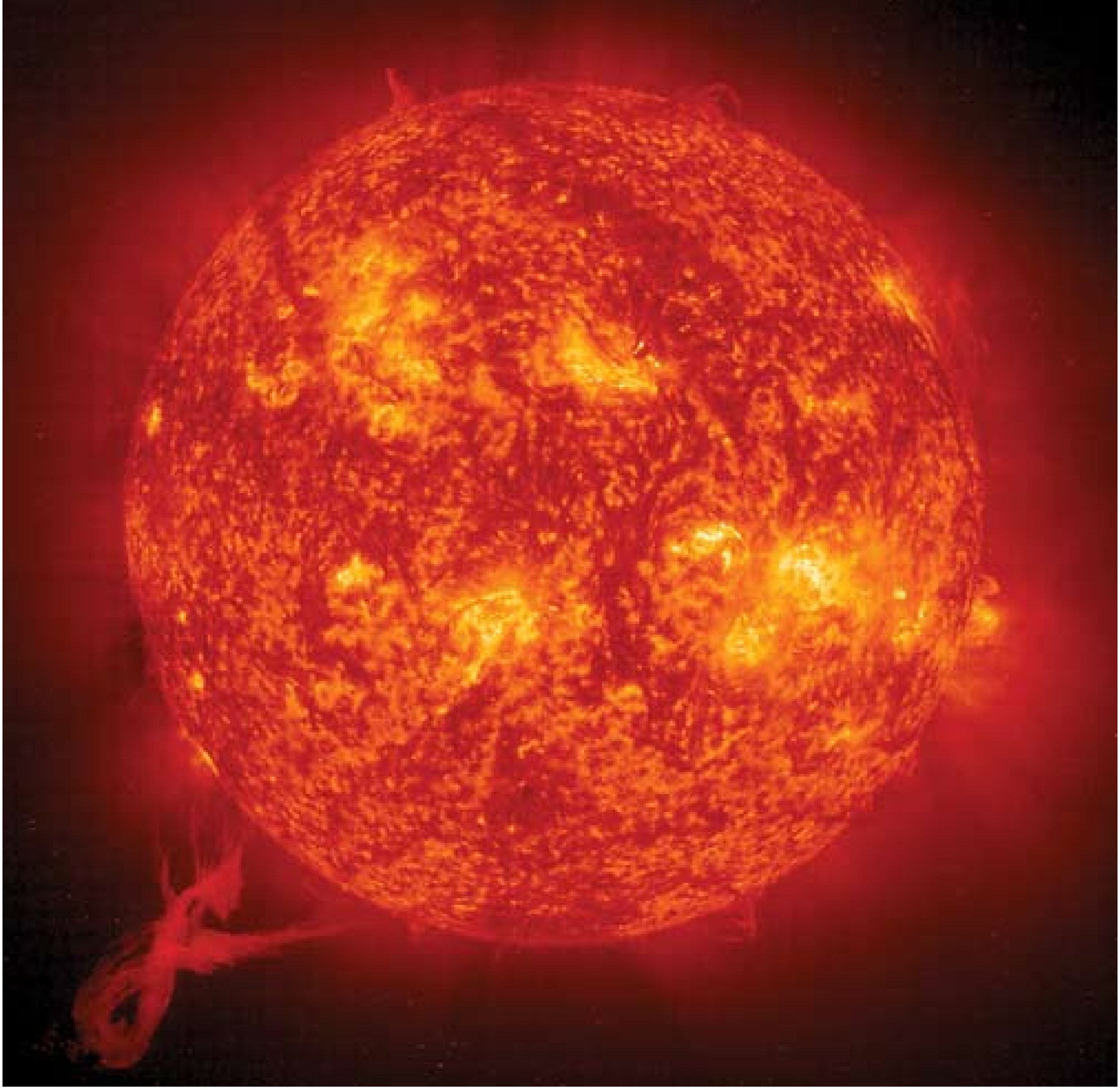


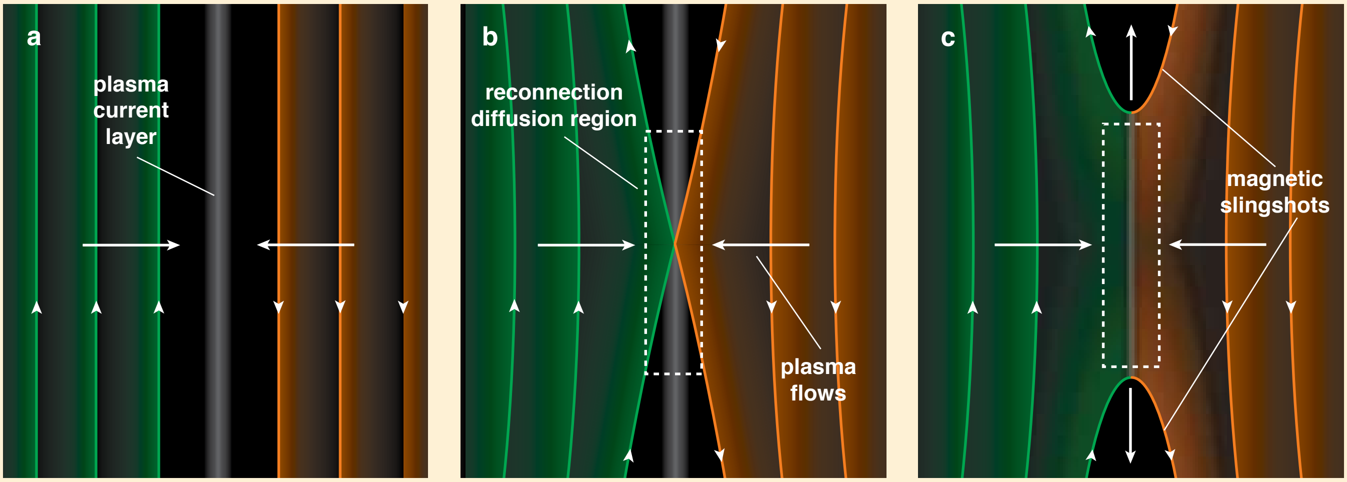
Figure 1. Extending over many thousands of kilometers and with a mass of more than 100 billion tonnes, a twisting solar prominence protrudes out of the Sun's corona in the bottom left of this image. Magnetic fields are heavily involved in the formation of these and other solar features, such as flares and coronal mass ejections. When these fields break apart and link up with each other, in a process called magnetic reconnection, such solar features can explosively release energy that can have consequences on Earth. (Image is courtesy of SOHO/ESA and NASA.)

Early Notions

The history of magnetic reconnection is generally traced back to the work of the Australian solar physicist Ronald Giovanelli, who noted in 1947 that solar flares often occur in locations where a neutral point in the magnetic field is expected. Ten years later, Peter A. Sweet of the University of Glasgow and Eugene Parker of the University of Chicago independently proposed a reconnection model of solar flares based on electrical-resistance effects causing energy dissipation in a diffusion region. This model requires a diffusion region with a very large aspect ratio of length to width, an aspect ratio of 10,000,000 in the case of the solar corona. This type of reconnection has been confirmed in the laboratory and is thought to occur in colliding plasmas that are found, for example, in the solar photosphere, the Sun's visible surface. However, it proceeds much too slowly to be able to explain explosive phenomena such as solar flares.

The breakthrough for flares followed Parker and Sweet's work by about seven years, with the analysis by American physicist and engineer Harry Petschek of a faster reconnection process involving standing shock waves in the plasma and a diffusion region with a modest aspect ratio. Even though to this day we don't know what processes lead to dissipation during magnetic reconnection, research over the past 50 years has established the importance of magnetic reconnection in producing huge explosions, such as flares and coronal mass ejections in the solar atmosphere. Moreover, Petschek's idea has formed the basis for research into the role of so-called "fast reconnection" in producing energetic phenomena in many space environments.

In 1961 Jim Dungey, an English scientist working at the time at Pennsylvania State University, suggested that neutral points should be formed where



A Four-part Mystery

