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Inside the Black Box: Magnetic Reconnection and the Magnetospheric Multiscale Mission

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Abstract The motivation for the recently launched Magnetospheric Multiscale mission is learning about the process of magnetic reconnection, especially the physics of what is called the diffusion region. The diffusion region is often treated as a black box but is the home of very important physics, which is of great significance to understanding space weather. This article is a brief review of what is known—and not known—about the diffusion region in magnetic reconnection, written for the broad space weather community and its stakeholders (with an appendix for readers interested in more technical matters). The focus is on the physics of magnetic reconnection and the diffusion region, why it has been challenging to study, how MMS will contribute, and how the community will benefit from its measurements.

Setting the Stage

NASA's Magnetospheric Multiscale (MMS) mission was successfully launched on 12 March 2015. The mission was conceived to help understand the somewhat mysterious process called magnetic reconnection. While it is widely appreciated that magnetic reconnection plays a crucial role in space weather (it is discussed in more than 70 *Space Weather Journal* articles), the many stakeholders of space weather may not be familiar with the process, why understanding it is useful for science and for space weather applications, and how MMS will contribute. The goal of this brief review is to offer clarity on these questions to the space weather community, its industrial stakeholders, and to policy makers.

What Is Magnetic Reconnection?

Magnetic reconnection, often simply referred to as reconnection, is a process that takes place in gases of sufficiently high temperature that electrons can remain apart from their nuclei. Such gases are called plasmas, and they naturally occur in every star in the universe and most of the regions between stars and between planets. They also can be produced on Earth; fluorescent light bulbs, TV and computer screens, and neon lights all contain plasmas. Plasmas are also important to the pursuit of energy production through fusion, where gases are made to be hot enough that their nuclei stick together when they collide.

Many plasmas, including those in stars and in interstellar and interplanetary space, are accompanied by a magnetic field; magnetic fields in plasmas are important because they interact strongly with the charged particles in plasmas, whereas they hardly have any effect on neutral gases such as the air we breathe. In the simplest description of a plasma (called magnetohydrodynamics, which is simply a description of a plasma as if it was a fluid like water except that it interacts with magnetic fields), one can show that magnetic field lines retain their identity. This means that one can follow magnetic field lines as they effectively move through space with their surrounding plasma.

While appealing due to its simplicity, the model is grossly oversimplified. It turns out that magnetic field lines, when they point in opposite directions in a small region of space, can effectively break and rejoin other broken magnetic field lines. This could not occur if field lines retained their identity. This effective breaking and rejoining of magnetic field lines is magnetic reconnection.

Reconnection can be seen pictorially in Figure 1; see also the figures in *Gross and Hughes* [2015]. Shown in white are magnetic field lines at two different times taken from a supercomputer simulation of magnetic reconnection. In Figure 1a, the magnetic field lines near the blue octagon are about to undergo reconnection; they point down on the left and up on the right. Figure 1b shows the field lines a little later in time. The field lines in question have effectively broken and cross-connected to each other. These field lines have undergone magnetic reconnection.

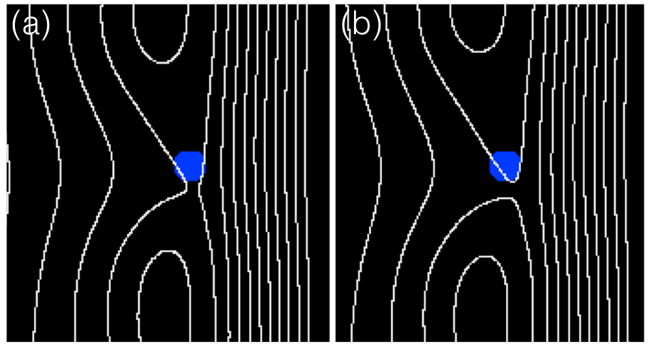

Figure 1. Magnetic field lines (in white) from a supercomputer simulation (a) before and (b) after reconnection of the magnetic fields near the center. The blue octagon represents the goal of MMS to measure data in the small region where the field lines break (the diffusion region).

Reconnection often happens explosively and usually leads to a significant conversion of much of the energy in the magnetic field into other forms of energy such as bulk flow of the plasma and heat to the surrounding plasma. In the figure, the plasma near the location where the field lines break would be heated and ejected in both vertical directions. Reconnection happens in essentially all naturally occurring magnetized plasmas. A number of technical reviews and textbooks on the subject have been written [e.g., *Zweibel and Yamada*, 2009], so interested readers are referred to those or the appendix of this paper for more details.

