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GRAND CHALLENGES CENTENNIAL COLLECTION

# Magnetic Reconnection in the Space Sciences: Past, Present, and Future

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**Key Points:**
- Magnetic reconnection is a key energy conversion and transport process in plasmas
- There has been recent, considerable, research progress understanding how reconnection works
- Many exciting research challenges await, while we can reap the benefits of our new understanding

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**Abstract** Magnetic reconnection converts, often explosively, stored magnetic energy to particle energy in space and in the laboratory. Through processes operating on length scales that are tiny, it facilitates energy conversion over dimensions of, in some cases, hundreds of Earth radii. In addition, it is the mechanism behind large current disruptions in fusion machines, and it can explain eruptive behavior in astrophysics. We have known about the importance of magnetic reconnection for quite some time based on space observations. Theory and modeling employed magnetized fluids, a very simplistic description. While successful at modeling the large-scale consequences of reconnection, it is ill suited to describe the engine itself. This is because, at its heart, magnetic reconnection in space is kinetic, that is, governed by the intricate interaction of charged particles with the electromagnetic fields they create. This complex interaction occurs in very localized regions and involves very short temporal variations. Researching reconnection requires the ability to measure these processes as well as to express them in models vastly more complex than fluid approaches. Until very recently, neither of these capabilities existed. With the advent of NASA's Magnetospheric Multiscale mission and modern modeling advances, this has now changed, and we have now determined its small-scale structure in exquisite detail. In this paper, we review recent research results to predict what will be achieved in the future. We discuss how reconnection contributes to the evolution of larger-scale systems, and its societal impacts in the context of threatening space hazards, customarily referred to as "space weather."

**Plain Language Summary** In space, huge amounts of energy are released explosively by a mysterious mechanism: magnetic reconnection. Reconnection can abruptly convert energy stored in magnetic fields to energy in charged particles, and power such diverse phenomena as solar and stellar flares, magnetic storms and aurorae in near-Earth space, and major disruptions in magnetically confined fusion devices. It is behind many of the dangerous effects associated with space weather, including damage to satellites, endangering astronauts, and impacting the power grid and pipelines. Understanding reconnection enables us to quantitatively describe and predict these magnetic explosions. Therefore, magnetic reconnection has been at the forefront of scientific interest for many years, and will be for many more. Measuring reconnection is incredibly difficult. However, recently scientists have been able to peek into its machinery. Combining measurements from NASA's Magnetospheric Multiscale mission with supercomputer modeling, scientists have now been able to analyze the inner workings of this elusive mechanism. Even though open questions remain, this new understanding has broad implications. Here, we describe magnetic reconnection, where it plays a role, its impacts on society, and what we now know about it. We point to future research challenges, including implications and the utility of our recently developed knowledge.

There is an imprecise—but useful—analogy to rubber bands that helps us picture magnetic reconnection. A loose rubber band cannot hold a pile of pencils in place, but a stretched rubber band can. This is because it takes energy to stretch the rubber band, and that energy can be thought of as stored in the rubber band. The energy in the stretched rubber band holds the pencils in place. The more you stretch a rubber band, the more energy it stores. Eventually, if you stretch a rubber band too much, it breaks, providing a painful lesson of how much energy it can hold!

There are ways that magnetic fields are analogous to rubber bands. Magnetic fields are invisible and intangible but permeate all space. Earth itself acts like a large magnet, and its magnetic field is felt

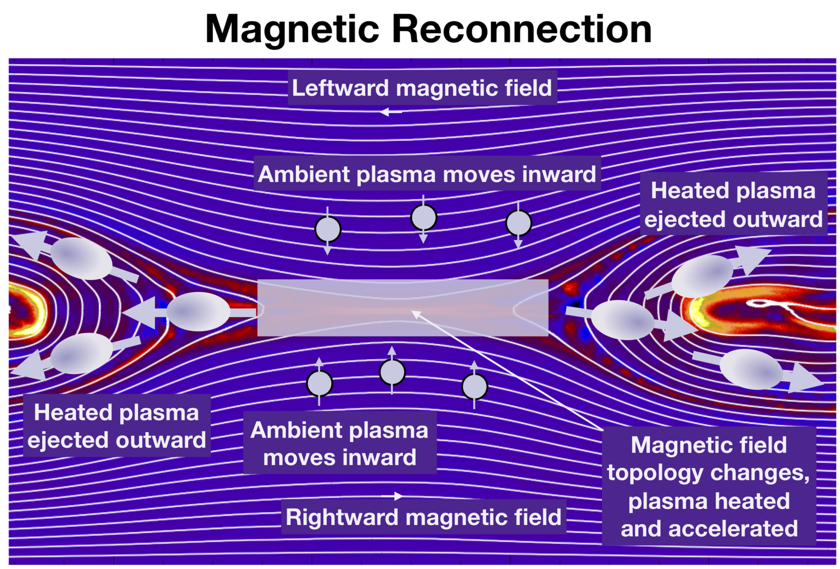


**Figure 1.** Simplified two-dimensional schematic diagram of magnetic reconnection. Oppositely directed magnetic fields (light blue lines) and ambient plasma (light blue circles) move into the diffusion region (shaded box in the center), where magnetic reconnection occurs. The plasma is heated and accelerated into jets to the left and right (shaded blue ovals).

hundreds of thousands of miles from Earth. The Sun also has a magnetic field, shaped vastly different than Earth's, which is felt 10 billion miles away! Like a rubber band, when magnetic fields get stretched, they store energy. It was historically thought that lines of magnetic field could not break, no matter how stretched they get. Unlike a rubber band, a single magnetic field line cannot break because magnetic fields cannot have free ends. However, if there is another stretched magnetic field line nearby pointing in the opposite direction, they can simultaneously break and cross connect so that there is never a free end. This is sketched in Figure 1. The light blue lines at the top and bottom are magnetic field lines pointing to the left and right, respectively, against a backdrop of the electric current. Magnetic field lines enter the shaded box in the center of Figure 1, called the diffusion region, where they effectively break and the broken ends from each immediately cross connect with each other. The field lines are said to have reconnected. The resulting two strongly bent magnetic field lines, threading the diffusion region, are stretched like rubber bands. They straighten out to the left and right and release their energy.

The matter in space is typically a super-heated gas called a plasma. Plasmas, the “fourth state of matter” joining solids, liquids, and gases, are so hot that some or all the atoms making them up cannot stay together—they break up into negatively charged electrons and positively charged ions that move fast enough to not recombine into neutral matter. To be a plasma, its temperature must be high enough and its density low enough. It is said that 99% of the known material in the universe is in the plasma state.

The fact that the plasma is present is very important for magnetic reconnection. The magnetic field lines in Figure 1 thread the ambient plasma, shown as light blue circles. The charged particles move with the magnetic field as they move toward the diffusion region. As the bent reconnected magnetic field lines sling out like rubber bands, the plasma mostly moves with the magnetic field. This produces two jets of plasma moving away from the diffusion region, shown by the ovals to its left and right. As the magnetic field line slings out, the plasma residing at the boundaries between magnetic fields that have reconnected already and those that have not is also accelerated. Depending on where magnetic reconnection in space is happening, the jets can be faster than a million miles per hour!

In addition to producing jets, magnetic reconnection heats the plasma, which is depicted by the shading of the plasma in the jets. The heating can happen within the diffusion region or at the boundaries between reconnected and unreconnected magnetic fields. This heating can be significant—depending on the setting, up to ~1/2 of the energy released by magnetic fields can go into heating the plasma.

The reason we care about magnetic reconnection is that it efficiently converts energy, both in the form of directed motion (the jets) and random motion (the increase in temperature). It is quite common for a magnetic field to change directions, so magnetic reconnection occurs in many settings. It is the mechanism behind solar flares, enormous bursts of light in the atmosphere of the Sun, which release up to 10,000,000,000,000,000,000,000,000 ($10^{25}$) joules of energy. For perspective, if we could harness all the energy released in a single large flare for human use, it would supply enough energy for the whole world for about 20,000 years!

Magnetic reconnection also happens in the space surrounding Earth. Earth's magnetic field forms a bubble around Earth protecting it from the solar wind, a stream of plasma and magnetic fields emanating from the Sun. When the magnetic field in the solar wind points in the opposite direction as Earth's, magnetic reconnection at the edge of the bubble occurs. This sets the magnetic field and plasma inside Earth's magnetic bubble into motion, accumulating its magnetic field on the side of Earth away from the Sun. There, magnetic fields are again oppositely directed, and magnetic reconnection drives hot plasma toward Earth during what are called geomagnetic storms or substorms. Some of the ambient plasma penetrates all the way down to Earth's atmosphere, where it excites molecules in the atmosphere, and they give off light as they de-excite. This is the origin of the auroral lights seen near Earth's poles. Consequently, researching magnetic reconnection is a major aspect of understanding the Sun and the Sun's impact on Earth's space environment; that field of study is called "heliophysics" or "geospace sciences."

There are numerous practical reasons we care about magnetic reconnection. When a flare occurs, it emits energetic radiation that travels through space and gets absorbed in Earth's atmosphere. Some of the neutral material gets ionized, increasing how much plasma is in the ionosphere. This has important consequences. Satellites can go off their desired course since there is more resistance in the ionosphere. Also, satellites send signals through the ionosphere, and the path those signals take changes, just like light bends when going from air to water and vice versa. This is called "scintillation" and impacts GPS signals as well as military, aviation, and commercial communications. The solar radiation also degrades solar cells on satellites, makes undesirable changes to instruments onboard satellites, and is harmful to astronauts. Changes to Earth's magnetic field during a geomagnetic storm drive electrical currents through conductors on the ground, which can degrade pipelines and overload transformers on the power grid. These effects are collectively referred to as "space weather," and governments worldwide are working to ensure readiness for space weather. Understanding magnetic reconnection, therefore, contributes to an ability to understand the science driving space weather and its eventual prediction and forecasting.

