Recent Progress in Understanding Solar Magnetic Reconnection

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Magnetic reconnection is a fundamental process occurring in a wide range of astrophysical, heliospheric and laboratory plasmas. This process alters magnetic topology and triggers rapid conversion of magnetic energy into thermal heating and nonthermal particle acceleration. Efforts to understand the physics of magnetic reconnection have been made across multiple disciplines using remote observations of solar flares and in-situ measurements of geomagnetic storms and substorms as well as laboratory and numerical experiments. This review focuses on the progress achieved with solar flare observations in which most reconnection-related signatures could be resolved in both space and time. The emphasis is on various observable emission features in the low solar atmosphere which manifest the coronal magnetic reconnection because these two regions are magnetically connected to each other. The research and application perspectives of solar magnetic reconnection are briefly discussed and compared with those in other plasma environments.

Keywords: flares, radio emission, X-rays, gamma rays, magnetic fields, energetic particles, particle acceleration

1. INTRODUCTION

Magnetic reconnection is a fundamental process in highly conducting plasmas, during which the magnetic topology is rearranged, and the magnetic energy is rapidly converted to kinetic energy, thermal energy, and particle acceleration (e.g., Kulsrud 1998). This process can occur in various magnetized plasma settings in nature and the laboratory. The longest known example is solar flares, for which magnetic reconnection was proposed as a viable mechanism as early as 1946 (Giovanelli 1946). Both observational evidence and theoretical understanding of this idea have accumulated over the decades (see, for review, Priest & Forbes 2000, 2002; Cassak et al. 2008). Magnetic reconnection in the sun is also a likely contributor to the formation and ejection of coronal mass ejecta (e.g., Gosling et al. 1995; Antiochos et al. 1999) and to coronal heating (e.g., Cargill & Klimchuk 1997). Similar processes are expected to occur in astrophysical plasmas such as stellar chromospheres, coronae and other extreme astrophysical environments (Kulsrud 1995).

In the Earth’s magnetosphere magnetic, reconnection occurs in response to driving by solar wind. It is believed to be responsible for the disturbances in Earth’s magnetosphere such as substorms (e.g., Angelopoulos et al. 2008; Lee et al. 2009) and magnetic storms (Paschmann 2008; Paschmann et al. 2013). Magnetic reconnection can also facilitate the entry of solar wind plasma and electromagnetic energy into the magnetosphere by either low- or high-latitude magnetopause reconnection (e.g., Paschmann et al. 1979; Sonnerup et al. 1981; Hwang 2015), and play a role in the formation of the auroral acceleration region (Atkinson 1978; Haerendel 1987). In the magnetotail lobes, proper magnetic reconnection converts energy stored there to the internal and kinetic energy of plasma. In controlled nuclear fusion, it is one of the mechanisms that prevents magnetic confinement of the fusion fuel. Dedicated reconnection experiments are now actively done to closely reproduce astrophysical plasmas in the laboratory (Yamada et al. 2010, 2014). All these efforts have led to the idea that the physics...
of magnetic reconnection should be studied with a wide range of settings. As a result, a comprehensive classification of magnetic reconnection has been developed in the form of phase diagrams (Ji & Daughton 2011; Daughton & Roytershtein 2012; Cassak & Drake 2013). It now becomes obvious that a complete understanding of reconnection requires a multi-disciplinary approach.

The main issue in magnetic reconnection research is that observed reconnections in nature proceed much faster than predicted by the early magnetic reconnection theory. Sweet (1958) and Parker (1957) presented a two-dimensional (2D) model, in which a current sheet stretches along the boundary between oppositely directed magnetic fields, but the resulting rate of reconnection is much too slow to explain the explosive energy release during a solar flare, for instance. Petschek (1964) presented another framework in which the central current sheet is small and much less elongated, and this mechanism does operate fast enough to explain a flare that proceeds at typically a tenth or a hundredth of the Alfvén speed. Some of the laboratory experiments have attempted to reproduce Petschek’s mechanism without full success yet. It is likely that anomalous resistivity builds up at the current sheet to be much more enhanced when turbulence and kinetic effects are included. However, how collisionless kinetic effects come into effect and how often a sudden onset to fast reconnection initiates remain as challenging problems. For astrophysical applications, we should also consider how small-scale physics interplays with global dynamics and how magnetic reconnection behaves in extreme astrophysical environments such as star formation regions, accretion disks, jets, and interstellar and galactic dynamos.