Magnetic Reconnection and Space Weather

Reconnection is the key driver of many important aspects of space weather both on the solar side and on Earth's side. In the solar corona (the Sun's hot and tenuous atmosphere), reconnection enables solar flares and coronal mass ejections (CMEs) [*Priest and Forbes*, 2002], the most energetic events in the solar system; indeed, it is in this context that reconnection was discovered in the 1940s. Shown in Figure 2a is a schematic diagram capturing the role of reconnection for a particular type of flare. The blue lines are magnetic field lines, which point in opposite directions near the middle of the sketch. When they break during reconnection, plasma is directed toward the solar surface (the downward pointing red arrow). When the plasma impacts the solar surface, it gives off the radiation we detect as a solar flare (including visible light, ultraviolet light, X-rays, radio waves, and sometimes gamma rays). When X-rays produced during flares reach the outer layers of Earth's atmosphere, they ionize more particles than usual in the ionosphere [*Hernández-Pajares et al.*, 2012], which alters the propagation of waves used for radars, communications, and—in severe events—those used in the global positioning system (GPS) [*Rodríguez-Bilbao et al.*, 2015]. Reconnection in solar flares is also a source of (impulsive) solar energetic particles (SEPs) [*Cane et al.*, 1986]; these energetic particles have a space weather impact when they damage spacecraft components such as solar cells and when they interfere with radio transmission on Earth.

Reconnection also allows large blobs of hot coronal material (at the top in Figure 2a, near the upward pointing red arrow) to escape since they are no longer held to the surface by magnetic fields [see *Fisher et al.*, 2015, and references therein]. If this material runs into Earth's magnetic field, it can cause geomagnetic storms.

The reaction by Earth to "storms from the Sun" are also strongly controlled by magnetic reconnection. The hot plasma coming off of the Sun is entrained by a magnetic field. This is shown on the right side of Figure 2b, a frame from a supercomputer simulation of the magnetic bubble surrounding Earth (the magnetosphere). Reconnection at the edge of the magnetosphere on the side closer to the Sun (the dayside magnetopause) can occur between the magnetic field coming off of the Sun and Earth's magnetic field if they are oppositely directed [*Dungey*, 1961], as shown by the blue oval on the right. When this occurs, the reconnected magnetic field lines (in white) get dragged antisunward (to the left). The field line motion drives flow throughout the magnetosphere including the ionosphere and thermosphere, another layer of Earth's atmosphere. This motion heats the atmosphere, just as driving a current through a wire generates heat as in car rear window defoggers. The hotter atmosphere expands, thus increasing drag on satellites, which can take them out of their intended orbit [e.g., *Bruinsma and Forbes*, 2008; *Lechtenberg et al.*, 2013].

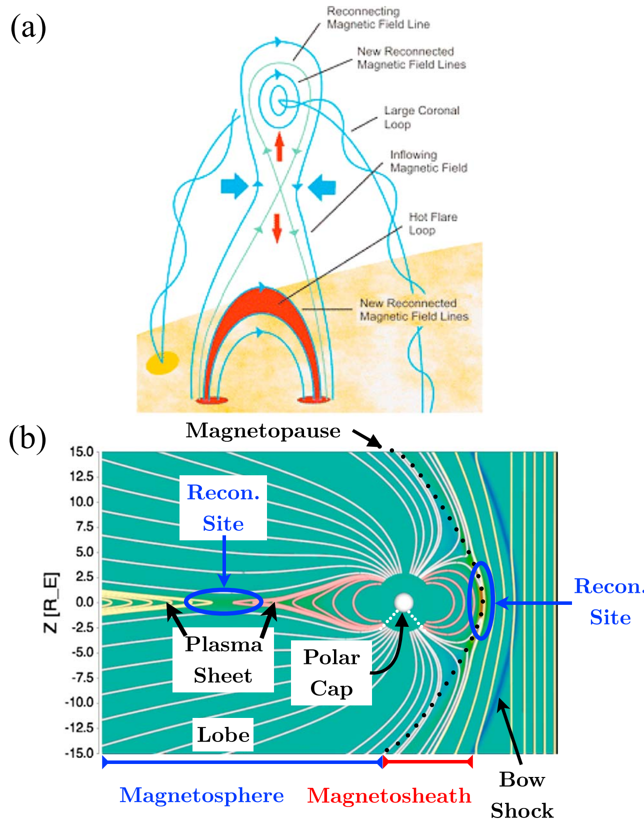

Figure 2. (a) Schematic of how reconnection works in some solar flares and coronal mass ejections. (Courtesy of NASA.) (b) Supercomputer simulation of the magnetic bubble around Earth (the magnetosphere). Blue ovals denote locations where reconnection occurs when the magnetic field coming in from the Sun (to the right) is opposite to Earth's. (Figure 2b is from Komar (2015). Used with permission by C. M. Komar.)