Recent References for the General Reader for the Boxed Text


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## 1. Magnetic Reconnection in the Space Sciences

Magnetic reconnection is a naturally occurring fundamental process in the space sciences, allowing for the large-scale—and often explosive—release of energy stored in magnetic fields. It underlies many processes of importance to space physics, including solar flares and coronal mass ejections (CMEs) from the Sun and geomagnetic activity in Earth's magnetic environment. Due to space weather applications, magnetic reconnection is societally relevant and continues to be an important area of research. Moreover, it impacts laboratory research including efforts to control nuclear fusion for energy production and occurs in planetary space environments and in numerous exotic astrophysical settings. In celebration of the 100th anniversary of the beginning of the American Geophysical Union, we take this opportunity to look forward—to envision what will come next for research in magnetic reconnection, how we will get there, what challenges we face to get there, and what achievements will be made for basic science and for the numerous applications of magnetic reconnection.

In the process, we aim to convey the rich and interesting history from whence magnetic reconnection came, the excitement of current magnetic reconnection research, and the challenges and rewards of advances in magnetic reconnection research. However, this paper is not intended as a comprehensive review of magnetic reconnection research and applications; many excellent reviews are available in other articles (e.g., Paschmann et al., 1979; Antiochos et al., 1999; Goodman & Uzdensky, 2008; Cassak, 2016; Drake et al., 2009; Gonzalez & Parker, 2013; Moore et al., 2015), and therefore, many references to important past and current work on the subject will be omitted.

This paper is organized as follows: Section 2 provides an introduction to the amazing physical process of magnetic reconnection, its scientific importance, and its societal relevance. Section 3 discusses the complexity and multiscale nature of magnetic reconnection, which render it extremely challenging to develop a deep understanding of its underlying physical processes. Section 4 briefly describes the historical development of our understanding of the magnetic reconnection process. Section 5 then provides a concise summary of our modern understanding of its physical machinery, including some recent, dramatic, breakthroughs provided by the National Aeronautics and Space Administration (NASA)'s Magnetospheric Multiscale (MMS) mission in concert with advanced numerical modeling and mathematical analyses. In section 6, we look toward the future. Here, we discuss implications of our new understanding and suggested avenues for further research enabled by it, including both the basic science of magnetic reconnection and applications to various fields including planetary sciences, astrophysics, and the societally-relevant space weather. The future of approaches to research magnetic reconnection are described in section 7, including observations, numerical modeling, and laboratory experiments. We summarize in section 8.

## 2. Magnetic Reconnection and Its Impacts

### 2.1. What Is Magnetic Reconnection?

The magnetic reconnection process is pictured schematically in Figure 1 and described nontechnically in Box 1. It can occur in regions where there is a boundary, either an interface between two distinct magnetized plasmas or a boundary between two magnetic domains in a single magnetized plasma.

The shaded blue box in Figure 1 denotes the boundary layer between two magnetically disconnected regions. Above and below the box, called the diffusion region, the ambient plasma (sketched as blue circles) is threaded by a magnetic field (thin blue curves). The key aspect of magnetic reconnection is that the magnetic fields above and below have a component that reverses at the boundary layer. This implies there is an out-of-plane current through the diffusion region, given as the background image in Figure 1. When magnetic reconnection occurs, the topology of the magnetic field changes, which can be thought of as a magnetic field line from above convecting into the diffusion region and effectively breaking and cross connecting with a similar magnetic field line convecting up from below. The diffusion region is where charged particles become decoupled from the magnetic field, either through complex orbits in geometries with steep spatial gradients, or through interactions with the electromagnetic fields in turbulent waves. Plasmas of interest for magnetic reconnection in space physics tend to be collisionless, where classical collisions between particles are ignorable. The physics of the diffusion region in collisionless magnetic reconnection will be discussed in section 5.2.

Newly reconnected field lines are strongly bent and therefore produce a magnetic tension force on the plasma to the left and right. A plasma jet is consequently ejected from the diffusion region, depicted by the arrows on the blue ovals in Figure 1. The diffusion region is a location of intense energy conversion from the magnetic field, and the plasma there gets heated, depicted as the shading in the outflowing plasma, and charged particles are accelerated. Therefore, the plasma to the left and right is hotter than the ambient plasma. The boundary layer to the left and right of the diffusion region bifurcates into two layers bounding the magnetic field lines that have already undergone magnetic reconnection. This boundary layer is also a location of heating and acceleration of the ambient plasma. This whole set of physical phenomena are collectively referred to as magnetic reconnection. What makes magnetic reconnection special is that the process can be, and typically is, self-driven—the ejection of plasma jets to the sides brings in more plasma from above and below, thereby bringing in more magnetic fields that also undergo magnetic reconnection. The process can continue self-sufficiently until its energy source is exhausted. This is what allows magnetic reconnection to release astronomically large amounts of energy.

### 2.2. Magnetic Reconnection in the Space Sciences

It is quite typical in naturally arising magnetized plasmas, and those created in the laboratory, for a component of the magnetic field to reverse at boundary layers. Therefore, magnetic reconnection has an incredibly diverse collection of settings where it occurs. In many of those settings, the process of energy release begins abruptly, leading to dramatic eruptions. Figure 2 provides a representative sample of places magnetic reconnection naturally occurs; we provide some background here on these examples and some others not pictured.

Magnetic reconnection was motivated by the study of solar flares (Giovanelli, 1939, 1947, 1948) in the solar atmosphere (the corona), shown in panel (a). Solar flares release up to $10^{25}$ J of energy. Magnetic reconnection also plays a crucial role in allowing CMEs to disconnect from the Sun, a numerical simulation of a CME (Karpen et al., 2012) is shown in panel (b). This is important to us on Earth because CMEs accelerate solar particles to high energies, which then fly through space and impact the atmosphere of Earth, as will be further discussed later in this section.

There are other phenomena on the Sun in which magnetic reconnection may play a key role. Amazingly, the corona is approximately 200 times hotter than the solar surface, which is counterintuitive because one would think the atmosphere would be cooler than the Sun. The fact that the corona is so hot is important, because it causes the solar wind to be ejected from the Sun. One reason the corona is this hot is a multitude of small flares caused by magnetic reconnection (e.g., Klimchuk, 2006). Magnetic reconnection plays a role in the eruption of prominences and filaments, huge magnetic structures jutting out into the solar corona as shown in panel (c). Jets of plasma are seen in the solar corona, shown in panel (d). They are thought to occur when a region of magnetic fields from beneath the solar surface emerge and reconnect with the overlying coronal magnetic field. Magnetic reconnection also takes place in the solar chromosphere, a cooler outer layer of the Sun that can be seen during a solar eclipse. So-called anemone jets shoot out into the corona as a result of magnetic reconnection. Also, chromospheric magnetic fields get bunched due to photospheric motion, slamming together oppositely directed magnetic fields and producing so-called Ellerman bombs. There is a possibility that bursts of plasma in the chromosphere called spicules and fibrils are caused by magnetic reconnection.

It was quickly realized (Dungey, 1953; Hoyle, 1949) that the same magnetic reconnection process happening in solar flares also occurs in Earth's magnetic field, sketched in panel (e). The solar wind flows away from the Sun at approximately a million miles an hour by the time it gets to Earth; as it does, it carries a magnetic field with it from the Sun. When this magnetic field runs into Earth's magnetic field, it forms a boundary layer between two very different source regions: the hot, tenuous plasma from inside the protection of Earth's magnetic field (the magnetosphere), with the cooler, denser magnetosheath plasma between the bow shock and Earth's magnetosphere (Levy et al., 1964; Phan & Paschmann, 1996). These magnetic fields can undergo magnetic reconnection if a component of the magnetic fields is oppositely directed (Dungey, 1961); this occurs on the dayside of Earth closest to the Sun. When a magnetic field line undergoes magnetic reconnection on the dayside, it is dragged away from the Sun by the solar wind, where it gets stretched on the nightside. Here it adds magnetic energy to the magnetotail lobes, the rarified plasma region between the magnetotail plasma sheet and the edge of the magnetosphere. This makes magnetic reconnection at the