Solar physicists have made an important contribution to the current understanding of magnetic reconnection in nature through observations of solar flares. A unique advantage of solar observations is that the magnetic structure and its dynamic evolution can be measured with sufficient spatial and temporal resolutions. Another important factor in solar research is that the so-called standard model for two-ribbon solar flares is available. As established by Carmichael (1964), Sturrock (1967), Hirayama (1974) and Kopp & Pneuman (1976), this model (also known as the CSHKP model) provides a unified paradigm which enables direct measurement of the coronal reconnection rate from observables. This has prompted a significant increase in research on solar magnetic reconnection during the last decade. This review will focus on the recent progress achieved with flare solar observations for physical understanding of magnetic reconnection in solar flares.

2. BASIC THEORETICAL ELEMENTS

Magnetic reconnection occurs in a region of a current sheet, or neutral sheet, where magnetic fields of opposite polarity approach to merge. To illustrate, we plot, in Fig. 1, the magnetic field configuration and other physical parameters around the current sheet. In Fig. 1a, the separatrices are shown as dotted lines and the current sheet as the shaded slab centered at the X-point. The vectors $A$, $E$, and $B$ represent the area, electric, and magnetic fields in the current sheet, respectively, used with the following subscripts: $i$ for incoming fields, $o$ for outgoing fields, and $f$ for the footpoint fields. In this configuration, $(B_i, v_i)$ have only an x-component while $(B_o, B_f,$ and $v_f)$ have only a z-component, and for simplicity, we drop the vector component notations for these quantities.

In general the electric field $E$ is contributed by both the convective motion of the magnetic field $B$ and the current density $J$ on the current sheet, and the relation of these quantities is described by Ohm’s law. In the magnetohydrodynamics (MHD) formulation, as appropriate for solar conditions, it is expressed as

$$E = -u \times B + \eta J$$

where $\eta$ is the electric resistivity and $u$ is the velocity of the magnetic field line.

In collisionless plasma, the electric resistivity is infinitesimally small ($\eta = 0$), and the second term is negligible even though there is a finite current density. In this ideal MHD regime, this equation states that magnetic field lines move with the fluid. In resistive MHD plasmas, hydromagnetic flows can lead to the formation of a neutral sheet in which the transverse plasma flow is reduced to near zero, and the electric field $E$ is balanced with $\eta J$ in

![Fig. 1. The magnetic field configurations around the current sheet. (a) Magnetic field, velocity, and area vectors (thick arrows) are shown together with the lengths of the sides of the current sheet (thin arrows). The shaded region represents the cross section of the current sheet in the x-z plane, and the dotted lines are the separatrices. (b) The current sheet and flare ribbon are shown together to illustrate their relationship. (Credit: Lee et al. 2006)](http://dx.doi.org/10.5140/JASS.2015.32.2.101)
equation (1). In this diffusion region, the effect of resistivity becomes sufficiently large that a magnetic field line can lose its original identity and reconnect to another field line. Therefore, \( E = \eta J \) is the quantity of interest in magnetic reconnection. However, there is no way to directly measure this electric field from remote observations.

What solar astronomers can do instead is to utilize a simple relation that exists in the 2D configuration between the rate of reconnection and the motion of the chromospheric footpoints of the separatrices (Forbes & Priest 1984). Because the magnetic field lines swept through by the kernel motion are those connected to the diffusion region at the reconnection point, we can express the electric field at the X-line as

\[
u \times B = u_B
\]  

where \( u \) and \( B \) refer to the velocity and strength of the incoming magnetic field lines to the diffusion region; \( u \) is the apparent velocity of the separatrix footpoint, and \( B \) is the vertical magnetic field at the location.

It is often stated without justification why equation (2) can replace equation (1). In the current sheet, the electric field is \( E = \eta J \) and outside of the current sheet \( E = -u \times B \). These two quantities should be in rough balance with each other in order to maintain the X-line configuration. It is very hard to measure either \( u \) or \( B \) (cf. Yokoyama et al. 2001). However, their product and thus, their counterpart in the footpoint, \( u \times B \), can directly be measured from solar images. By Faraday’s law, this quantity is equivalent to the magnetic flux change rate per unit length. Furthermore, by multiplying the length of the ribbon, we can determine the magnetic flux change rate associated with magnetic reconnection. For this reason, we call it the coronal magnetic reconnection rate and denote it simply by \( u_B \) hereafter.