The motion of magnetic fields away from the Sun also loads the magnetotail (the portion of the magnetosphere away from the Sun) with magnetic energy. When the fields squish the magnetotail to be sufficiently thin, reconnection occurs in the blue oval on the left side; this sets off geomagnetic storms or their associated brethren, geomagnetic substorms [*Angelopoulos et al.*, 2008]. Large enough geomagnetic storms can cause significant damage [*Loto'aniu et al.*, 2015]. When reconnection in the magnetotail occurs, hot particles are injected toward Earth. The additional material causes satellite signals in the ionosphere to refract and disperse and causes scintillation (modification) of radio waves in Earth's polar regions due to rapid changes in the density of the ionosphere [e.g., *Kintner et al.*, 2007; *Jiao and Morton*, 2015]. These can interfere, for example, with GPS receivers trying to lock signals from the ground. Furthermore, the particles injected by magnetotail reconnection change the current in the ionosphere (the auroral electrojet), which can cause significant changes to the magnetic field at Earth's surface. Changes in magnetic fields are associated with the generation of current; this is Faraday's law of induction and is the governing principle of how motors and electric generators work. This happens on a large scale when Earth's magnetic field is changed by reconnection in the magnetotail; large-scale currents are driven on Earth's surface. These so-called geomagnetically induced currents (GICs) have caused major power outages due to damage of the power grid [*Gaunt*, 2016] and lead to degradation of pipelines [*Marshall et al.*, 2010].

In summary, reconnection plays a crucial role in many aspects of space weather. If reconnection did not occur in the solar corona, there would neither be flares nor CMEs, and the impact on Earth of space weather would be greatly reduced! If reconnection in Earth's magnetosphere did not occur, there would be very little response by the magnetosphere to material coming in from interplanetary space. Consequently, understanding reconnection is a key aspect both on the solar and magnetospheric sides of the science of space weather.

The Black Box (the Diffusion Region)

As implied by Figures 1 and 2, the breaking of magnetic field lines takes place only in a very small region of space. When scientists study the solar corona or Earth's magnetosphere in the larger context, the small region where reconnection occurs is often treated as a black box. There are topics for which not knowing the details inside the black box is acceptable. However, there are numerous applications for which the physics inside the black box, referred to as the "diffusion region" or "dissipation region," is critical. Understanding the physics of the black box is the primary motivation for the MMS mission. It differs from all previous missions by being specifically designed to see what is going on inside the black box.

Outside the black box, the plasma is typically well described by the simplest plasma model, magnetohydrodynamics, which is well understood. However, entirely new physics becomes important inside the diffusion region, and it is this physics that allows the magnetic fields to break. There are many reasons that the physics of the diffusion region is so important to understanding reconnection and, therefore, predicting space weather phenomena. First, magnetic field lines do not break unless there is irreversible dissipation. The rate at which reconnection occurs, meaning how fast the magnetic field lines can be broken by reconnection, is directly related to the dissipation. The large-scale behavior depends strongly how rapidly field lines reconnect, so it is important to know how fast reconnection proceeds and why. Another important aspect is that the small-scale processes produce strong, localized electric fields. Electric fields can accelerate charged particles to high energies. Such particles can participate in the deleterious effects of space weather as discussed in the "Magnetic Reconnection and Space Weather" section. This is why understanding the diffusion region is so important; one cannot fully understand the reconnection process without knowing what happens inside the black box, and one cannot use this understanding to make reliable predictions about large-scale effects such as CMEs and how Earth's magnetosphere responds to them without it.

The Challenge

There are (at least!) two reasons understanding the dissipation processes in reconnection is so challenging. At a fundamental level, the only way to get irreversible dissipation in plasmas (or most any physical setting) is collisions. Indeed, in the example of running a current through a wire to melt ice on a car window, collisions between the electrons making up the current and the molecules making up the wire provide dissipation which is manifested in the form of heat. Magnetic reconnection in strongly collisional plasmas has been studied since the mid-1950s and is well understood. However, the first challenge in understanding reconnection for space weather applications is that collisions play only a very weak role; this is the case both in the solar corona and Earth's magnetosphere. The need for an understanding of dissipation in nearly collisionless systems was appreciated in the 1970s, but despite 40 years of research, the problem has not been solved.

The second reason understanding the mechanism allowing reconnection is so challenging is that the dissipative processes in question occur at very small length scales—at and below the scale of the electron gyroradius, the size of the loops that electrons make around magnetic fields. For the solar corona, this size is only a few centimeters; in the magnetosphere it can be 1–20 km depending on the location. Magnetic fields in the solar corona have structure on scales up to 10^5 km and the magnetosphere is close to 1.5 million km long, so the regions where dissipation occurs are extremely small compared to these large magnetic field structures. This "multiscale" nature of the reconnection problem has made it difficult to study. For satellite observations, instrument cadence needs to be extremely high to measure small scales. Furthermore, until now, one required a chance encounter to find a tiny reconnection site in such a large system. The same is true in laboratory experiments; diagnostics need to have high time resolution and be physically very small to study dissipation processes in reconnection. Numerical simulations can help, but standard codes have the drawback that they require dissipation to run smoothly and this dissipation can mask the physical dissipation allowing reconnection.