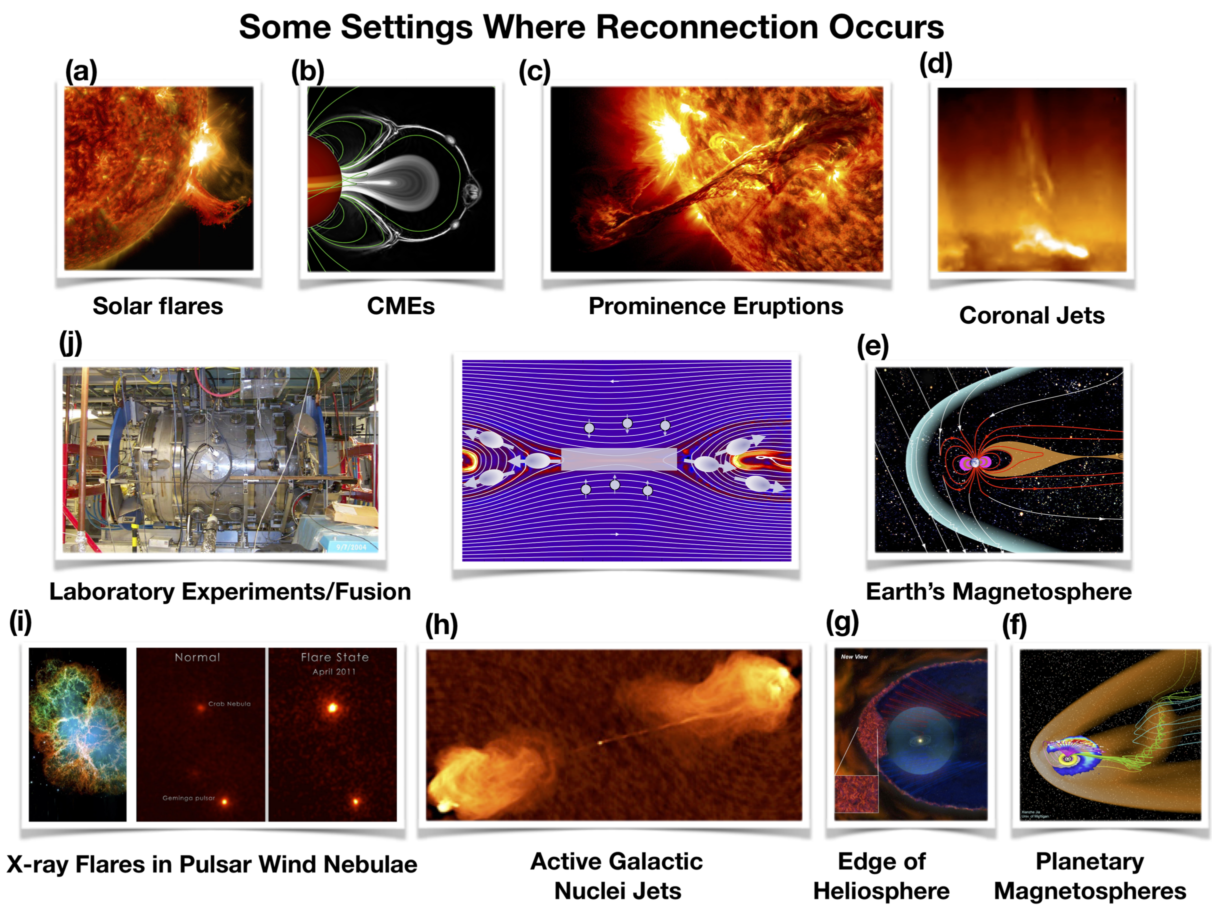


**Figure 2.** Some settings where magnetic reconnection occurs, with descriptors beneath each panel. Panels (a), (c), (d), (e), (g), (h), and (i) are courtesy of NASA. (b) Credit: J. Karpen; used with permission. (f) Credit: X. Jia; used with permission. (j) Credit: H. Ji, used with permission.

magnetopause the primary mechanism responsible for the transport of energy, mass, momentum, and magnetic flux transport into Earth's magnetic cavity.

The magnetic fields on the nightside again are laid out in a way where they are oppositely directed on each side of the magnetotail plasma sheet, on the right of panel (e), so they can undergo magnetic reconnection. Magnetotail magnetic reconnection drives superheated plasma back toward Earth, where it can penetrate all the way down to Earth's atmosphere. The cycle, from magnetic reconnection at the magnetopause to reconnection in the magnetotail is referred to as the "Dungey cycle." Magnetic reconnection, therefore, indirectly powers a large variety of phenomena, ranging from dynamics in the radiation in the Van Allen belts to the excitement of atmospheric molecules causing the auroral light displays. The spatial extent, rate, and duration of magnetic reconnection, therefore, determine the overall internal dynamics of the magnetosphere.

Magnetic reconnection can also happen at other celestial bodies. A number of other planets in the solar system have magnetospheres. Mercury's magnetosphere has some similarities to Earth's and therefore the reconnection process there is similar, while the magnetospheres of the outer planets are very different. Jupiter and Saturn rapidly rotate, which changes their global circulation pattern as depicted in the simulation data (Jia et al., 2012) in panel (f). The axes of the dipole moments of Uranus and Neptune are not normal to the ecliptic like in the other planets, leading to an exotic magnetosphere vastly different than Earth's. These other planets provide a variety of testbeds to compare Earth's magnetosphere with and to better understand the physics of reconnection. In addition, comets and some planets like Venus and Mars do not have intrinsic magnetospheres, but their outer layers are ionized by the solar wind. This makes the surface nearly perfectly conducting, so the magnetic field in the solar wind drapes over the comet or planet.

Magnetic reconnection can happen in the draped magnetotail of the comet or planet, as has been seen in satellite observations. Another surprising setting for magnetic reconnection is simply in pristine regions of the solar wind (Gosling et al., 2005). It can occur between disparate sectors in the solar wind, and observations reveal the signatures can extend over huge distances (Gosling et al., 2007; Phan et al., 2006). Finally, magnetic reconnection can occur within Earth's magnetosheath, the region of shocked solar wind between the bow shock and Earth's magnetopause.

The last decade has seen a new thrust of studies of magnetic reconnection at the edge of the solar system where it borders the interstellar medium, called the heliopause and sketched in panel (g). As the solar wind and magnetic field go out through interplanetary space, the magnetic field is corrugated, forming sectors with mostly northward or southward directed magnetic field due to the misalignment of the Sun's magnetic axis and rotation axis. At the heliopause, these sectors are compressed, bringing oppositely directed fields together where magnetic reconnection has been proposed to occur. Recent research suggests that the heliopause is “porous” rather than the abrupt transition seen at Earth's magnetopause.

### 2.3. Impacts of Magnetic Reconnection Beyond Space Research

While our focus is on solar and space physics, there are numerous examples of magnetic reconnection in other settings. In astrophysical settings, other stars have flares similar to the Sun. While it was long thought that stellar flares and solar flares were not related by common physics, it is now widely accepted that they are similar. There are other eruptive events that also are thought to be associated with magnetic reconnection. Active galactic nuclei, one of which is shown in panel (h), are thought to be caused by accretion of matter into a supermassive black hole in the center of some galaxies. Relativistic jets stream out along the rotation axes of the black hole. The jets are in the plasma state and are threaded by magnetic fields from the black hole. The magnetized jets can kink, leading to magnetic reconnection releasing bursts of magnetic energy. Another example is related to pulsars, rapidly rotating remnants of supernova explosions, shown in the left part of panel (i). The pulsar rotation axes and magnetic dipole direction are thought to be misaligned, creating corrugated sectored regions similar to the heliopause. When this runs into a shock, it can get compressed and reconnect. The middle and right images in panel (i) show before-and-after images of an X-ray flare in a pulsar wind nebula.

There are other exotic astrophysical settings where magnetic reconnection could play a role, but there is much more to be learned. For example, gamma ray bursts eruptively release as much as $10^{47}$ J, but they are likely caused by a star undergoing a supernova explosion. However, there is a class of energetic gamma ray events called soft gamma repeaters (SGRs). One SGR in our galaxy essentially ripped off Earth's magnetosphere for a short time. What is special about SGRs is that the same source releases this energy multiple times, so it cannot be explained by an event like a supernova that destroys the source. One possible model for SGRs is a magnetic eruption in magnetars, a class of neutron stars with especially strong magnetic fields. An event analogous to a solar flare in such settings could release the amount of observed energy. However, other potential explanations exist, so it remains an active area of research. Another recent area of excitement in astrophysics are so-called fast radio bursts Lorimer et al. (2007). These extragalactic bursts of radio waves were discovered only recently. While only a handful have been observed, it was astonishing when it was discovered that they could occur multiple times from the same source. This has prompted research into plasma physics phenomena of extreme magnetospheres as the cause of these events, including the possibility of magnetic reconnection events in magnetars. This, too, remains an active area of research. Reviews of astrophysical reconnection can be found in, for example, Zweibel and Yamada (2009), Uzdensky (2011), and Lazarian et al. (2015).

Magnetic reconnection also occurs as a secondary process in other geophysical and astrophysical phenomena. For example, in a turbulent magnetized plasma, the flow and magnetic field motion is quite complicated. Magnetic fields get twisted and magnetic domains appear. The boundaries of these magnetic domains can undergo magnetic reconnection. It is only in the past 15 or so years that it has been appreciated that termination of the turbulent cascade in a magnetized plasma often is mediated by magnetic reconnection (Servidio et al., 2009, 2011); there has been a flurry of recent work to understand how this impacts the turbulence. Another example is the generation of magnetic fields, also called the dynamo. The leading qualitative picture of the dynamo is that a magnetic field gets stretched, twisted, and folded, which increases the magnetic field strength. The process allowing the increase in magnetic energy to remain is magnetic reconnection of the twisted magnetic field. Another example is in shocks in magnetized plasmas. Magnetic reconnection can happen as a secondary process downstream of the collisionless bow shock between Earth and the Sun. Thus, understanding magnetic reconnection is also impactful to other fundamental plasma physics processes occurring in heliophysics and in other settings.

Finally, there are processes analogous to magnetic reconnection that happen in settings far outside of plasma physics, which shows the amazing unity that binds disparate areas of science. When a neutral fluid rotates, making a vortex, it is said to have "vorticity." It turns out that the properties of vorticity in a neutral fluid (Thomson, 1869) are analogous to a magnetic field in a plasma. Thus, vortex lines can undergo a process like magnetic reconnection. This can be seen vividly with the naked eye, such as in a recent video showing the contrails from a high-speed aircraft (https://www.youtube.com/watch?v=uV06pi_OPZM). Similarly, in quantum fluids that are studied in the field of condensed matter physics, such as helium-3 for which quantum mechanical effects impact the evolution of the fluid, vortex reconnection can occur (Feynman, 1955). This can also be seen by the naked eye, as demonstrated by laboratory experiments (Bewley et al., 2006; Paoletti et al., 2010). It was recently predicted that vortex reconnection can also happen in the field of quantum optics, where nonlinear structures in lasers called solitons have a vorticity (Fedorov et al., 2019). The most exotic example of an analogous process to magnetic reconnection is in string theory (e.g., Copeland et al., 2004), where fundamental particles are represented as strings. Those strings can interact with each other through a magnetic reconnection-type process. There are undoubtedly many settings where a process analogous to magnetic reconnection happens that we are not even aware of yet! Thus, fundamental research into magnetic reconnection in space physics can be fruitful in multiple areas of science.