Magnetic fields pointing in opposite directions can annihilate one another, releasing energy through magnetic reconnection. Consider a boundary that separates two bodies of plasma, or ionized gas, containing magnetic fields with opposite directions *(a)*. What if by some means adjacent magnetic fields "break" and cross-link with each other (or "reconnect," as we generally say) across the boundary *(b)*? The field line pointing upward is now connected to that pointing downward. The resulting bent magnetic field line has tension like a rubber band, so the motion of the magnetic field and the plasma that is attached to it are like two back-to-back slingshots: The magnetic field accelerates the plasma away from the reconnection region *(c)* and in the process releases magnetic energy.

The outward vertical motion of the plasma pulls in the magnetic field and plasma on either side of the reconnection region. The arrows indicate the direction of motion of the plasma and magnetic field. The new magnetic fields coming from the sides are now ready to reconnect and release their energy. The result is an explosive release of magnetic energy that is self-driven. In contrast to a traditional explosion where the outward moving blast wave is the same in all directions, during magnetic reconnection the high-speed flow is only in the direction of the two magnetic "slingshots." The plasma flows slowly inward in the other directions. The release of energy during magnetic reconnection is the driver of powerful explosions throughout the universe, from storms in the Earth's magnetosphere to flares in the coronas of our Sun and other stars.

What would cause the two magnetic fields to reconnect with each other? Two oppositely directed magnetic fields must be separated by an electrical current directed inward in the boundary between them *(a)*. The plasma filling the region between the two magnetic fields must carry this current and provide a medium for energy transfer. Another necessary ingredient is an electric field (which also would be pointing into the page). In any electric circuit, including this one, an electric field parallel to the current flow acts as a load on the circuit, which dissipates electrical energy into heat or other forms of energy. It is this dissipation that allows the two magnetic fields to interconnect.

The box in *(b)* and *(c)* encloses the diffusion region, within which magnetic dissipation occurs. Outside of this box the plasma and magnetic field remain connected to one another and everywhere move together; the magnetic field is therefore "frozen in" to the plasma. Within the box, however, dissipation causes the "frozen in" condition to fail and the plasma flow becomes disconnected from the magnetic field, allowing the magnetic fields to reconnect. In the rather rarified environments where magnetic reconnection takes place, the classical particle collisions that produce dissipation in electrical circuits are negligible. What then produces "dissipation" in a collisionless plasma, allowing reconnection to occur, is the first great mystery of reconnection.