A New Tool: MMS

The MMS mission was designed to address these challenges. Much has been written about MMS [e.g., *Burch et al.*, 2015], so only the most salient points are summarized here. It is a four-satellite mission, similar in flavor to the Cluster mission [*Escoubet et al.*, 2001]. The use of multisatellite missions allows for measurements to be made over a swath of space instead of along a single line, and extra information is obtained by taking

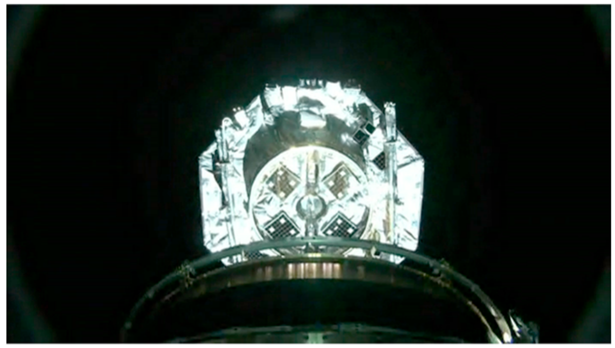

Figure 3. Picture of the last of the four MMS spacecraft separating from the Centaur Upper Stage after launch on 12 March 2015. Image provided by Jim Burch. (Courtesy of NASA.)

differences between data measured on the different satellites. These missions fly in a tetrahedral formation orbiting Earth. Cluster has a variable spacecraft separation typically at least 100 km, which is comparable to proton gyroscales, the radius of the loops protons make around magnetic field lines which is typically 50–100 times larger than the loops made by electrons. The time resolution for instruments on Cluster is a few seconds. While studying reconnection was not the sole purpose of the Cluster mission, it has provided invaluable information about reconnection during its chance encounters. However, this information is largely at the scale of the proton gyroradius and above, which is important for large-scale effects of reconnection, but it was not designed to address questions about dissipation at electron scales and below.

The MMS satellites have a variable separation that has been made as small as 10 km, comparable to electron gyroscales. Significant effort went in to making the unprecedented small spacecraft separation possible, including using extremely weak GPS signals from below the MMS orbits for some of its navigation. Allowing the spacecraft to be closer together than previous missions allows MMS to address previously unaccessible questions about the diffusion region.

The success of the MMS mission goes beyond putting spacecraft close together. Resolving structure on electron scales requires instruments that measure with a resolution of milliseconds. On board are plasma analyzers with a full 360° view which measure the velocities of particles at 30 ms resolution for electrons and 150 ms for protons and other positively charged ions. This is 100 times faster than that achieved previously. In addition, there are booms which measure all three components of electric and magnetic fields; this is an important feature as the electric field parallel to the magnetic field is particularly important for reconnection.

MMS was successfully launched from Kennedy Space Center. Figure 3 shows the last of the four spacecraft separating from the launch vehicle. As of this writing, MMS has finished its commissioning phase and is successfully taking data and transmitting it to Earth. Phase 1 of the science mission is a nearly equatorial orbit with farthest distance of 12 times the Earth's radius away from Earth, which typically pierces the dayside magnetopause multiple times per orbit. This trajectory makes it likely to pass through dayside reconnection sites, the right oval in Figure 2b. In Phase 2, the farthest distance will be doubled, so the trajectory will make multiple passes through where reconnection is expected to occur in the magnetotail, the left oval in Figure 2b.

The two phases are not simply two opportunities to measure the same thing. The magnetotail tends to have magnetic fields that are nearly perfectly oppositely directed and are of relatively similar strength on either side of where reconnection occurs. At the dayside, however, the reconnecting magnetic fields on either side tend to be quite different, so the reconnection is asymmetric. The magnetic fields can be nearly anti-parallel, but they often make an oblique angle with each other (when the interplanetary magnetic field is not due southward). The dissipation mechanism of reconnection is not necessarily the same in these two scenarios [*Hesse et al.*, 2014]. Therefore, MMS will not solely get a single data point about what allows field line breaking in a single setting, but also how it differs in different settings.

What Will be Gained From MMS

As MMS is a NASA mission, its main goal is the science of reconnection in its various settings as opposed to space weather forecasting. However, it is certainly expected that MMS will improve our understanding of magnetospheric physics and space weather. What will be gained from MMS measurements and how will it impact magnetospheric physics and space weather?

The science goal of MMS is to uncover what goes on inside the black box — inside the diffusion region. The trajectories of the spacecraft have been selected to maximize the likelihood that they will pass near or through the black box where reconnection occurs, as sketched by the blue octagon in Figure 1. Between the dayside measurements in Phase 1 and the magnetotail measurements in Phase 2, it is hoped that MMS will have determined what physics causes the irreversible dissipation allowing magnetic field lines to break. Due to its ability to measure speeds of collections of individual particles (distribution functions), it is hoped that MMS will help determine what dissipative effects occur at these scales. For example, MMS should be able to determine whether or not there is a collisionless (anomalous) resistivity from correlated fluctuations in the density and electric field as a long-standing model suggests, but which has escaped detection and is not prevalent in numerical simulations.

One reason researchers will find the kinetic physics of the diffusion region to be useful is that there is no accepted explanation for the size of the electric fields produced during reconnection as seen in numerical simulations and solar and magnetospheric observations. Understanding this could be crucial for applying our knowledge of reconnection to the many disparate situations where it occurs.