### 2.4. Impacts of Magnetic Reconnection to Society

There are numerous reasons that research into magnetic reconnection has societal benefits. The primary reason is because of space weather implications (Cassak, 2016); a number of physical phenomena causing space hazards to our technological infrastructure are discussed in the boxed text. Space weather impacts a staggering array of aspects of public life and public policy (e.g., Cassak, Emslie, et al., 2017). The potential damage to satellites impacts commerce (space communication), transportation (airlines losing communication during polar routes), the military and homeland security (communication), agriculture (communication), the environment/public works and infrastructure (the power grid), energy (pipeline erosion), and manned space travel (radiation danger for missions to the Moon and/or Mars). In order to quantify essential space weather-related phenomena, such as CME formation and eruption, or the acceleration of particles inside the magnetosphere, it is essential that magnetic reconnection be properly assessed and understood. The inclusion of magnetic reconnection physics, parametrically or otherwise, into large-scale dynamic models will ultimately lead to better space weather forecasts.

Beyond space applications, magnetic reconnection has impacts on the energy sector, through its impact on fusion energy (Figure 2j). Historically, it was posited that magnetic fields could be used to confine a plasma to allow the nuclei in the plasma to undergo fusion. Toroidal devices called tokamaks were developed to achieve this, but they did not successfully confine the plasma to produce energy because of disruptive events. This was discovered in parallel to the development of magnetic reconnection theory in solar flares, and it was quickly realized that magnetic reconnection could also be happening in tokamaks (Furth et al., 1963). It was later established that the twisted magnetic field confining the plasma was, indeed, reconnecting. Modern fusion devices are designed to avoid these "major" disruptions. However, so-called "minor" disruptions, also known as sawtooth crashes, are also magnetic reconnection events that limit the temperature of the plasma and spoil confinement (Edwards et al., 1986; Kadomtsev, 1975; von Goeler et al., 1974; Yamada et al., 1994), so producing controlled fusion for the purposes of energy production also requires an understanding of magnetic reconnection.

Another frontier area of research involving magnetic reconnection with societal impacts is plasma thrusters, which are used to propel rockets. In the last decade, there has been increased interest in harnessing the conversion of magnetic energy into directed jets that occurs during magnetic reconnection for use in thrusters (e.g., Bathgate et al., 2018). Therefore, basic research into magnetic reconnection has far reaching societal implications.

## 3. Challenges to Studying and Understanding Magnetic Reconnection

Given that magnetic reconnection happens in so many places, one might think it would be easy to study. This, unfortunately, could not be further from the truth. The main challenge of studying magnetic reconnection, which makes it a grand challenge problem, has always been that it is a multiscale process. This means that understanding magnetic reconnection and its effects requires knowledge of physics on both small and large spatial and temporal scales simultaneously. The physics allowing magnetic reconnection to occur takes place at electron gyroscales, and can have an impact over phenomena at the system size. To put this into perspective, the electron gyroradius in the solar corona is approximately a few centimeters, while magnetic flux ropes participating in solar flares can be as large as $10^9$ cm. In magnetic reconnection sites at Earth's magnetosphere, the electron gyroradius is 1–10 km, while the impact of the magnetic reconnection is felt on scales of the whole magnetosphere, which stretches $1.5 \times 10^6$ km. Thus, there is a 6–9 orders of magnitude difference between the small and large scales that are important for understanding magnetic reconnection in space physics. The numbers are equally staggering in planetary and astrophysical systems where magnetic reconnection takes place. This disparity of scales leads to challenges in all the approaches that have been used to study magnetic reconnection.

The electron scale is relatively small in all settings magnetic reconnection occurs. Until MMS, there were no satellite missions that could resolve electron-scale physics. Assuming a typical speed of a structure passing a spacecraft at Earth's dayside magnetopause to be 100 km/s, and a typical electron gyroscale to be 10 km, this implies the need to record plasma measurements at a cadence of 100 ms. New technologies were invented to achieve electron distribution measurements with a cadence of 30 ms or better in MMS, which is what has allowed it to revolutionize our understanding of electron-scale physics in magnetic reconnection.

In laboratory experiments, the situation is equally daunting. At the small-scale, the electron gyroscale at the Magnetic Reconnection eXperiment is typically approximately 0.5 mm (e.g., Yamada et al., 2010). This means that any diagnostic to measure electron-scale effects needs to resolve these scales. This is an extreme challenge for laboratory diagnostics. Meanwhile, fully capturing the large scales of magnetic reconnection including the coupling to ions requires a system size of tens of ion gyroradii, which is approximately 1 m. Thus, one would need a device on the scale of tens to hundreds of meters, while simultaneously resolving electron scales—and controlling the experimental system well enough to know where the tiny magnetic reconnection layer occurs to measure the small-scale physics. The costs and logistics of building such an experiment with diagnostics are large, so this type of device will likely remain out-of-reach for the foreseeable future. Alternate approaches are necessary to address these important science questions in the lab.

Moreover, the measurements that have historically been taken in laboratory experiments of magnetic reconnection are the fluid quantities—densities, bulk flow velocities, temperatures, and electric and magnetic fields. However, with the advent of the Cluster, Time History of Events and Macroscale Interactions during Substorms (THEMIS), and MMS satellite missions taking measurements of plasma distribution functions, experimental support of space satellite missions must evolve to also measure distribution functions. This is not an easy task for the same reasons it is challenging in space. Moreover, many techniques for measuring distribution functions in the lab are perturbative (e.g., Gosselin et al., 2016), thereby reducing their viability. Nonperturbative techniques using lasers have been developed and have been used for experiments in high energy density plasma physics experiments, but thus far have not been deployed for space-relevant magnetic reconnection experiments.

The multiscale property of magnetic reconnection presents the same kind of challenges for studying it with numerical simulations. Since magnetic reconnection in space is typically collisionless, a kinetic description of the plasma is required to properly capture the small-scale physics. We estimate how long a fully kinetic large-scale simulation using realistic system parameters would take. An explicit particle-in-cell simulation typically resolves electron layers with a few cells. Thus, to do a global magnetospheric simulation over $1.5 \times 10^6$ km with an electron scale of 1 km, one would need ~5 million cells in each direction, for a total simulation size of $10^{20}$ cells and approximately ~$10^{22}$ (macro)particles in the simulation. To even perform a single calculation for each particle on the fastest supercomputers in the world at ~150 PFLOPS ($150 \times 10^{15}$ floating point operations per second) would take 18 hr, so performing a simulation for the hundreds of thousands of time steps necessary would take hundreds of years. Moreover, a single data set would produce billions of terabytes of data, which would be impossible to write or store. Thus, brute force realistic global simulations of space physics that capture both physics at large and small scales are completely impossible for the foreseeable future.

The importance of small-scale physics introduces more challenges to the study of magnetic reconnection. MMS is teaching the community how much useful information is contained in distribution functions that was not being fully exploited in theoretical and numerical work prior to its launch. While there had been important research at the single-particle and distribution function level before MMS, MMS data triggered a vast expansion of this type of research. The high-resolution and high-cadence measurements by MMS are therefore challenging theoretical and computational researchers to develop new theoretical approaches to understand magnetic reconnection at the kinetic scale.

Another challenge about understanding the magnetic reconnection process is that some of its properties can be different in different external settings. In other words, what is learned about simple symmetric, antiparallel, two-dimensional magnetic reconnection, as sketched in Figure 1, may or may not apply to systems in which these assumptions are relaxed. Much has been learned about magnetic reconnection that is asymmetric, has an out-of-plane (guide) magnetic field, or has an upstream bulk flow (Doss et al., 2015; Wilder et al., 2014). In particular, asymmetric magnetic reconnection occurs at the dayside magnetopause and has attracted considerable recent attention in spacecraft observations (e.g., Mozer & Cully, 2008; Paschmann et al., 2013; Phan et al., 2006; Walsh et al., 2014), as well as in theory and modeling (e.g., Cassak & Shay, 2007; Mozer & Pritchett, 2011; Roytershteyn et al., 2012). Recently, the MMS mission provided unprecedented high-resolution electron-scale measurements of asymmetric magnetic reconnection (e.g., Burch et al., 2016; Burch & Phan, 2016; L. J. Chen et al., 2017; Ergun et al., 2016; Webster et al., 2018). Consequently, asymmetric magnetic reconnection has seen multiple new fronts in observations and modeling (e.g., Bessho et al., 2016; Hesse et al., 2014; Øieroset et al., 2016), including discoveries of the electron diffusion region at the magnetopause in both planar geometries (Burch et al., 2016) as well as in configurations with out-of-plane (guide) magnetic fields (Burch & Phan, 2016). Putting these more complicated effects together is challenging. Moreover, three-dimensionality introduces much additional complexity and, despite considerable progress, many questions remain regarding the three-dimensional nature of magnetic reconnection. Answering those remains one of the greatest reconnection research challenges.

## 4. Historical Development and Basic Physics of Magnetic Reconnection

### 4.1. Historical Beginnings of Magnetic Reconnection

The historical context for the development of our understanding of magnetic reconnection began with solar flares. It was known since the early 1900s that the only source of energy big enough to produce the energy seen in a large solar flare is the magnetic field. At the time, the only known mechanism for dissipating magnetic energy was through electrical resistivity, caused by collisions between electrons and positively charged ions. This causes magnetic fields to diffuse, converting their energy to heat of the surrounding plasma. However, the time it would take to diffuse the magnetic energy in a solar flare would be millions of years, far longer than the tens of minutes that large flares take. A new mechanism to release magnetic energy faster than diffusion was needed—that mechanism is magnetic reconnection.