The shape of the diffusion region, specifically its aspect ratio (the ratio of its length to its width), controls the rate of release of magnetic energy. In a high aspect-ratio diffusion region, the release of energy is slow—all of the plasma flowing into the diffusion region from the sides must flow out the ends, which act like a pair of nozzles. The resulting rate of inflow of magnetic field from the sides is low and so is the rate of energy dissipation. Thus the diffusion region, a very narrow boundary layer of unknown structure and dynamics, controls the release of magnetic energy in a macroscopic system. What determines the aspect ratio of the dissipation region and the rate of release of magnetic energy is the second great mystery of reconnection.

Magnetic reconnection often occurs as an explosion, with solar and stellar flares being obvious examples. Magnetic energy builds up slowly as plasma twists the magnetic fields in the solar corona or as the magnetic field in the solar wind drapes over the Earth's magnetosphere. What is the "spark" that causes the magnetic energy that has built up over a long period of time to be suddenly released? Why doesn't the magnetic energy instead simply dissipate at the same rate at which it is generated? Does a sudden increase in the strength of "dissipation" set off reconnection? That's the third great mystery of reconnection.

Since early observations of solar flares and the Earth's magnetosphere, evidence has been accumulating that a significant fraction of the magnetic energy released in reconnection appears in the form of energetic particles, typically high-velocity electrons and protons, which make up on the order of 50 percent of the energy in the case of flares. Particles reach kinetic energies that far exceed those expected from the fluid flows thought to be involved in magnetic reconnection *(as shown in c)*. Therefore the acceleration mechanism cannot be described through classical fluid dynamics. What is the mechanism for such efficient conversion of magnetic energy into the kinetic energy of charged particles? This question is the fourth great mystery of reconnection.

magnetic fields from the Sun and the Earth interconnect, which should be responsible for driving plasma flow throughout the Earth's magnetosphere and possibly producing the aurora (as had been theorized by his graduate advisor, Fred Hoyle, in 1948, with whom Giovanelli had discussed his model). Since then researchers on the Earth's magnetosphere have gradually seen Dungey's magnetic reconnection idea move from questionable to highly controversial (owing to the inability at the time to make actual observations to back up the predictions) to universally accepted as the main driver of space storms around the Earth.

The idea of a connection with the aurora has also turned out to be true, but for all types of auroras except one, the link is only indirect. For the most part, the widespread and violent auroral displays associated with severe space storms are caused by processes internal to the magnetosphere, which nonetheless rely on magnetic reconnection at much higher altitudes for their existence *(see figure 3 for an illustration of the process).* The idea here is that magnetic fields from the Sun and the Earth reconnect on the dayside of the Earth (the side facing the Sun), after which the solar wind carries the reconnected magnetic flux along the magnetopause (the boundary of the magnetosphere) to the nightside, resulting in a build-up of magnetic energy in the tail of the magnetosphere. A second reconnection event in the tail, which reconnects northern and southern magnetic flux and releases the solar field lines, is established after some time delay (a half hour or so), and it is this event that leads to widespread magnetic and auroral activity known as the magnetospheric substorm, as well as to strong beams of high-energy particles. The question of whether reconnection triggers the substorm or is a secondary effect was answered in 2008 by the five-spacecraft NASA THEMIS mission, launched specifically to study space storms, which showed conclusively that reconnection is in fact the trigger mechanism.

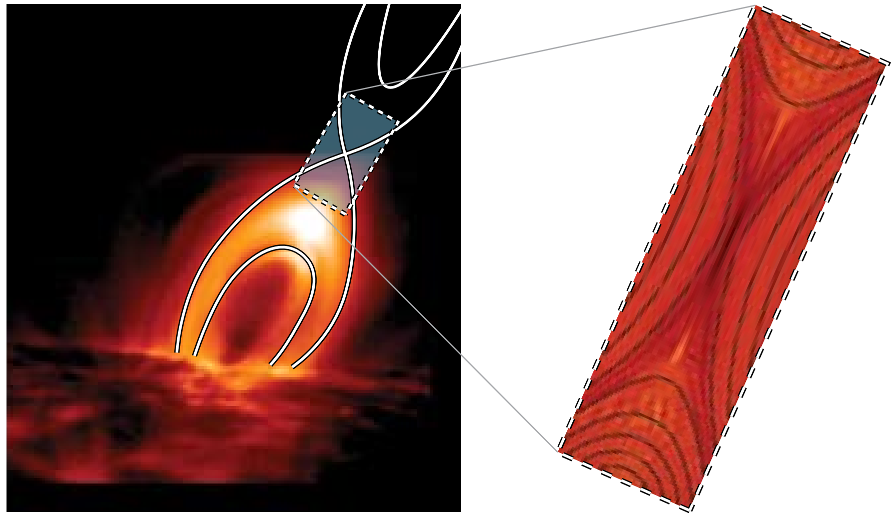


Figure 2. An x-ray image of a solar coronal structure from Japan's Hinode spacecraft *(left)* is overlaid with an illustration of the magnetic field lines and the reconnection region *(dotted box)* that produces it. Computer simulations of electron populations in reconnection regions *(right)* have been key in deciphering more about how this event unfolds. (Left image is courtesy of the Japanese Space Agency, right image is courtesy of James Drake and Michael Shay, University of Delaware.)