MMS data will also be useful for studying aspects of reconnection beyond the diffusion region. Shock waves predicted to occur near reconnection sites have not been seen in collisionless simulations. Recent work has suggested that the predictions must be modified when collisionless effects are taken into account [*Liu et al.*, 2011]. MMS is likely to yield insight through its high-resolution data — 100 times faster than previous missions.

Another key aspect for which MMS may provide insight is particle acceleration, as discussed in "The Black Box (the Diffusion Region)" section. Some particle acceleration does occur in the diffusion region, and MMS should be able to resolve this physics. However, the location where most particles that are accelerated during reconnection occur is at the boundaries of the jets of flowing plasma. A leading model for this is the strongly kinked magnetic fields created when the field lines break and reconnect slingshot particles to high energies [*Drake et al.*, 2006]. The region where this happens extends far from the diffusion region. Thus, even when MMS is not directly in the relatively small diffusion region, it will still give important information about how particles are accelerated by reconnection. As discussed earlier, understanding particle acceleration is extremely important for applications. Reconnection produces solar energetic particles (SEPs) in solar flares and energetic particles in the magnetotail that get injected toward Earth, both of which are important for space weather. Beyond the Sun-Earth system, bursts of X-rays are seen in many astrophysical settings and can only come from energetic particles; reconnection is a leading candidate for how these particles gain their energy [*Uzdensky*, 2011].

In the context of how MMS will give insight into magnetospheric reconnection for space weather applications, it will provide unprecedented in situ information about where dayside reconnection occurs for given interplanetary conditions. MMS may provide data on the nature and prevalence of magnetic bubbles produced during reconnection, known as flux transfer events on the dayside magnetopause [*Russell and Elphic*, 1979]. In the magnetotail, MMS will help understand the nature of energy release in substorms, which is now understood to be bursty and localized in dipolarization fronts (also known as reconnection jet fronts) and bursty bulk flows [*Angelopoulos et al.*, 1992; *Runov et al.*, 2009; *Sitnov et al.*, 2009]. A better understanding of how substorms inject particles to the inner magnetosphere, including how these particles reach the auroral zone [*Kepko et al.*, 2015], will have an impact on space weather prediction.

Due to the unprecedented spatial and temporal resolution of MMS, magnetospheric physics will benefit from MMS using the magnetosphere as its laboratory. The cadence and spatial scales that MMS employs are completely new to NASA's Heliophysics System Observatory and will give rise to unprecedented resolution of electron-scale physics whether or not reconnection is being measured. MMS will measure high-resolution detail about the turbulent structure of the magnetosheath, the region just outside the magnetosphere (see Figure 2b). It will observe the Kelvin-Helmholtz instability at the flanks of the magnetopause, potentially giving insight into another mechanism for transporting magnetosheath material into the magnetosphere [*Hasegawa et al.*, 2004].

In summary, magnetic reconnection is of fundamental importance in many plasma physics settings from the heliosphere to fusion to astrophysics, and it is also a crucial aspect of space weather. The physics allowing magnetic field lines to effectively break in collisionless plasmas takes place at scales smaller than the electron gyroradius in the diffusion region, so it has been challenging to study observationally, experimentally, theoretically, and numerically. MMS will provide the first electron-scale measurements of the magnetosphere and is likely to provide an unprecedented look inside the black box of reconnection.

Appendix A: A More Technical Review

The first portion of this review was intended for an audience not necessarily requiring technical detail. This supplementary material revisits the question of what physically allows magnetic field lines to break from a more technical point of view. The target audience here is people with a background in solar and space plasma physics that are not necessarily familiar with the reconnection process or people who have studied systems for which reconnection is important without necessarily studying the process itself.

The Diffusion Region

The MMS mission was designed to study the physics of the diffusion region, so a reasonable starting point is to define the diffusion region. Unfortunately, this is problematic; there is no rigorous definition for the diffusion region. However, one can motivate some of its properties. For the magnetic field lines in Figure 1, the field line connectivity changes at a single point where oppositely directed magnetic field lines come together. Since the magnetic fields make the shape of an X, the point where the field line breaks is called the X point. In the real three-dimensional world, connecting the points in adjacent planes where reconnection occurs forms a one-dimensional curve, called the X line.

The physics allowing field lines to break is important not only at a single point or line but over a small but finite-sized region of space around that point. This is the diffusion region, so-called because magnetic fields diffuse through (or decouple from) the plasma in this region. It is alternately called the dissipation region since irreversible dissipation occurs within this region. It is often described that ideal magnetohydrodynamics (ideal MHD) is valid outside the diffusion region and it breaks down inside. If this delineation was rigorously true, the region where ideal MHD breaks down would be the diffusion region. What really happens is that there is a smooth transition from the ideal-MHD region to where it breaks down. For the purposes of this discussion, the diffusion region is defined as where nonideal-MHD contributions exceed ideal-MHD contributions.