The standard way to understand magnetic reconnection is to contrast it with a system where it is impossible, which is described by ideal-magnetohydrodynamics (MHD). This is a model of a plasma as a single fluid for which there is no dissipation (such as viscosity or electrical resistivity). In this model, one can show that magnetic field lines are effectively tied to the plasma; the plasma is said to be "frozen-in" to the field. In such a system, a magnetic field line cannot "break" because it would no longer be frozen-in to the plasma. It is in this context that we can understand magnetic reconnection as a breakdown of the assumptions of ideal MHD. Thus, when physical features left out of the ideal-MHD model are reinserted, one finds that the frozen-in condition does not hold at the small scales where these physical effects become important. This implies magnetic field lines can effectively break. This fact, discovered by Dungey (1953), forms the basis of magnetic reconnection theory.

### 4.2. Basic Magnetic Reconnection Physics and the Sweet-Parker Model

The first self-consistent theory of magnetic reconnection was developed by Parker (1957) based on a physical picture proposed by Sweet in 1956 but not published until 1958 (Sweet, 1958). The idea is that relatively straight oppositely directed magnetic field lines come together. Back then, the assumption was that the magnetic fields have to be pushed together in order to reconnect, but we now know that magnetic reconnection can happen spontaneously. The magnetic field lines come in to a small region, the diffusion region, where small-scale physics allows them to effectively break and cross connect. In Parker's model, the small-scale physics is electrical resistivity brought about through collisions between electrons and positively charged ions in the boundary layer region between the oppositely directed magnetic fields. Parker showed that the inflow of plasma and magnetic field can be exactly balanced by the diffusion of the magnetic field caused by electrical resistivity, so a steady state of magnetic reconnection proceeding continuously can be attained. To understand the conversion of energy during the steady process, a simple bookkeeping of the magnetic energy coming in and the kinetic and thermal energy going out reveals that approximately half the magnetic energy gets converted to kinetic energy of the plasma and half goes into thermal energy in the Sweet-Parker model (e.g., Birn et al., 2010; Priest & Forbes, 2000). Moreover, the speed at which the plasma must enter to be in a steady state follows from equating the rate of magnetic flux injection to the diffusion region with the rate of magnetic diffusion within it; it was found that this speed is much faster than the rate of magnetic diffusion (Parker, 1957), but far slower than inferred speeds (Parker, 1963).

Modern research into magnetic reconnection in solar and space settings has revealed that it is unlikely that magnetic diffusion via classical electrical resistivity is playing an important role. Rather, the plasmas where magnetic reconnection takes place are nearly collisionless, so classical electron-ion collisions are too infrequent. In summary, Parker's analysis of magnetic reconnection was valid within the assumptions that were made (for small enough systems—the model breaks down for larger systems), but it is not likely the model applies to most of space physics. Going beyond Parker's theory to understand how magnetic reconnection works in weakly collisional systems remains at the forefront of modern magnetic reconnection research.

The outputs of the Sweet-Parker model that describe the reconnection process are the magnetic reconnection rate, that is, the electric field allowing the magnetic topology to change in the diffusion region, and the energy partition. This information is important to understand applications where magnetic reconnection occurs. The magnetic reconnection rate gives direct information about how fast the process goes and also how much magnetic flux is reconnected in time. This allows one to calculate how much magnetic energy is released in a given time. This very important for understanding eruptive events such as flares and substorms, where the energy released and the release time are clear observables. At the dayside magnetosphere, magnetic reconnection sets up the Dungey convection cycle (Dungey, 1961); the faster magnetic reconnection goes, the faster the convection. Thus, understanding the rate is important for understanding global convection and its consequences. Determining the dissipation mechanism has historically been seen as the path to understanding what the magnetic reconnection rate is, but there have been recent suggestions that the rate may not be determined by the microphysics (e.g., Birn et al., 2001). Nonetheless, the dissipation mechanism additionally provides insights into particle acceleration and heating in the magnetic reconnection diffusion region. The energy partition is extremely valuable for understanding observations because this quantity is often observable and measurable. Studies of the energy partition have been carried out for magnetic reconnection in solar flares, the solar wind, the dayside magnetopause, and the magnetotail. Moreover, for settings such as solar flares and some astrophysical settings, knowing how energy is distributed among the various energy channels allows one to predict how much electromagnetic radiation would be produced at various energies, which is another important observable in naturally occurring settings. Thus, a significant portion of understanding collisionless magnetic reconnection has focused on the reconnection rate, the dissipation mechanism, and the energy partition.

## 5. What We Have Learned About Magnetic Reconnection

### 5.1. Magnetic Reconnection in Space Physics Occurs and Is Nearly Collisionless

A major advance in the last 30 years is the appreciation that magnetic reconnection in most space settings is collisionless, though there are some situations where collisional magnetic reconnection, that is, magnetic reconnection in which collisions play a major role in the dissipation, does occur. Examples are some laboratory experiments, the solar chromosphere, and in accretion disks around compact astrophysical objects (Ji & Daughton, 2011). However, classical particle collisions are extremely rare in Earth's magnetosphere. Therefore, magnetospheric magnetic reconnection is collisionless, that is, based on more complex interactions between charged particles and electromagnetic fields. There are relatively easily observable signatures of the magnetic reconnection process that differ between collisional and collisionless magnetic reconnection. The most widely discussed is the out-of-plane magnetic field; in antiparallel collisional magnetic reconnection, there is no magnetic field normal to the magnetic reconnection plane, but in antiparallel collisionless magnetic reconnection, an out-of-plane magnetic field with quadrupolar structure is self-generated near the magnetic reconnection site within a distance of one ion gyroradius of where the magnetic field reverses (Sonnerup, 1979). This generation mechanism is based on differences in electron and ion behavior at scales below the ion gyroradius (i.e., by the Hall effect) (Mandt et al., 1994) and sets up a two-scale structure to the diffusion region often called the inner or electron diffusion region and the outer or ion diffusion region. The theoretical and numerical predictions of this phenomenon would eventually be seen observationally using in situ satellite observations, and collisionless laboratory experiments feature similar structures, confirming that magnetospheric magnetic reconnection is collisionless. Interestingly, in the solar wind, the Hall out-of-plane magnetic field is even observed over large scales in the exhausts far from the magnetic reconnection site (Mistry et al., 2016), so it is not merely located in the region near the diffusion region.

In situ observations are not possible in the low solar corona, so the Hall quadrupole magnetic field cannot be resolved by remote observations. However, it is still expected that the magnetic reconnection process is essentially collisionless. The inferred magnetic reconnection rates are associated with electric fields that are orders of magnitude stronger than the so-called Dreicer electric field above which classical collisions become relatively unimportant. It is possible that coronal magnetic reconnection experiences effective collisions due to turbulent fluctuations, which is a matter of ongoing research, but it is clear that classical collisions as in the Sweet-Parker model cannot play a role in the coronal magnetic reconnection beyond an early transient phase.

### 5.2. How Does Collisionless Magnetic Reconnection Work?

Much has been learned about the physics of collisionless magnetic reconnection, aided by in situ and remote satellite observations, numerical simulations using high-performance computing, theoretical and analytical techniques, and laboratory experiments. Some significant results from the last few decades are discussed here.

Once it was realized that collisions were too infrequent to explain space applications of magnetic reconnection, the first question became whether it could occur at a rate that is as fast as is inferred by observations. Both in solar and magnetospheric settings, it was inferred from observations that the normalized magnetic reconnection rate, effectively the ratio of the bulk flow speed of the inflowing plasma to the Alfvén speed, was close to 0.1 (Parker, 1973), that is, the inflowing plasma carries in magnetic flux at a tenth of the Alfvén speed based on the reconnecting magnetic field strength and the ambient plasma density.

Since Parker's estimate of the magnetic reconnection rate from the time scale of flares and substorms, numerous observations have inferred a range of values around 0.1, such as through the speed of ribbons in solar flares or local measurements of the plasma properties near a magnetic reconnection site in the magnetosphere. Numerical simulations have proven useful as well; it was shown that even in simple two-dimensional simulations of magnetic reconnection that the normalized rate of collisionless magnetic reconnection is approximately 0.1, and this value is mostly independent of system parameters. It is now known that the magnetic reconnection rate can have a temperature dependence and a dependence on the presence or lack of an out-of-plane magnetic field.

The physical reason why the collisionless magnetic reconnection rate seems to typically be near 0.1—much faster than in the Sweet-Parker model—has undergone much scrutiny (Cassak, Liu, & Shay, 2017); much has been learned but it remains an open question. Two ideas have largely been followed, which we refer to as "inside-out" and "outside-in." In the former, local physics at or near the magnetic reconnection site controls the rate. Examples of this include dispersive-wave physics set up by newly reconnected magnetic fields slinging out, electron pressure tensor effects, and instabilities and/or turbulence near the magnetic reconnection site. The "outside-in" idea is that the large-scale physics limits how fast the magnetic reconnection process can proceed, which occurs because bending an upstream magnetic field line to reach the magnetic reconnection site costs energy, which diminishes the available energy for release (Liu et al., 2017).

The energy partition of collisionless magnetic reconnection has been a research focus just in the last decade. The question is as follows: What fraction of the incoming (magnetic) energy gets converted to various forms in the outflowing plasma, including bulk flow energy, thermal energy, and nonthermal energy of particles. It was shown with satellite data at the dayside magnetopause that electrons gain about 2.5% of the magnetic energy converted during magnetic reconnection (Phan et al., 2013) and the ions gain about 20% of the available magnetic energy (Phan et al., 2014). Numerical simulations are consistent with the observations of electron energy gain (Shay et al., 2014). Based on a simple picture of ions getting accelerated by the Fermi mechanism, it was previously predicted that ions would gain about 50% of the released magnetic energy (Drake et al., 2009), which is greater than the amount observed. It was then shown theoretically that the electrons streaming out of the exhaust go out faster than the ions, which creates a parallel electric field (Egedal et al., 2013) that confines the electrons and increases their temperature at the expense of the ions (Haggerty et al., 2015). Experimentally, it was found that the fraction of magnetic energy going into electron and ion heating during magnetic reconnection was largely consistent with satellite observations (Yamada et al., 2014).