The above-defined coronal reconnection rate is weighted by the magnetic field and is large for a large flux system. The quantity representing the reconnection efficiency regardless of dimension called the dimensionless magnetic reconnection rate is defined by the ratio of the inflow speed to the outflow speed from the diffusion region. Because the latter is given by the local Alfven speed, \( V_A \), it is given by

\[ M = \frac{u_f}{V_A} \]  

According to the RCS geometry shown in Fig. 1a, this ratio is, in fact, simply the aspect ratio of the RCS, which in turn, corresponds to the definition of the reconnection rate \( M \) (Petschek 1964): \( M = L / L_c = |B_y / B| < 1 \). In fact, \( M \) is very small on the order of \( 10^{-5} \) – \( 10^{-4} \) for the Sweet-Parker type reconnection and \( 10^{-3} \) – \( 10^{-2} \) for the Petschek type reconnection. In other words, the shaded box in Fig. 1 is very slim and elongated for the former and moderately slim for the latter. Determining the value of \( M \) is therefore a crucial step toward identifying which mechanism dominates in a given magnetic reconnection process.

Another useful quantity is the magnetic energy release rate. Because both electric and magnetic fields are present, we can calculate the Poynting flux, \( S = (c/4\pi) (E \times B) \), under this paradigm (Isobe et al. 2005). Noting also that the Poynting flux in this case is the electromagnetic energy passing through the current sheet per unit area and time, we can further calculate the energy release rate by multiplying the Poynting flux by the area of the diffusion region. In the simplest form of the standard model, reconnection occurs on the X-line, and the concept of area of the diffusion region is missing. Lee et al. (2006) presented a modified framework to enable this calculation shown in Fig. 1b. In this setting, total electromagnetic energy change solely due to the Poynting fluxes coming from both sides into the current sheet is then expressed by

\[
\frac{\partial \varepsilon}{\partial t} = -\frac{2 |u_f B_f A|}{\pi M}
\]

where \( \varepsilon \) is the total electromagnetic energy. To claim this quantity as the energy release rate in the current sheet, it should be that most of the incoming energy flux \( (S_A \) is consumed inside the current sheet and the outgoing energy flux \( (S_A \) carries a negligible amount of energy. Lee et al. (2006) showed that this approximation holds when the reconnection is efficient, as is often the case.

3. SOLAR MAGNETIC RECONNECTION

In this section we review the studies on magnetic reconnections using solar flare observations. Traditionally filtergrams from the Big Bear Solar Observatory (BBSO) have provided high quality Ha images that are used to locate flare ribbons. Coronal images at UV and EUV wavelengths are useful indicators of coronal magnetic field lines and thermal heating, which have been obtained from the Transition Region and Coronal Explorer (TRACE), the Coronal Diagnostic Spectrometer (CDS) and Extreme ultraviolet Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory (SoHO). Magnetic field information is obtained from both the BBSO magnetograms and the SoHO Michelson Doppler Imager (MDI)
magnetograms. In addition, the Hard X-ray Telescope (HXT) and Soft X-ray Telescope (SXT) aboard Yohkoh, the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and the Owens Valley Solar Array (OVSA) have been used to provide information on high energy electrons accelerated during flares. With these data, solar physicists were able to determine the coronal magnetic reconnection rate (eq. [2]) to advance our basic understanding of magnetic reconnection in two-ribbon eruptive flares. Major topics addressed by such studies are discussed below.

3.1 Coronal Reconnection Rate and Hard X-ray lightcurves

The first task of finding evidence for the standard reconnection model was to verify whether the the quantity uB shows a temporal correlation with any high-energy flare radiations. As an earlier work in this line, Qiu et al. (2002) studied high-cadence and high-resolution Hα observations of an impulsive flare to determine a systematic kernel motion and relate them to the reconnecting current sheet in the corona. They found that the velocity of the kernel motion is as high as 20–100 km s\(^{-1}\), which yields, together with the BBSO magnetograms, an electric field as high as 90 V cm\(^{-1}\) at the flare maximum. This is a much stronger electric field than the previously cited value on the order of ±10 V cm\(^{-1}\). This could be a useful finding because a higher cadence and spatial resolution were used in that observation. Searching for a similarity between the ribbon motion and the hard X-ray lightcurves from Yohkoh/HXT was only partly successful.