To quantify this, the frozen-in condition is quantified by a generalized version of the ideal-MHD Ohm's law,

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \mathbf{R} \tag{A1}$$

(in SI units), where $\mathbf{E}$ is the electric field, $\mathbf{u}$ is the bulk plasma flow, and $\mathbf{R}$ is any term on the right-hand side. In the ideal-MHD limit, $\mathbf{R}$ is ignored and the frozen-in condition is valid. However, when a component of the magnetic field goes to zero, the convective electric field $-\mathbf{u} \times \mathbf{B}$ vanishes, allowing $\mathbf{R}$ to become dynamically significant. The physics of $\mathbf{R}$, which allows an electric field in the reference frame of the plasma, breaks the frozen-in condition and is what can allow a change in field line connectivity.

A Simple Case: Collisional Reconnection

The dissipation during reconnection can be understood in a simple limit. The original studies of reconnection employed the resistive MHD model, so that $\mathbf{R} = \eta \mathbf{J}$, the same Ohm's law as for a current passing through a wire. Here η is the Spitzer resistivity [*Spitzer and Härm*, 1953] and $\mathbf{J}$ is the current density. In this model, the physical reason field lines can break is relatively simple—while in a perfectly conducting material the electrons move extremely fast to short out any electric fields, in a resistive plasma the electron-ion collisions impede the electrons from doing so, and an electric field can exist. These collisions provide irreversible dissipation as is necessary for reconnection to occur. The plasma is heated through Ohmic heating. The well-known Sweet-Parker model [*Sweet*, 1958; *Parker*, 1957] quantifies the properties of collisional reconnection.

The Sweet-Parker prediction for collisional reconnection was too slow to explain observations, leading to the development of a faster model in which magnetic field line curvature helps accelerate the plasma [*Petschek*, 1964]. Interestingly, using a localized resistivity in MHD produces the fast Petschek rate and is used in many studies to get the right answer out of the black box [*Sato and Hayashi*, 1979]. Because of this, many thought that reconnection was a solved problem. However, it was realized that the collisional theory does not apply to many settings in space including Earth's magnetosphere [*Vasyliunas*, 1975; *Sonnerup*, 1979]. This raises the question—what breaks the frozen-in condition in an essentially collisionless plasma, or equivalently, what produces an electric field and causes irreversible dissipation required for field lines to break in an essentially collisionless plasma?

Fluid Description of the Diffusion Region

One approach to describe diffusion region physics (the form of **R**) is the fluid approach, though we return to a subtle issue later. We consider a perfectly collisionless plasma; the electron equation of motion is calculated from the first moment of the Vlasov equation. Solving for the electric field gives the generalized Ohm's law [*Vasyliunas*, 1975]:

$$\mathbf{E} + \mathbf{u}_p \times \mathbf{B} = \frac{\mathbf{J} \times \mathbf{B}}{ne} - \frac{\nabla \cdot \mathbf{p}_e}{ne} - \frac{m_e}{e}\frac{\mathrm{d}\mathbf{u}_e}{\mathrm{d}t}, \tag{A2}$$

where only a single species of protons is assumed. Here $\mathbf{u}_p$ is the proton bulk flow velocity (which replaces $\mathbf{u}$ on the left-hand side relative to equation (A1)), $\mathbf{u}_e$ is the electron bulk flow velocity, n is the number density (assumed equal for protons and electrons), e is the proton charge, $\mathbf{p}_e$ is the electron pressure tensor, and m_e is the electron mass. Here $\mathbf{u}_e$ has been eliminated from the convective electric field using $\mathbf{u}_e = \mathbf{u}_p - \mathbf{J}/ne$. The right-hand side is completely rigorous within the confines of the perfectly collisionless model — it is even true for non-Maxwellian distribution functions — so it is the most common starting point for representing terms that can produce an electric field in the reference frame of the ions and gives invaluable insight into the macroscopic physics of import.

Before discussing what allows field lines to break, it should be pointed out that there is a happy — and unexplained — "coincidence" that the large scale physics, including how rapidly the collisionless reconnection process occurs, tends to be relatively independent of the dissipation mechanism used in **R** (provided it is not simply electron-ion collisions or electron inertia). Indeed, numerical studies suggest that the electric field E during collisionless reconnection is about 0.1 of the product of the Alfvén speed and the component of the magnetic field undergoing reconnection [*Shay et al.*, 1999; *Birn et al.*, 2001], which is about an order of magnitude faster than reconnection with a Spitzer resistivity can achieve [*Daughton et al.*, 2009; *Shepherd and Cassak*, 2010]. The same rate occurs using a localized resistivity, but whether a localized resistivity self-consistently occurs in collisionless systems is an open question [*Che et al.*, 2011]. It is natural to expect that the reconnection rate is set by the physics allowing the field lines to break right at the X line, but this is not necessarily the case. It is possible that an effect away from the X line controls E, while a separate mechanism breaks the field lines and matches the same E. These matters are under debate.

Each of the terms in **R** in the collisionless generalized Ohm's law is now considered for whether it can allow field lines to break. For simplicity, first consider 2-D, planar, nonrelativistic, electron-proton steady (time-independent) reconnection with purely antiparallel magnetic fields. Defining z as the out-of-plane direction, terms that can produce an electric field in the z direction at the X line are candidates for what allows reconnection.