The dissipation mechanism of collisionless magnetic reconnection—analogous to electron-ion collisions in the Sweet-Parker model—has been the first main focus of the MMS mission and spawned much research activity. For magnetic reconnection to occur, there must be an electric field, either at a topological boundary (Vasyliunas, 1975) or, more generally, in a localized region parallel to the magnetic field (Schindler et al., 1988). This requirement is a simple consequence of Maxwell's equations and the need to transport magnetic flux from the inflow to the outflow regions.

Beginning with Vasyliunas (1975), the problem was framed in terms of what physics could produce the necessary electric field. This was done through writing the generalized Ohm's law, which is effectively the momentum equation for an electron fluid solved in terms of the electric field:

$$\vec{E} = -\vec{v}_e \times \vec{B} - \frac{1}{en_e} \nabla \cdot \vec{\vec{P}}_e - \frac{m_e}{e} \left( \frac{\partial \vec{v}_e}{\partial t} + \vec{v}_e \cdot \nabla \vec{v}_e \right)$$

The terms that arise that can produce an electric field are convection ($v \times B$), where $v$ is the bulk velocity and $B$ is the magnetic field, electron inertia ($m_e/e$) ($dv_e/dt$), where $m_e$ and $e$ are the electron mass and charge and $v_e$ is the electron bulk velocity, and the divergence of the electron pressure tensor $\boldsymbol{P_e}$. In phrasing it this way, we treat the electron momentum equation as the first moment of the Vlasov equation, so that the electron pressure is naturally a tensor.

For simple, antiparallel, symmetric, magnetic reconnection configurations, the possible causes of the electric field are reduced. The convection term vanishes at the magnetic reconnection site because the magnetic field vanishes ($B = 0$). The same can be concluded for electron inertia term, since the in-plane velocity vanishes at the magnetic reconnection site and the time derivative term is significant only in the presence of very fast fluctuations on time scales of the electron plasma period (Vasyliunas, 1975). In the absence of collisions, the only remaining option is the divergence of the electron pressure tensor. This tensor needs to be nongyrotropic to provide the electric field. Hence, it was proposed that this pressure tensor should be the main contributor to the magnetic reconnection electric field, at least in symmetric situations (Dungey, 1988; Hesse et al., 1999; Lyons & Pridmore-Brown, 1990; Vasyliunas, 1975).

An alternative possibility is that the electric field is caused by fluctuations in the diffusion region. Fluctuations can be generated by kinetic instabilities such as Buneman modes or lower hybrid drift effects and could effectively scatter electrons near the magnetic reconnection site leading to an effective resistance. The effects of such fluctuations are captured by temporally or spatially averaging the generalized Ohm's law. Three terms arise that can produce an electric field from the fluctuations, often referred to as anomalous drag, anomalous momentum transport, and anomalous viscosity (e.g., Price et al., 2016).

Two-dimensional models demonstrate, without exception, that nongyrotropic electron pressure tensor effects dominate at the location where reconnection occurs for symmetric configurations. Three-dimensional models of collisionless magnetic reconnection, however, can show significant contributions of the anomalous terms and the presence of substantial fluctuations at the reconnection site (e.g., Muñoz & Büchner, 2016). However, some local analyses continue to show the dominance of nongyrotropic electron pressure terms, and a recent, very large simulation demonstrated the near absence of significant fluctuations at the reconnection site if effects of periodic boundaries can be excluded (Liu et al., 2018). Prior to the MMS mission, these two theories were competing.

### 5.3. Recent Progress From the MMS Mission

MMS had as a key goal to determine which of these theories was matched by reality. Beginning with the first key observation of an electron diffusion region at the dayside magnetopause (Burch et al., 2016), observations have shown a remarkably quiet structure of electron diffusion regions, whether they are asymmetric with (Burch & Phan, 2016) or without a mean out-of-plane (guide) magnetic field (Burch et al., 2016), or whether they are in the magnetotail plasma sheet (Torbert et al., 2018). While it has been difficult to measure electron pressure tensor effects directly, there has been some indication that these are indeed important (Genestreti et al., 2018), and a recent observation shows that the analytic prediction of Hesse et al. (1999) provides a reasonable match to the observed magnetic reconnection electric field (R. Nakamura, Genestreti, Nakamura, et al., 2018). Furthermore, a tailored, translationally invariant, numerical simulation (T. Nakamura, Genestreti, Liu, et al., 2018) provides an exceptionally good match between observations and model results. While observations around the outflow region show significant fluctuations and turbulent effects there is rapidly increasing evidence that the central electron diffusion region is indeed relatively quiet and properly described by the quasi-viscous, electron nongyrotropy-based model (Hesse et al., 1999, 2011). Therefore, it appears that MMS has accomplished its first objective: to determine the machinery of the electron diffusion region (Torbert et al., 2018).

This discussion has largely focused on the simplest possible reconnecting system—antiparallel magnetic fields, symmetric, and two-dimensional. Relaxing these assumptions can change the results. In an asymmetric configuration, the magnetic reconnection rate becomes a function of upstream parameters for asymmetric magnetic reconnection (Cassak & Shay, 2007), as does the energy partition (Shay et al., 2014). Another major difference is the dissipation mechanism. This is because the electron inertia term does not necessarily vanish identically at the magnetic reconnection site since the magnetic field reversal location and the flow location are no longer typically at the same place (Cassak & Shay, 2007; Cassak & Shay 2009). Therefore, the electron inertia term contributes part of, or even the majority of, the magnetic reconnection electric field at this location (Hesse et al., 2014). However, nongyrotropic pressure tensor effects still need to exist at the flow stagnation point, where the convection and electron inertia terms vanish (Hesse et al., 2014, 2016). A simple analysis shows that nongyrotropic electron pressure effects are not only expected at the flow stagnation point but are essential for a consistent magnetic flux transport. Recent research has further indicated that the magnetic reconnection electric field is a consequence of the need to maintain the current density in the electron diffusion region, which would otherwise be reduced by nongyrotropic electron pressure effects (Hesse et al., 2018). The thermal interaction of accelerated particles with the adjacent magnetic field, which gives rise to nongyroptropic electron pressures and quasi-viscous current reductions, simultaneously leads to electron heating. This electron heating appears to be the key contributor to maintaining pressure balance in the electron diffusion region.

Within the data sets obtained by MMS, these conclusions appear to apply across the spectrum of magnetic reconnection geometries, whether symmetric or not, whether with or without a guide field, and whether inside or outside of the magnetosphere. The evidence is therefore very strong that our understanding is generic—but there is a need for additional verification. Even though we cannot expect strong instability growth in a diffusion region, where particles spend an extremely short amount of time, it is, at least in principle, possible that there are situations where particles may be confined longer by as of now undiscovered processes or by very strong guide fields. Therefore, more research is warranted. At the same time, we can embark on exploring the benefits of our new knowledge. This research as well as knowledge applications are discussed in the following sections.

## 6. Future Research Directions for Magnetic Reconnection

Even though many questions remain open, our new knowledge paves the way for an exciting scientific future, in expanded basic magnetic reconnection research, in applications of our new knowledge to other environments, and in understanding how a large-scale plasma system interacts with its basic engine. Each of these targets constitutes rewarding and compelling new research directions, among them the particularly societally relevant topic of harmful space weather effects.

### 6.1. Basic Magnetic Reconnection Physics

Courtesy of the unprecedented space measurement provided by MMS and modern theory and modeling have we now an excellent understanding of the mechanisms at work in the inner (electron) diffusion region. This breakthrough opens the way for tackling the next set of questions related to the basic physics of the magnetic reconnection process.

Moving out from the electron physics-dominated inner diffusion region, the next target is the outer shell of the magnetic reconnection diffusion region. Traditionally, this region has been seen as ion physics-dominated (Sonnerup, 1979), but there is mounting evidence that electron-scale processes play a major role here, as well. While there is direct coupling between the inner and outer diffusion regions, it is highly likely that the "ion diffusion region" is dominated by different dynamics than the electron diffusion region. Specifically, there are various indications that the ion diffusion region is considerably more impacted by turbulent phenomena, occurring on electrons scales, than the inner electron diffusion region. In fact, electrons reside here long enough to allow strongly nonlinear instability growth, and the associated turbulent effects can provide a considerable amount of the energy dissipation in this region. This region needs to be understood to the same degree as the electron core—a task the MMS mission is well suited for.

Continuing on the path to even larger scales, we note that energy conversion by magnetic reconnection involves spatial scales much larger than the electron diffusion region or even the ion diffusion region around it. Hence, energy conversion in these two regions cannot contribute appreciably to the overall energy budget of the magnetic reconnection process. Larger-scale processes, presumably located at the boundary between reconnected and unreconnected magnetic fields, must be at work, but dissipation can also occur within the outflow jet. There has been some research addressing how ions and electrons can get energized on larger scales when transiting from the inflow to the outflow regions, but researchers have barely scratched the surface on this topic. Addressing how this energy transfer takes place, and how whichever processes at work depend on ambient conditions, is of critical importance to understanding the magnetic reconnection process overall and to assessing its effectiveness and impact on the larger-scale environment.

Likely related to these questions is that of the magnetic reconnection rate, that is, the rate at which magnetic flux transport and energy conversion takes place. This question has far-ranging implications as this rate determines not only the rapidity of the process itself, for example, how quickly a solar eruption can occur, but also the effectiveness of downstream processes such as the acceleration of particles to high energies. We now know that numerical models, which accurately represent many features of magnetic reconnection physics measured using satellites and laboratory experiments, show repeatedly that the magnetic reconnection rate is approximately 0.1 times that of the product of the Alfvén speed and magnetic field strength in the inflow region, and MMS measurements have confirmed that magnetic reconnection typically occurs at this rate (Y. Chen et al., 2017). What we do not know is why this rate should be universal (Parker, 1973; Shay et al., 1999)—or whether it actually is – and what its precise value is. While there have been a number of theoretical models suggesting explanations and spacecraft measurements are by and large consistent, we still lack basic physical understanding as to if and why a universal rate exists.