There were two types of motions: one moving along the field strength gradient and the other moving along the isogauss contour of the longitudinal magnetic field. For the former type of kernel motion, the temporal variation of the electric field inferred from it is correlated with 20-85 keV hard X-ray light curves during the rise of the major impulsive phase in support of the standard reconnection model. However, there is no such correlation for the latter type of motion. This raised a question whether the high electric field obtained in that study is due to the high time cadence and spatial resolution of the data or to an overestimation by including an irrelevant component of motion altogether. Many follow-up studies after this focused on the non-standard behaviors of flare ribbons or kernels, as further described in the next section.

3.2 Parallel Component of Footpoint Motions

The subsequent debate on the contradictory behaviors of ribbon motion to the standard 2D model was centered on how to interpret the motions parallel to the PIL, while in the standard model, we should see only the ribbon motion perpendicular to the nearest point in the PIL. For convenience, we call it simply parallel motion. Grigis & Benz (2005) studied RHESSI observations that exhibit continuous motions of double hard X-ray sources which can be regarded as footpoints of magnetic loops. It, however, moves parallel to the PIL, as opposed to the standard model. This means that the observed flare elements are not a modulation of the reconnection process but originate as this process progresses along an arcade of magnetic loops. Neither did the footpoint motion correlate with the hard X-ray flux to contradict the predictions of the standard reconnection model. Another new feature of footpoint motion was reported by Fletcher et al. (2004) in which groups of UV footpoints on TRACE images move as the flare progresses, which defines flare ‘ribbons’. This ribbon emission is spatially non-uniform, maybe even discrete. They tracked individual bright kernels within the flare ribbons and applied this to a flare observed by TRACE in the 1600 Å passband at 2-s cadence. In this event, the footpoints have an average speed of 15 km s\(^{-1}\), with a superposed random component, consistent with the footpoint magnetic field being anchored around the edges of granular cells. The peaks in UV brightness is temporally correlated with the peaks in the product of the footpoint speed with the coronal reconnection rate as calculated from equation (2). Even at Hα, the parallel motions are commonly visible. This phenomenon had not received much attention until Lee & Gary (2008) presented an event of Hα ribbons whose parallel motion shows good correlation with the hard X-ray emission. The correlation was argued as evidence for the standard model, but with a modification of the model to allow the reconnection region to increase in length, a feature missing from the standard 2D model. Under this simple modification of the 2D standard model, they were able to (i) incorporate the parallel motion into the estimation of the magnetic reconnection rate, (ii) explain why a fast change in the coronal area does not necessarily result in a larger increment in the chromospheric width, and (iii) explain why hard X-ray light curves are more impulsive than those deduced solely by perpendicular Hα ribbon motions in some events.

3.3 Spatio-temporal Properties of Flare Ribbons

While the dynamic behavior of flare ribbons should be the main source of information on the coronal magnetic reconnection, determining the dynamic properties turned out to be far from straightforward. In the simplest treatment, the coronal reconnection is assumed to occur on the X-line so that energetic particles precipitating along the field lines produce only a line-shaped ribbon in the chromosphere.
The displacement and reshaping of this line should be all that needs to be measured. In reality, the actual ribbons appear in a more complicated form with a finite area, and its shape keeps changing with time in all directions. Asai et al. (2004) proposed to use only the leading edge of the expanding ribbon and the velocity component perpendicular to the local PIL for consistency with the standard theory. Jing et al. (2005) used an algorithm to compute a vector average of the velocities determined from the incremental change in area per unit time. Lee et al. (2006) used the center-of-mass location that appears to be more appropriate for isolated flare kernels. This helps avoid any peculiar velocities due to expansion or shrinking of the area that can be confused with the mean velocity. Fig. 2 shows the flare kernel at selected time intervals (left panel) and the locations of the centers of mass at multiple times as colored filled circles (right). Points concentrated within a narrow region signify that the ribbon is more or less stationary in that region, and the gaps between groups of concentrated points correspond to the locations where the ribbon speeds up under the enhanced magnetic flux reconnection, and thus, the ribbon motion is not uniform but rather stepwise. Fig. 3 shows the center-of-mass location of the ribbon (cross symbols) as a function of time together with solid guide lines showing the speed determined at selected time intervals. The first stepwise motion, for instance, occurs around 7:43:30 UT at which time the ribbon is advancing about 5 arc sec in ~20 s achieving a speed of ~160 km s\(^{-1}\) (see the solid guide lines indicating the speed). Other stepwise motions also incur high velocities ranging from 60 to 220 km s\(^{-1}\), much higher than the typically reported ribbon velocity which is a few tens of kilometers per second (Jing et al. 2005). Another fit to the average motion over the whole period of the flare activity leads to an overall speed of only ~18 km s\(^{-1}\) (shown by the thick guide line marked as \(t_{\text{ub}}\)). These stepwise motions do agree, in timing, with the multiple peaks of the hard X-rays, and led to the conclusion that the ribbon motion is faster than previously thought and highly intermittent in time and space.