The $\mathbf{J} \times \mathbf{B}/ne$ term is the Hall term, physically describing the decoupling of ion and electron bulk flows at scales smaller than the ion gyroradius. Its z component vanishes at the X line since $\mathbf{B}$ is zero at that location, so this term cannot cause field lines to break. However, the Hall term has been identified as being crucial to collisionless reconnection. The GEM Challenge study [*Birn et al.*, 2001] revealed that adding the Hall term into resistive MHD gives reconnection rates comparable to those of kinetic simulations, while not including it leads to resistive reconnection. One explanation for this is that the Hall term leads to faster flows at small scales (it is dispersive), which leads to an open exhaust and therefore faster reconnection [*Rogers et al.*, 2001], though this interpretation remains controversial [*Liu et al.*, 2014]. Thus, while not being the effect that breaks field lines, the Hall effect can be very important.

Skipping to the last term on the right-hand side of equation (A2) is the electron inertia term. Note that there are two terms in the convective derivative, the $\partial/\partial t$ term and the $\mathbf{u}_e \cdot \nabla$ term. The first part vanishes for steady reconnection, and the second vanishes because there is no flow at the X line for symmetric reconnection, so this term cannot cause the electric field at the X line either. An alternate way of recognizing that this term does not allow field lines to break is that it is not dissipative, so it does not lead to irreversible dissipation. Further, when including the electron inertia term in MHD, the resulting reconnection looks very different than in kinetic simulations.

The second term on the right side is the electron pressure gradient term. In general, even within the fluid model, $\mathbf{p}_e$ is a tensor which can be written in terms of its diagonal and off-diagonal elements. The z component of the diagonal elements in $-\nabla \cdot \mathbf{p}_e/ne$ is only the single term $-(1/ne)(\partial p_{e,zz}/\partial z)$, which vanishes in the simplified 2-D limit in consideration. Note that this is the case whether the electron pressure tensor is isotropic

($p_{e,xx} = p_{e,yy} = p_{e,zz}$), gyrotropic ($p_{e,\perp} \neq p_{e,\parallel}$, where $\perp$ and $\parallel$ are relative to the local direction of the magnetic field), or agyrotropic ($p_{e,xx} \neq p_{e,yy} \neq p_{e,zz}$). Thus, the diagonal part of the electron pressure tensor does not play a role at the X line. (Interestingly, if there is a gyrotropic electron pressure, even though it does not contribute at the X line [*Egedal et al.*, 2013], it can lead to fast reconnection just like the Hall term [*Cassak et al.*, 2015] if there is a component of the magnetic field out of the plane.)

This leaves the off-diagonal elements of the electron pressure tensor. The out-of-plane contribution to **R** is $-(1/ne)(\partial p_{e,xz}/\partial x + \partial p_{e,yz}/\partial y)$, which need not vanish. Particle-in-cell numerical simulations have confirmed that this term is nonzero at the X line [*Hesse and Winske*, 1998; *Hesse et al.*, 1999], so it is the likely term in the fluid description allowing reconnection (in 2-D steady symmetric systems). Physically, the off-diagonal pressure tensor terms, in the fluid sense, correspond to effects of velocity shear and therefore act like a viscosity. As with neutral fluids, viscosity leads to irreversible heating, a requirement for the mechanism for causing field line breaking.

Equation (A2) provides a way to estimate the thickness of the diffusion region in the inflow direction [*Vasyliunas*, 1975], which is useful to predict how close MMS needs to be to an X line in order to see diffusion region physics. For antiparallel reconnection, ideal MHD breaks down when the Hall term becomes important. The length scale at which the magnitude of the convection term is comparable to the Hall term is the ion inertial scale, $d_i = c/\omega_{pi}$, where c is the speed of light and ω_{pi} is the ion plasma frequency. This scale is equivalent to the gyroradius for a particle moving at the Alfvén speed of the upstream plasma. At this scale, ions decouple from the magnetic field, while electrons with their smaller gyroradius remain frozen-in to the magnetic field. This is the approximate scale of the ion diffusion region. Similarly, the location where the electron inertia term becomes a similar size to the Hall term is where the electrons decouple from the magnetic field. Balancing these terms leads to the thickness of the electron diffusion region: the electron inertial scale $d_e = c/\omega_{\rm pe}$, where $\omega_{\rm pe}$ is the electron plasma frequency. For densities of 0.1 cm^{-3} as is typical in the magnetotail, $d_i \simeq 720$ km and $d_e \simeq 17$ km. At the dayside, the relevant length scale associated with d_i [*Cassak and Shay*, 2009] is close to 50 km, with d_e just larger than 1 km. At scales below the electron inertial scale, irreversible dissipation allowing field lines to break occurs, so this is the region of interest for MMS.