Evidence Mounts

Much of the original evidence for the importance of magnetic reconnection in the Earth's magnetosphere was statistical—strong auroral and magnetic activity was found to be correlated with southward-directed solar-wind magnetic fields that reconnect with the northward pointing field of the Earth. The southward fields were also associated with inward movement of the dayside boundary of the magnetosphere, as magnetic flux is stripped from the dayside and transferred to the nightside because it is connected to the flowing solar wind. Later on, predictions of reconnection theory, regarding plasma outflow from the reconnection region and magnetic penetration of the boundary, were both confirmed by spacecraft data. As more recent spacecraft data pour in, especially from the European Space Agency Cluster II mission (which studies how the Earth's magnetic field interacts with the solar wind), the evidence that magnetic reconnection plays a dominant role in driving the dynamics of the magnetosphere has become overwhelming.

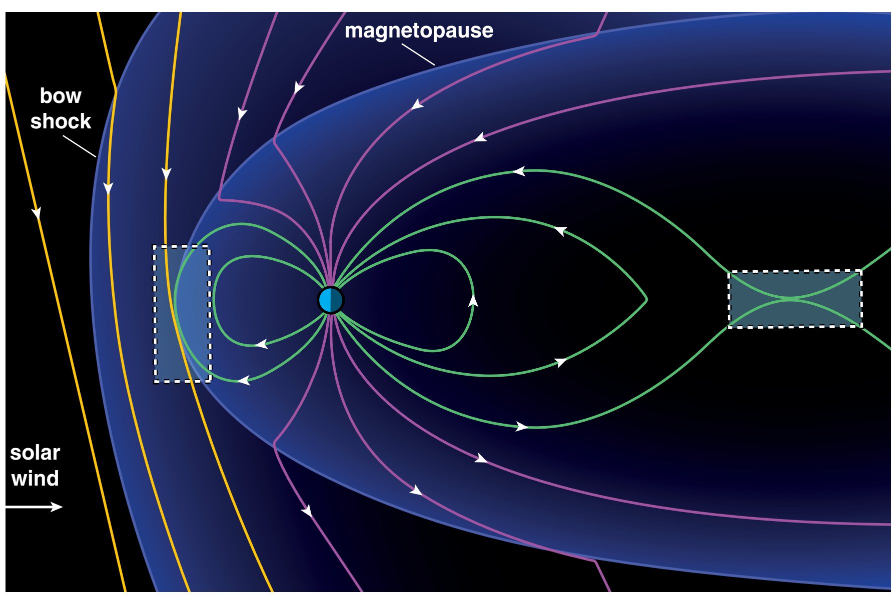


Figure 3. The solar wind carries the interplanetary magnetic field *(yellow lines)*, here oriented southward, into the northward-facing geomagnetic field lines emanating from the Earth *(green lines)* at the dayside of the magnetopause. The reconnection of these fields *(dotted box at left)* allows energy and charged particles from the solar wind to enter the magnetosphere. Open magnetic field lines *(purple lines)* are carried downstream in the solar wind and eventually reconnect in the distant tail of the magnetosphere *(dotted box at right)*. This figure shows only a noon-to-midnight cross-section of the three-dimensional magnetosphere.

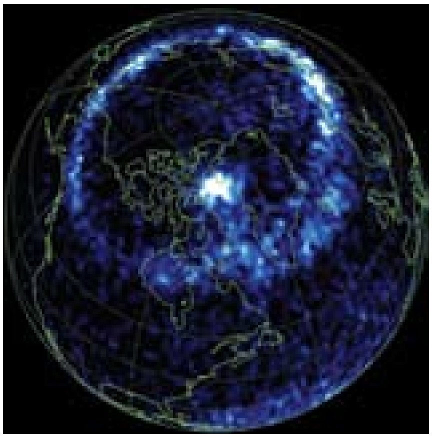


Figure 4. Auroras are usually created by electrons but this image shows a North Pole aurora emitted by protons, which glow brightly in the ultraviolet range. The nearly circular white spot results from reconnection with a northward-directed interplanetary magnetic field. (Image courtesy of the NASA IMAGE mission.)

Auroras are most often caused by electrons interacting with oxygen and nitrogen in the Earth's upper atmosphere. But sometimes the auroras result from collisions between the elements and protons, which are heavier and thus cause a more energetic display, particularly in the ultraviolet region. Using images of energetic hydrogen atoms precipitating into the atmosphere, scientists working with the NASA IMAGE satellite, launched in 2000 as the first mission dedicated to imaging the Earth's magnetosphere, were able to identify localized auroral spots of the proton aurora produced by reconnection of northward interplanetary magnetic fields with the Earth's field. Northward interplanetary fields, being parallel to the Earth's field, are generally associated with quiet periods between storms.