The rate question relates directly to the basic question of whether large-scale physics controls diffusion region physics or vice versa (the "outside-in" or "inside-out" problem discussed in Section 5.2). For example, it is conceivable that the engine operating in the diffusion region forces the outer regions to play along, that is, to adjust itself to whatever rate is being demanded by the diffusion region. On the other hand, the much larger outer region possesses much higher inertia and may not be able to react to changes imposed by the diffusion region. In this situation, back pressure from the larger environment could simply limit the action within the core. Either of these scenarios could apply, and it is perhaps likely that they both do simultaneously. Regardless, we are not at a point where we can explain the apparent generality of the above-mentioned magnetic reconnection rate—a challenge still waiting for its ultimate resolution.

A fascinating question being addressed recently is whether magnetic reconnection produces entropy, and, if so, in what sense. Stemming from the Sweet-Parker model which relies on electron-ion collisions, we would expect that magnetic reconnection produces entropy and is hence irreversible. This conclusion is considerably less obvious in a collisionless environment. Entropy generation here should be based on information loss, such as generated by chaotic particle orbits or super-fine phase space segmentation due to kinetic instabilities. The former may be expected in the inner diffusion region, and the latter in larger regions around the outflow, leading to the expectation that collisionless magnetic reconnection is indeed irreversible—an expectation consistent with the apparent lack of observations of magnetic reconnection reversing. However, some models indicate that careful reversal of time, particle motion, and magnetic fields can lead to reversible behavior for some system parameters (Ishizawa & Watanabe, 2013). Determining where entropy is produced, to what degree, and how it can best be measured is both one of the most challenging and rewarding future research topics.

The last example we will highlight is that we do not know how the highly localized ion and electron diffusion regions conspire and combine to produce dynamics and eruptions on hugely larger scales. This multiscale coupling is most dramatic in the solar environment, but scale size differences in the magnetosphere are already large enough to provide an excellent laboratory to study this interaction. Related also to the magnetic reconnection rate question, we need to understand how a large-scale current sheet, which is "ready to reconnect," forms one or more diffusion regions, which somehow combine to produce large-scale dynamics. This problem, and the related questions whether magnetic reconnection regions form as needed by the larger evolution, or whether their formation determines the size of that same evolution, are fundamental problems still waiting to be resolved.

### 6.2. The Role of Magnetic Reconnection in Environments Outside the Magnetosphere

As discussed in section 2.3, magnetic reconnection naturally occurs in many different space and astrophysical environments, in addition to controlled experiments in the laboratory. Among these environments, perhaps the most visually tantalizing is the atmosphere of the Sun. The solar corona can appear like a boiling cauldron of magnetic fields and particles, constantly in motion, and, at times erupting violently. There are ideas how relatively small magnetic reconnection events in the lower part of the corona can provide the heating needed to explain the extreme temperatures in the outer corona. The most dramatic manifestation of magnetic reconnection is solar eruptions, which entail a trifold phenomenology: a burst of radiation, acceleration of particles to energies up to a GeV, and the ejection of magnetic energy and particles in the form a CME. Up to $10^{11}$ tons of matter moving at speeds of millions of miles per hour can be ejected in large CMEs.

It is universally agreed that magnetic reconnection is the process directly or indirectly powering these dramatic phenomena, but we are facing daunting challenges connecting the dots. As discussed in section 3, the kinetic length scales setting the scale of the diffusion region are orders of magnitude smaller than the large system sizes. Due to the inaccessibility of the lower solar corona to direct measurements, we have so far had to rely primarily on extrapolations of our growing knowledge of magnetic reconnection physics in the magnetosphere and in the laboratory to learn about coronal magnetic reconnection. Based on this knowledge, we have surmised that the occurrence of plasmoids (secondary islands) and/or turbulence are possible mechanisms to, in effect, spread the effect of a single magnetic reconnection diffusion region into many, which can, when combined, explain the large-scale phenomenology behind a flare. The combination of many magnetic reconnection sites could, in principle, generate the total effect of a much larger diffusion region, leading to the acceleration of energetic particles, large radiation emissions, and the ejection of the aforementioned CMEs.

Whether this turbulence-based idea is correct, or whether magnetic reconnection works differently with a rather phenomenal coupling between these huge spatial scales, remains a subject of scientific debate. With the advent of NASA's Parker Solar Probe, which is designed to transit the solar corona to within nine solar radii of the solar surface, we now have a chance to address this extremely challenging question. Parker Solar Probe measurements, combined with the knowledge obtained from MMS and modern simulation methods, provide an unprecedented opportunity to extend our knowledge horizon to the plasma physics of the solar corona.

Equally fascinating is the role magnetic reconnection plays in the magnetospheres of the magnetized planets, that is, Mercury, Jupiter, Saturn, Uranus, and Neptune. Looking across the spectrum, we here find magnetic reconnection with ion diffusion regions comparable to the dimensions of the magnetosphere (Mercury) to magnetic reconnection transporting energy provided by planetary rotation instead of the solar wind (Jupiter). Researching magnetic reconnection processes in these magnetospheres has provided and will continue to provide, insight into how the dynamics of these magnetospheres evolve. Furthermore, comparing magnetic reconnection in these environments provides an outstanding opportunity to test our ability to extrapolate our knowledge from the near-Earth environment to other plasma environments.

Another class of plasma systems of immediate interest are to be found in the laboratory, especially in fusion devices. The objective in fusion is to achieve tight confinement of a plasma with a magnetic field, so tight that nuclear fusion between the fastest particles in a thermal distribution is enabled. In these systems, magnetic reconnection is a very unwanted process, as it both destroys plasma confinement and, possibly worse, releases so much magnetic energy that the plasma device itself can be damaged. Therefore, one objective in fusion research has been to suppress magnetic reconnection, that is, to achieve fusion configurations where magnetic reconnection is suppressed. However, suppressing reconnection entirely leads to a large buildup of energy, which, when released, is catastrophic, so the strategy on newer machines is to allow magnetic reconnection to occur in controllable small bursts that are less deleterious to the plasma and the machine. Neoclassical tearing modes, related to magnetic reconnection, compromise magnetic surfaces designed to hold in a plasma, which is a significant concern for fusion reactor design. Understanding the physics of how to suppress magnetic reconnection is closely related to understanding the circumstances in which reconnection occurs. A thorough understanding of the suppression of magnetic reconnection has been elusive so far—yet it is a key component to the complete understanding of the magnetic reconnection cycle. Detailed measurements of the magnetic reconnection physics can be obtained in fusion devices and specially designed laboratory experiments, which provide the opportunity to measure particle-related processes. Going forward, the synergy between space-based research and that involving fusion and specially-designed laboratory experiments has excellent potential to enable further progress in the development of fusion devices.

In astrophysical systems, magnetic reconnection is expected to play a major role in as diverse a set of systems such as pulsar magnetospheres, the galactic halo, and in accretion disks around neutron stars and black holes. Magnetic reconnection also facilitates eruptions on other stars, thereby powering space weather in exoplanetary systems. This is important for determining whether exoplanets can be life bearing. These systems are by their nature inaccessible to direct measurements, but they are rewarding targets to apply our new knowledge of reconnection. In particular, plasma astrophysics research has to focus even more on producing predictions for the kind of remote sensing we have access to, for example, gamma ray production or flare signatures in different types of stars. While these objectives are very challenging, knowledge obtained from present and future magnetic reconnection research in space is inevitably going to be extremely useful in achieving these goals.

### 6.3. Magnetic Reconnection in Larger Plasma Systems as an Example of Micro-Macro Coupling

Magnetic reconnection in large-scale plasma systems happens in current layers, which are usually generated by larger-scale plasma processes (as opposed to the magnetic reconnection process itself). For example, in Earth's magnetosphere, large-scale convection processes and the interaction of Earth's magnetic field with the solar wind set up current sheets, which can become the sites of magnetic reconnection. In turn, magnetic reconnection enables and powers major parts of the evolution of the large-scale system, such as geomagnetic substorms and storms. Magnetic reconnection thus reacts to the conditions it encounters yet also changes these conditions substantially through its actions. This situation is an example of the coupling of a large, “macro,” system to a critical, very small-scale, “micro,” process. The magnetosphere is therefore an example of a micro-macro coupled system. In systems of this type, the most compelling questions are related to whether macroscales or microscales rule the overall dynamics, and how these scales communicate with each other. Researchers have made much progress understanding the microphysics, which opens the door to addressing coupling to the larger-scale system. Research here has the potential to generate valuable knowledge for multiscale processes far removed from space- or even plasma-physical systems.

## 7. Paving the Way: Future Research Tools

### 7.1. Outlook of Satellite and Ground-Based Studies of Magnetic Reconnection

The immediate future of magnetic reconnection research will exploit current assets in new and novel ways. For example, magnetic reconnection in the magnetotail has been investigated by many missions, most recently by Cluster and THEMIS, and now by MMS. MMS is still operational and will continue to measure magnetic reconnection in the magnetotail, magnetopause, and magnetosheath, and will continue to lead to new insights about the microphysics of magnetic reconnection due to its unprecedented suite of high-resolution instruments. An approach which has been employed and will continue to have a major impact is using conjunctions with other missions in NASA's Heliophysics System Observatory. Such conjunctions can be useful to study the precursors or after effects of magnetic reconnection. THEMIS/ARTEMIS and Cluster continue to provide in situ measurements at and near magnetic reconnection sites at the dayside, magnetotail, polar cusps, and at lunar distances.