Kinetic Physics in the Diffusion Region

Identifying that the off-diagonal elements of the electron pressure tensor is physically what allows an electric field at the X line which therefore allows field lines to break is certainly important — even if only for the simplified system in question – but it is not the whole story. The (collisionless) fluid approach described in the "Fluid Description of the Diffusion Region" section does not describe what physically causes the appearance of nonzero off-diagonal electron pressure tensor elements nor how it leads to dissipation. To understand the cause, the kinetic description of a plasma is required.

In a neutral fluid, the physics causing viscosity requires two things — a non-Maxwellian distribution function and interparticle collisions. It is important to note a subtle and often overlooked point — the same is required in a plasma. Thus, in the purely collisionless limit in which the kinetic physics is described exactly by the Vlasov equation, one can show rigorously that the entropy of the system is conserved. Thus, there is no irreversible heating in the Vlasov model. Formally, it is not a well-posed question to ask what causes dissipation allowing reconnection in a purely collisionless plasma.

However, collisionless plasmas are prone to produce non-Maxwellian distribution functions. In some cases, distribution functions are far from Maxwellian. In such systems, physics that was previously considered ignorable can become important, including kinetic physics ultimately related to collisions. Therefore, in addition to the importance of determining which fluid term describes the dissipation, it is also important to understand what — kinetically — allows field lines to break. This requires understanding what gives distribution functions their structure at and near the X line and what collisional physics governs the evolution of plasmas with non-Maxwellian distributions. By combining the two, one can hope to determine what physically allows field lines to break in "collisionless" systems.

The magnetic field geometry during reconnection is ripe for producing distribution functions that differ greatly from Maxwellian. A particle gyrating around a reversing magnetic field changes direction when it sees an oppositely directed magnetic field [*Speiser*, 1965], producing distribution functions with semicircular structures. Numerical simulations have been useful for investigating distribution functions near the X line [e.g., *Ng et al.*, 2011, 2012; *Shuster et al.*, 2014]. Another important effect setting the distribution function structure near the X line is the bending of the magnetic field both upstream and downstream of the X line [*Egedal et al.*, 2013]. Some particles mirror as they travel in these curved fields, which produces a gyrotropic (anisotropic) distribution function [*Egedal et al.*, 2008; *Le et al.*, 2009]. How information about the structure of the distribution function leads to field line breaking is not yet solved, but the ability of the MMS instruments to measure distribution functions for both ions and electrons at subsecond resolution will help address this physics.

The mechanism allowing reconnection at the dayside magnetopause, which is the subject of Phase I of the MMS mission, may be different from that of the assumed symmetric system discussed here (which is more typical at the magnetotail reconnection site). For reconnection at the dayside magnetopause, there is a bulk flow of plasma through the X line in the reconnection plane [*Cassak and Shay*, 2007; *Murphy et al.*, 2010]. The pressure gradient at the X line tends to be small, so the term in the generalized Ohm's law that is significant is the electron inertia term rather than the electron pressure tensor gradient [*Hesse et al.*, 2014]. If there is a strong enough guide field, it can magnetize the particles in the diffusion region, therefore changing the Speiser orbit structure of the distribution function of antiparallel reconnection. The dissipation mechanism with a guide field was identified as having contributions from both the off-diagonal electron pressure tensor and electron inertia, with the electron heat flux becoming dynamically important [*Hesse et al.*, 2004]. Asymmetric reconnection with a guide field is also complicated by diamagnetic effects [*Swisdak et al.*, 2003; *Phan et al.*, 2013], which cause the X line to move in the reconnection plane and can suppress reconnection entirely. The flow of the solar wind around the magnetopause can also affect the reconnection process [*Cassak and Otto*, 2011; *Doss et al.*, 2015].

Another aspect of kinetic effects in reconnection, with an eye toward the practical consideration of how to know when MMS crosses a diffusion region, is to find measurable quantities that indicate a diffusion region is near. This is necessary because an electric field parallel to the X line is a property of reconnection [*Hesse and Schindler*, 1988], but it tends to be relatively small compared to other electric fields near a reconnection site and there are other mechanisms that produce parallel electric fields, so its identification is potentially difficult or ambiguous. Among many approaches, it was identified that an agyrotropic electron pressure tensor, though not producing an electric field right at the X line, is localized in the region immediately surrounding the X line [*Scudder and Daughton*, 2008]. Recent models have extended this approach [*Aunai et al.*, 2013; *Swisdak*, 2016]. Recently, it was suggested that a Lorentz invariant measure of dissipation could identify diffusion regions [*Zenitani et al.*, 2011], importantly removing contributions from the diagonal parts of the electron pressure tensor. For asymmetric reconnection, it was suggested that an in-plane electric field appears just upstream of the reconnection site [*Malakit et al.*, 2013]. How to best identify the diffusion region in observational data remains an important question, especially in the MMS era.

The high-resolution data collection through MMS is making studies of the diffusion region possible. In order to identify a diffusion region, MMS data of electric and magnetic fields, in addition to bulk properties of the plasma and the distribution functions of ions and electrons will need to be used. The future promises to deliver exciting and important new insights into how magnetic reconnection works.

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