### 3.4 Implications of Elementary Magnetic Reconnection

Solar flare emissions often exhibit fine temporal structures, especially at hard X-ray and radio frequencies emitted by high energy electrons. This led to the idea that a flare as a whole is a superposition of numerous elementary bursts. It is of interest how to incorporate the concept of elementary bursts into the standard reconnection model. The afore-mentioned works help to some extent because \(u_B\) evolves in a discrete manner both spatially and timely. Grigis & Benz (2005) studied hard X-ray footpoint motion along a magnetic arcade and found them to be discrete on a time scale of some tens of seconds. They regarded the hard X-ray footpoint motions to indicate the temporal evolution of many distinct emission peaks and called them hard X-ray elementary bursts, which are then interpreted as instabilities or oscillations of the reconnection process leading to an unsteady release of magnetic energy. The elementary nature of magnetic reconnection was also clearly demonstrated by Fletcher et al. (2004) who showed that at the UV wavelengths, solar flare emission consists of small isolated elements at a time, and each element obeys the standard model prediction. In this case, a flare ribbon is defined by a group of UV footpoints that move altogether as the flare progresses. Lee et al. (2006) showed that even at the H\(\alpha\) wavelength, the footpoint motion can be discrete using the high cadence and high resolution data of BBSO. This is, of course, unclear at the H\(\alpha\) centerline but found

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Fig. 2. Areas of flare kernels at four selected time intervals (left) and their time-stamped locations (right) determined from the high-cadence BBSO H\(\alpha\) blue-wing images during the 2002-Sep-09 flare (adapted from Lee et al. 2006).

Fig. 3. The distance of the center-of-mass of the ribbon (symbols) as a function of time during the event on 2002/09/09. Five time intervals where the distance rapidly increases are marked with solid red guide lines along with the inferred speeds. Another fit to the overall motion in the entire period is also shown as a thick line for comparison (adapted from Lee et al. 2006).
at the Hα off-band, where the emission is more sensitive to high energy electron precipitation. These elementary motions show good correspondence to individual peaks in the hard X-ray lightcurves in a flare, and may indicate the repetition of a cycle consisting of intense reconnection (speed up) and relaxation (speed down). Stepwise motion reflects the intermittent reconnection rate which in turn implies the sudden onset of anomalous resistivity and rapid decay in the diffusion region. An important question that needs to be addressed in this context is whether the intermittent behavior of the coronal reconnection rate, \(uB\), is due to the flow speed \(u\) or magnetic field \(B\). As shown in Fig. 4, it turns out that it is not \(B\) but \(u\) that coincides with the multiple peaks of the hard X-ray lightcurves. They argued that this result supports the pulsating current sheet model (Kliem et al. 2000) which explains multiple emission peaks in a solar flare in terms of a self-organized cycle of current instability.