Outside the magnetosphere, Parker Solar Probe is successfully taking data, and the first research on the reconnection process in this unexplored region of the solar corona is now being done; the near future will see numerous studies of magnetic reconnection in the solar wind and lower solar corona. Moreover, the numerous solar satellites, including Solar Dynamics Observatory and Interface Region Imaging Spectrograph, will continue to study eruptive phenomena in the solar corona in which magnetic reconnection takes place. Ground-based assets are also a continued resource for eruptive solar phenomena, including the Green Bank Telescope and the Very Large Array. The recent development to use radio emission to measure magnetic field strengths in the solar corona—previously not directly accessible and available only from imprecise modeling techniques—is a significant advancement to quantitative studies of coronal phenomena that will likely bear fruit in the near future.

The future of observations of magnetic reconnection and its associated phenomena will include a number of assets currently being developed. The Daniel K. Inouye Solar Telescope solar telescope, which will see first light in 2020, will have a 4-m diameter aperture capable of resolving structure at 70 km on the Sun. It will be capable of new studies of solar flares. In the magnetosphere, ESA's Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) mission, slated for launch in 2023, will be in a polar orbit and measure X-rays and ultraviolet light, which will be used to image magnetic reconnection phenomena at the dayside magnetopause. NASA's Interstellar Mapping and Acceleration Probe mission, slated for launch in 2024, will study the heliopause, where magnetic reconnection has been hypothesized to make the boundary porous and potentially accelerate anomalous cosmic rays. In addition, magnetic reconnection will continue to be studied in planetary contexts. Juno has been orbiting Jupiter since 2016 and has detected signatures of magnetic reconnection. The BepiColombo mission to Mercury was launched in 2018 and will arrive in 2025.

We expect that the rapid expansion of cubesats for remote measurements of the Sun and in situ measurements in the magnetosphere will provide a new way to study the physics and impacts of magnetic reconnection. There are cubesat missions currently under planning or development that will provide a new way to look at magnetic reconnection, such as the Experiment for X-ray Characterization and Timing (EXACT) 3U cubesat to measure X-rays from solar flares, and the Cusp Plasma Imaging Detector (CuPID) Cubesat Observatory to investigate dayside magnetic reconnection.

Looking further ahead to the future, the main science problem not currently being addressed is the micro-macro coupling problem discussed in section 6.3. The best way to address these questions directly is to conceive a space mission that allows simultaneous measurements on all relevant scales in the magnetosphere. Obtaining understanding of how this coupling works is of basic physics interest and will likely revolutionize our understanding of plasma systems across the spectrum, from space to laboratory to astrophysical systems. This idea, the so-called “cross-scale mission” has, to date, not been implemented. A recent step toward a mission of this type is the Self-Adaptive Magnetic Reconnection Microscope mission of at least 12 cubesats combined with the high-capability mothership to measure electron-scale, ion-scale, and macroscales of magnetospheric reconnection. While challenging due to its complexity, a multinational consortium could form the basis for support of such a fundamental mission, and enable pursuit of this elusive, cross-scale, goal.

### 7.2. Outlook of Numerical Modeling of Magnetic Reconnection

Even though high-performance numerical modeling has been a key contributor to our progress in understanding magnetic reconnection, there remain substantial limitations to our ability to simulate large-scale systems. Unlike, for example, meteorological systems, the dynamics of which is governed by fluid-like behavior (and chemical and photochemical reactions), many plasma systems in space and in the laboratory are kinetic in nature. These plasma systems are, often to a large degree, governed by details of the interactions of charged particles with electromagnetic fields and thus require a much more complex modeling approach than fluid behavior-dominated systems. However, modeling both this complex physics and the huge spatial scales is far beyond the capacities offered by even the largest supercomputers today. Until such time when sufficient computational resources become available, we hence need a different, simpler, approach to describe these systems numerically. Finding and applying such approaches is not only fruitful in a basic research environment but also of key importance to developing better predictive capabilities in the realm of space weather.

Short of the impossible task of modeling, for example, the entire solar corona kinetically, one possible path forward is to include key kinetic physics at critical locations by means of simplified so-called "transport models" that attempt to capture kinetic physics within the fluid description. In the context of magnetic reconnection, this means that we attempt to locally force the system to act reasonably correctly even if we cannot resolve the magnetic reconnection physics itself in the model. In order for this to be successful, we need to develop a detailed understanding of how magnetic reconnection changes the larger-scale environment in its vicinity based on properties of the environment itself. If we could develop this knowledge, we could introduce these effects into models based on the conditions in the environment where we expect magnetic reconnection to occur. In principle, such an approach can provide much more detailed and accurate specifications of, for example, the magnetic field of Earth and the near-Earth particle environment than by simply using the fluid description. Further, this capability would provide a much more accurate forecast of space weather effects subsequent to magnetic reconnection, such as the acceleration of harmful energetic particles, and the generation and evolution of current systems, which induce voltages in conductors on the surface of Earth.

Another approach is to introduce self-consistent kinetic models into large-scale models to represent kinetic physics correctly in special regions of interest. The particularly important regions here are regions where magnetic reconnection occurs. One recent approach is to embedding kinetic models, such as recently introduced (Y. Chen, Tóth, et al., 2017; Daldorff et al., 2014; Tóth et al., 2017) offer the promise of even higher fidelity of representation of key kinetic physics. Another approach is the global Vlasov-hybrid approach, treating ions like distribution functions and electrons as a fluid in global numerical simulations (von Alfthan et al., 2014). Even in these approaches, we need to develop detailed understanding of how the large-scale physical system interacts with its smallest scales—knowledge we are only beginning to scratch the surface of. However, proceeding in this direction provides a path toward the most accurate representation of sudden and rapid temporal changes facilitated by magnetic reconnection.

In addition to using more realistic descriptions of magnetic reconnection in numerical models for basic science, it could have a strong impact on space weather modeling. Since magnetic reconnection at the dayside drives magnetospheric convection and magnetic reconnection at the magnetotail drives geomagnetic storm and substorm activity—those explosive changes that are both scientifically tantalizing and are critical for space weather—a more realistic description of magnetic reconnection will undoubtedly enhance the ability of global magnetospheric codes to model and predict space weather. Efforts to do so are already underway to use the SWMF code suite at University of Michigan for space weather prediction in collaboration with the National Oceanic and Atmospheric Administration.

### 7.3. Outlook of Laboratory Magnetic Reconnection Experiments

Laboratory experiments have played, and continue to play, an important role in understanding the physics of magnetic reconnection. We believe the future of laboratory experiments of magnetic reconnection will advance beyond present capabilities in two key areas—diagnostics and system size. On the need for advanced diagnostics, as mentioned in section 3, current capabilities in space-relevant magnetic reconnection experiments are largely confined to fluid-type measurements. Diagnostics to go beyond this will be crucial for complementing existing spacecraft capabilities. Advances are already underway—the ability to measure pressure anisotropies is currently being developed at the Terrestrial Reconnection EXperiment. The ability to nonperturbatively measure three-dimensional (in both position space and velocity space) electron and ion distribution functions is underway at the PHAse Space MApping (PHASMA) experiment.

On the need for larger system sizes, activities are underway to build bigger fundamental magnetic reconnection experiments; one is the Facility for Laboratory Reconnection Experiments (FLARE). The larger system size will allow researchers to study the impact of secondary islands/plasmoids on magnetic reconnection and better understand the transition from collisional to collisionless magnetic reconnection, which is potentially relevant at the onset of solar flares.

Looking beyond the immediate future, the next big advancement will likely be the combination of capabilities currently held only at disparate machines. Thus, a single device that captures aspects of cross-scale coupling with a full suite of diagnostics for both large-scale and small-scale (kinetic) physics, including distribution functions. Such a machine will facilitate a number of studies that are not feasible now, including the cross-scale coupling, three-dimensional aspects of magnetic reconnection, the properties and impacts of turbulence in the magnetic reconnection layer and in the exhausts, and continued refinement of our knowledge of the magnetic reconnection rate, dissipation mechanism, and energy conversion and partition currently being studied on smaller devices.

## 8. A View of the Past, A Vision for the Future

Magnetic reconnection is a fascinating process in plasmas. As a classical example of a multi-scale process, it facilitates energy transport and conversion on huge spatial scales by means of processes localized on comparatively miniscule kinetic scales. It plays a dominant role in as diverse environments as the solar corona and chromosphere, magnetospheres of Earth and other planets, astrophysical systems such as pulsars, and in magnetically confined fusion devices.

The role of magnetic reconnection is built upon its ability to convert, often explosively, huge amounts of stored magnetic energy into particle energy. This energy release powers solar eruptions, geomagnetic storms in Earth's magnetosphere, astrophysical jets and flares, and powerful current disruptions in fusion devices. The underlying energy conversion provides, in addition, the engine behind many of the harmful effects associated with space weather, and it is also fundamentally behind the energy transport needed to power the aurora.

The development of our understanding of magnetic reconnection has been multidisciplinary, with strong foundations made in the early years. However, the last 30 years has brought the great appreciation that we need to go far beyond the original models to explain magnetic reconnection in space. Our understanding of how magnetic reconnection works at kinetic scales has grown steadily, and recently made giant strides forward. Despite the great challenges posed by such an extreme multiscale problem as magnetic reconnection, we now understand the functionality inside the diffusion region—the extremely localized region dominated by kinetic physics, which is enabling the hugely larger energy conversion.

As magnetic reconnection research enters its eighth decade, the community is embarking on the path to the next great discoveries about the process. Research into how precisely the tiny diffusion region couples to the large scales, and how this multiscale interaction occurs as effectively as it does will be of prime importance. The community is furthermore beginning to reap the benefits of our new knowledge and is poised to investigate how it impacts plasma systems far beyond the reach of in situ measurements. As space weather modeling improves, our knowledge of magnetic reconnection will aid both further understanding and forecasting. Hence, further research of magnetic reconnection itself promises to be exceptionally rewarding, both in basic scientific understanding and in developing knowledge applications for practical purposes.

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