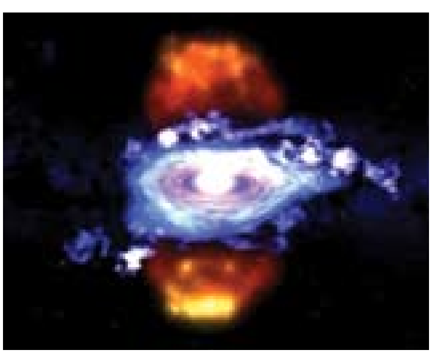


Figure 5. The supermassive black hole Sagittarius A and its accretion disk have been observed to emit massive flare ejections, which may be caused by magnetic reconnection. (Illustration courtesy of the NASA Compton X-ray Laboratory.)

However, as predicted by Dungey in 1963, reconnection should still occur high over the polar caps between northward fields and the swept-back, generally southward magnetic fields that form the Earth's magnetic tail. Although the motions of these spots, in concert with the changing east-west components of the generally northward field, were consistent with a reconnection source, the smoking gun came with a simultaneous observation of reconnecting magnetic fields above the spots by Cluster II, as reported by Tai D. Phan of the University of California, Berkeley, and his colleagues in 2006. These observations confirmed Hoyle's original 1948 prediction.

One of the reasons it took so long to confirm this simple prediction is that a sophisticated experiment had to be performed with simultaneous measurements from a spacecraft in the solar wind, a cluster of four spacecraft that straddled the reconnection point with high-resolution measurements, and a spacecraft capable of imaging the proton aurora.

The Exploding Universe

Could it be that the same type of reconnection that powers the Earth's magnetosphere and aurora is responsible for energetic phenomena throughout the universe? Of course, our own Sun is strong evidence in favor of this possibility. The soft x-ray emission from the million-degree solar corona reveals loop-like structures that are effectively images of coronal magnetic field lines, because high-temperature particles in the solar corona rapidly spread along magnetic fields and therefore provide an effective image of the magnetic fields. The study of the dynamics of these loops, measured with NASA's TRACE and Japan's Hinode satellites (both launched to study the magnetic fields of the Sun), has dispelled any doubt about the central role of reconnection in producing explosive phenomena in the solar corona.

Similarly, throughout the universe explosive phenomena are observed through the energetic photons and charged particles they emit. For many years gravitational collapse and explosive shock waves were thought to explain most of what we observed. But as more exotic phenomena have been discovered, they often are found to contain strong magnetic fields and to undergo mysterious interactions that are sometimes best explained by magnetic reconnection.

An early insight into the role of magnetic fields in driving astrophysical dynamics came in 1979 from Albert Galeev, Robert Rosner and Giuseppe Vaiana of the Harvard-Smithsonian Center for Astrophysics. They described a gravitationally bound magnetized accretion disk—a collection of matter surrounding a gravitationally collapsed object in outer space—within which magnetic fields are both continuously created by a dynamo and annihilated by magnetic reconnection. As happens in the solar corona, they discovered magnetic loops forming and reconnecting while producing the x-ray emissions that were observed. Numerous experimental and theoretical studies since that time have generally confirmed the validity of this model.

Some of the most energetic phenomena in the universe are associated with the supernova explosions that are part of the death throes of stars. After such an explosion, the star collapses into a neutron star and often into a black hole. Although accretion disks are usually connected to stars or protostars, they also surround neutron stars and black holes, with angular momentum and plasma being transferred between these three objects by turbulent magnetic fields. Any nearby stars also can be distorted and literally sucked into the black hole through its magnetically connected accretion disk.

In addition to localized accretion-disk x-ray emissions, massive flare activity has also been observed from black-hole accretion disks. A dramatic example of massive flare ejection was observed from the supermassive black hole Sagittarius A, located at the center of our galaxy. It has been proposed that such massive flare ejections are caused by magnetic reconnection, as in solar flares. A neutron star can also evolve into a pulsar or, in extreme cases, into a magnetar, which exhibits very energetic flare-type emissions that also are very likely produced by magnetic reconnection.

In general, astrophysicists consider reconnection as a possible mechanism for any phenomena exhibiting plasma heating, particle acceleration, magnetic field collapse or magnetic topology changes. Remote sensing of these phenomena provides vast amounts of information on their scale, temporal development and energy transfer. However, the lack of in-situ measurements limits the information that can be gleaned about the processes that drive reconnection.

Insights from Theory

The rapid increase in computer capacity over the past decade has facilitated numerical simulation of reconnection. Insights gained through these computations have dramatically advanced our understanding of magnetic reconnection and for the first time have enabled quantitative comparisons with observations. The simulations are now able to treat single-particle motions of billions of electrons and protons in three dimensions and at time scales appropriate to the dynamical behavior of the plasma. The main limitation now is the requirement to use ion/electron mass ratios in the hundreds, rather than the several thousands common in nature. With continued increases in computing power, this limitation too will gradually be overcome. These simulations and observations have enabled scientists to address the "reconnection mysteries."

As noted before, resistivity based on classical electron-ion collisions, as first proposed by Sweet and Parker, produces insufficient dissipation to explain the explosive release of magnetic energy seen in nature—most plasmas of interest are tenuous and as a result collisions are rare. So the first mystery was what replaces classical resistivity in nearly collisionless plasma. In 1984 Galeev and Roald Sagdeev, now at the University of Maryland in College Park, proposed that the intense layers of current produced during reconnection generate turbulent electric-field fluctuations that scatter electrons. The result is a dramatic enhancement of the rate at which electrons take energy from the magnetic field, producing an enhanced effective, or "anomalous," resistivity. The swirling electric-field vortices that develop in reconnection are similar to the gusty vortices of wind that develop during the passage of a strong weather front, which is a boundary layer of the neutral atmosphere of the Earth. With turbulence, the field lines would be strongly twisted so that multiple ones could reconnect simultaneously, vastly increasing the reconnection rate.

Confirmation of the anomalous resistivity idea with numerical simulations had to wait nearly 20 years until computers were sufficiently powerful to explore reconnection and self-generated turbulence. The bottom line from this modeling effort is that anomalous resistivity develops, but only when the current layer and associated diffusion region are sufficiently narrow. The transition from classical resistivity to anomalous resistivity takes place when the diffusion region thins down to the "skin depth," also called the electron inertial length, which is the depth to which waves can penetrate into a conductor. There are tantalizing measurements of electric-field fluctuations from satellites in the Earth's magnetosphere and radio bursts during flares which suggest that turbulence does develop in the current layers that form during reconnection. There is as yet no observational smoking-gun evidence, however, that this turbulence acts as an effective dissipation mechanism for magnetic energy.

A laminar, or non-turbulent, mechanism for dissipating magnetic energy has been described by Michael Hesse and his colleagues at the Goddard Space Flight Center. In this model, electrons take energy from the magnetic field in the diffusion region as they are accelerated by the reconnection electric field. Because of their high thermal mobility, they are able to rapidly transit through, and carry energy away from, the diffusion region. The effect appears in the form of a pressure that is non-isotropic, or not the same in all directions. Therefore it cannot be described by conventional fluid dynamics, although it has been well documented in computer simulations.

Thus, the first great mystery of reconnection, which addresses how magnetic field lines break and magnetic energy is dissipated in a collisionless plasma, can be restated: Can the non-isotropic electron pressure explain the rapid reconnection over the vast scales of space and astrophysics, or is turbulence and its associated anomalous resistivity required? Unfortunately, because the breaking of magnetic field lines happens at very small spatial scales, comparable to the electron skin depth, the present fleet of heliospheric satellites is incapable of resolving the issue.

One of the major successes of reconnection research over the past two decades relates to the second great mystery of reconnection, which concerns what controls the rate of energy release. Bengt Sonnerup in 1979 noted that ions and electrons, because of their large mass difference, would move differently at the small spatial scales of the diffusion region. Mark E. Mandt, Richard E. Denton and one of us (Drake) in 1994 showed that this differing motion completely changes the dynamics and structure of the diffusion region. The ion motion can be neglected at very small scales; freed from the heavier ions, the

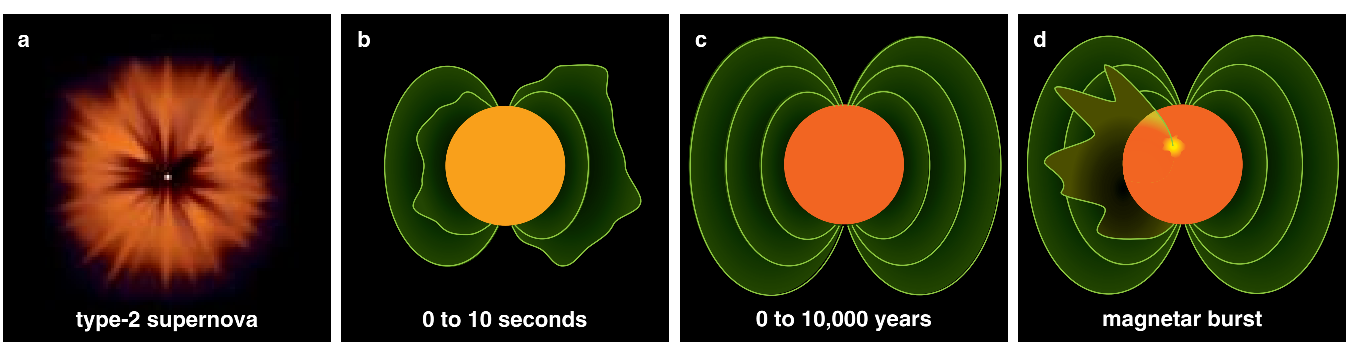


Figure 6. Massive stars die in type-2 supernova explosions; their stellar cores implode into a dense ball of subatomic particles *(a)*. If the newly formed neutron star is spinning fast enough, it will generate an intense magnetic field, and field lines inside the star will become twisted from the rapid movement *(b)*. Over the first 10,000 years of its life, the star will settle down so that there are turbulent fields inside but smooth field lines on the surface *(c)*. At some point these internal stresses crack the solid surface, resulting in a quake that creates an electrical current burst and a flow of material that emits x rays *(d)*. The material dissipates in a matter of minutes.

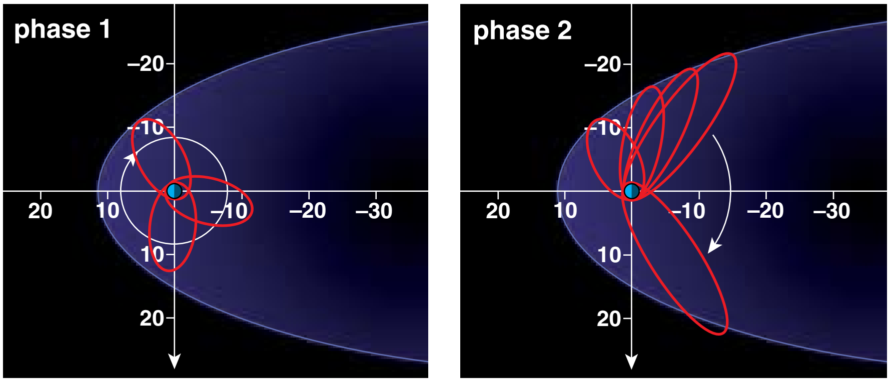


Figure 7. The Magnetospheric Multiscale mission will use a set of four satellites to probe magnetic reconnection at the boundary of the magnetosphere. The tetrahedrally aligned satellites will gradually precess their orbit in each phase of the mission over a period of many months. In phase one, at a distance of 12 Earth radii, the group will be on the day side so that the crafts hover near the boundary between the magnetosphere and the solar wind. In phase two, at a maximum distance of 25 Earth radii, the group will move to the night side, where reconnection in the tail of the Earth's magnetic field is most common.

electrons—together with the embedded magnetic field—can flow away at very high velocity. In the flurry of papers that followed, scientists showed that the rate of reconnection dramatically increased from the classical Sweet-Parker rate, the aspect ratio of the dissipation region was modest and the rate of reconnection was controlled by ions and not electrons.

The key signature of what has been dubbed "Hall reconnection" is the out-of-plane or Hall magnetic field that develops as a result of the relative motion of electrons and ions in the reconnection plane. The structure of the Hall magnetic field has been extensively documented in magnetospheric satellite observations, which brought positive closure to the idea of electron-ion decoupling within the small spatial scales of the dissipation region. Moreover, for the first time since reconnection was first proposed in the 1950s, the theoretical predictions for the rate of reconnection agree with astrophysical observations. This rate of reconnection means that when two magnetized plasmas (such as the solar wind and the Earth's magnetosphere) interact, the coupling of energy by reconnection has an efficiency of about 10 percent.

To the Laboratory

One of the major efforts in plasma physics has been the quest to sustain high enough temperatures to trigger nuclear fusion on a continuous basis. If this process could be done efficiently, it could solve the world's energy crisis safely and permanently. One approach, magnetic confinement fusion, has yielded very promising results with devices such as tokamaks, which produce a ring-shaped magnetic field to confine plasma inside. However, energy leakage caused by small-scale turbulence or larger-scale disruptive events driven by reconnection continues to be an issue in these devices. Magnetic reconnection in tokamaks typically begins if the plasma pressure or current exceeds a threshold.

One common result is a *sawtooth crash*—the core electron temperature slowly rises and then suddenly falls in a rapid crash of 50 to 100 microseconds that repeats nearly periodically, causing a massive transfer of energy out of the plasma core. Diagnostic evidence strongly supports the idea that these sawtooth crashes are caused by impulsive reconnection. The surprisingly short time scale of these events, which contradicted the traditional Sweet-Parker reconnection model, catalyzed an intense theory and modeling effort to understand fast magnetic reconnection and its explosive onset.

For many years, laboratory investigations of reconnection were limited to the collisional regime within which the predictions of slow (Sweet-Parker) reconnection were verified. However, Masaaki Yamada and his colleagues at the Princeton Plasma Physics Laboratory recently reported that fast reconnection could be driven when the ion skin depth was greater than the Sweet-Parker resistive layer. This result is another confirmation that the reconnection rate is determined by ion-scale dynamics; phenomena such as the out-of-plane magnetic field component predicted by Hall reconnection have now been confirmed in the laboratory as well as in space.

More recently the spontaneous onset of fast reconnection has been identified by Jan Egedal and his colleagues in the Versatile Toroidal Facility's reconnection experiment at the Massachusetts Institute of Technology, providing hope that further measurements will provide insight into the third great mystery of magnetic reconnection, namely why it is so often explosive.

A Space Experiment

What are the next major steps in magnetic reconnection research? In addition to continuing the current aggressive program of astronomical observations, laboratory investigations and numerical modeling, NASA has initiated a carefully crafted experiment in space. The mission, named Magnetospheric Multiscale (MMS), will begin with the launch of a four-spacecraft constellation currently scheduled for 2014. This mission is made possible by the existence of nearly continuous reconnection in the boundary regions of the Earth's magnetosphere, particularly along its dayside boundary with the solar wind and the boundary between open and closed magnetic field lines in the magnetic tail.

The significance of these two regions is that they provide the only accessible laboratories in space for a reconnection experiment. They are nearby, are not too hot and are known to contain explosive reconnection of the type that has been found to be important throughout the universe. To be sure, the scaling between these regions of very tenuous plasma and the more extreme environments of the Sun, accretion disks, neutron stars and fusion machines extends over many orders of magnitude. Nonetheless, the next important goal is to determine what causes magnetic field lines to reconnect in a collisionless plasma. Then it will be up to a theoretical research program to bridge the gap to other environments and make predictions that can be tested by future observations.

There are several very stringent requirements for a definitive experiment on reconnection in the Earth's magnetosphere. Guidance from theory and modeling, and from numerous previous space missions (particularly the European Space Agency's Cluster II, which also uses a constellation of four spacecraft), have allowed these requirements to be defined quite accurately. First, the spacecraft must sample the most likely reconnection sites repeatedly and probe both those regions in which the magnetic fields are very nearly antiparallel (which is usually the case in the tail) and regions where a significant guide field exists (which is generally true at the dayside boundary).

Next, since the reconnection regions are generally moving rapidly (Sunward and Earthward on the dayside and tailward on the nightside), the spacecraft need to hover in these regions. This means their orbit apogees must be near the expected reconnection sites. On the dayside, this distance is on the order of 10 Earth radii, whereas on the night side it is between 20 and 30 Earth radii (one Earth radius is 6,371 kilometers). For this reason alone, two different orbits are needed.

Once near a reconnection region, four identical spacecraft are needed in order to identify it by its two areas of inflow and two zones of outflow. Once reconnection regions have been found, the distances between satellites can be reduced in later encounters so that first the ion diffusion region and then the electron diffusion region can be sampled in detail. The directions and intensities of currents, electric and magnetic fields, and plasmas and accelerated particles all need to be determined in unprecedented detail in order to identify the physical processes responsible for the non-classical resistivity and the resulting reconnection of the magnetic field.

From previous missions we know the speed with which reconnection layers move through space to be from tens to hundreds of kilometers per second. With computed electron skin depths of 5 to 10 kilometers, this means that the full three-dimensional electron population has to be sampled at rates greater than 10 per second. The MMS fast-plasma instrument will make this measurement at a rate of more than 30 per second.

Because the ion skin depth is larger, the ion measurement-rate requirement is more relaxed, so MMS will make full ion measurements at rates of greater than 6 per second. By comparison, Cluster II, with its single orbit apogee of 19 Earth radii, makes plasma measurements only once every four seconds.

Three-dimensional electric field measurements are also required (only a two-dimensional measurement is made by Cluster II) for a sufficient description of the physical processes at work in reconnection, and MMS will make this important measurement once every millisecond.

In order to determine the complete plasma distribution and the current it carries, the plasma measurements need to extend downward to a few electron volts and upward to at least 20,000 electron volts. In sunlight, spacecraft continuously emit photoelectrons that tend to charge it up to a positive voltage that can reach 50 to 100 volts. This voltage will interfere with low-energy plasma measurements and also with the electric field measurements. As implemented by Cluster II, MMS will use an active spacecraft potential control device, which emits indium ions to neutralize the photoelectron current and keep the spacecraft from charging to more than a few volts positive.

Because ion dynamics in Hall reconnection depend sensitively on ion mass, MMS includes a new-generation plasma mass spectrometer that defeats some problems with high proton fluxes that have bedeviled previous ion-composition measurements near the dayside magnetospheric boundary. Finally, energetic ion and electron measurements of up to 500 kiloelectronvolts are included, both as remote sensors of boundary regions and as diagnostics of the particle acceleration processes that are produced in reconnection.

In addition to the need to straddle the reconnection regions and measure the four inflow and outflow regions, four spacecraft are needed to provide simultaneous measurements in the ion and electron diffusion regions, and also to be able to determine the spatial gradients that exist in magnetic and electric fields and plasma flow velocities. These gradients can be used to compute important quantities such as currents, magnetic field variations and vorticity. The three gradients will be determined simultaneously by maintaining the four spacecraft in a tetrahedral configuration with an adjustable scale size.

MMS will also be able to answer the question raised before about the possible role of turbulence in increasing the reconnection rate. With a 1-millisecond time resolution for magnetic and electric fields and vector magnetic wave measurements up to 6 kilohertz, MMS will be able to measure the level of turbulence within the diffusion region while simultaneously measuring the electron pressure. At the same time it can determine the reconnection rate through the electric field and current, and independently check it with the plasma flow velocities.

Even now, before it has left the ground, MMS includes a comprehensive theory and modeling team that is providing the inputs required for an optimum experiment. A major issue is that MMS will make very high rate measurements that will exceed by far the available downlink capacity. For this reason, theory and modeling are being used to design a system that will be able to evaluate data quality in near real time and select the most promising intervals for full downlink. This system will be implemented by a large, on-board computer memory and the capability to select intervals for downlink based on both the software's sampling of the highest-rate data and the evaluation of lower-rate data by scientists on the ground.

By all accounts, MMS will provide the most definitive in-space experiment on reconnection that can be designed with our current knowledge. Although it is probably not the final step, it will be an important one toward an understanding of the microscopic physics at the heart of the reconnection process and the many energetic phenomena throughout the universe that reconnection unleashes.

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