### 3.5 Area of Reconnecting Current Sheet

In the simplest form of the standard model, the reconnection occurs in the X-line, and in principle, its chromospheric counterpart should also be a line consisting of footpoints. In reality, a flare footpoint has a finite area which is changing in time. However, it was unclear whether the width implies the coronal reconnection occurs over a finite area (i.e., extended Y lines) or is simply due to the finite cooling time of the footpoint radiation. This issue did not receive much attention therefore. However, it turned out that the finite area of the coronal current sheet is an essential element in the reconnection theory. First, the pulsating current sheet model that explains the observed episodic time variations of the hard X-ray peaks is based on the interplay between the build-up of the current density due to anomalous resistivity and its relaxation due to the increased area of the current sheet. Second, the area of the reconnecting current sheet in the corona provides a way to determine the amount of energy released during the reconnection from the electromagnetic Poynting flux on the current sheet. An observational requirement is that the ribbon radiation should represent only the instantly illuminated chromospheric part connected to the coronal diffusion region. Hα centerline images are certainly inadequate for this use because they retain the previously heated areas to some extent. The results shown in Fig. 5 are obtained by applying the technique introduced in Section 2 to the ribbon images obtained at the Hα blue wing. Not only the velocity but also the kernel area shows episodic variation, which clearly supports the pulsating current sheet model (Kliem et al. 2000); however, the RCS area can, at least, be involved in a self-organized evolution, in such a way that an increase in current density and thus, anomalous resistivity (Huba 1985) makes the RCS area expand, leading in turn to a decrease in the current density. A series of such self-organized cycles would, in this view, produce the multiple peaks in the X-ray/microwave light curves as observed. The amount of energy estimated under this theoretical formulation well agrees with that deduced from the RHESSI hard X-ray spectra. The concept of the ribbon area as a dynamic quantity therefore not only provides a way to determine the amount of energy released but also provides physical insight into the dynamical evolution of the coronal reconnection.

### 3.6. The Ribbon-like Hard X-Ray Emission

Although Hα ribbons’ shape and motion are the main elements for the standard model, the ribbon structure had not been observed in the Hard X-rays for a long time. Absence of the hard X-ray ribbons had remained a mystery until recently. Asai et al. (2002) first addressed this issue in terms of the coronal magnetic reconnection rate. They argued that the hard X-ray source is located in places of locally strong magnetic fields, which therefore corresponds...
to the local maxima of $uB$ or $uB^2$. Implication of this argument is that the hard X-ray ribbons may be found if the sensitivity of instruments improves. This finding of the hard X-ray source in the stronger magnetic field section of the Hα ribbons has been further discussed as evidence for the standard model (Asai et al. 2002; Miklenic et al. 2007; Temmer et al. 2007). Later, the ribbon-like hard X-ray source was indeed discovered by Liu et al. (2007) during a study of a flare (the 2005 May 13 flare) from a sigmoid type active region at energies as high as 25-100 keV with the RHESSI observations. The images of the ribbon-like hard X-ray emission at selected time intervals are shown in Fig. 6. Jing et al. (2007) further analyzed the hard X-ray intensity distribution observed along the Hα ribbons. The results of the study are selectively reproduced in Fig. 7. The upper panels show the 25-50 keV RHESSI images (contours) on top of the inverse Hα images from the Optical Solar Patrol Network (OSPA). The two frames shown here correspond to before and after the flare maximum, respectively. The bottom panels show $B$ and $B^2$ which are taken as proxies for the local reconnection rate and for the energy release rate (green and blue curves, respectively), against the hard X-ray 25-50 keV intensity (red curve), as functions of the ribbon distance index $j$ as defined in the upper panels.

In the early phase, there are two footpoint hard X-ray sources located in regions with a strong magnetic field. After the flare maximum phase, the elongated ribbon-like hard X-ray sources show up, lacking spatial correlation with the magnetic field. With these examples alone, it was unclear whether there is a conflict between the theory and this observation and why the ribbon-like hard X-ray sources are so rare. This 2005 May 13 flare is the only event ever reported for the ribbon-like hard X-ray structure; it is classified as a 2B/M8.0 flare and thus, not among the strongest events of hard X-rays. One property to note in this regard is that it is at and after the flare maximum phase that the hard X-ray sources become spatially extended to resemble Hα ribbons in morphology. In the early phase of the flare, the hard X-ray sources appear to be concentrated in strong field sections within the Hα ribbons, as suggested by Asai et al. (2002). Shown in Fig. 8 are three possible scenarios considered in an attempt to explain why the ribbon-like hard X-ray (R-HXR) source is so rare within the paradigm of the standard 2D model. Scenario A depicts that the 3D magnetic arcade is a stack of 2D structures which are independent of each other. The ribbon sections with a stronger magnetic field are connected to the coronal parts with a higher energy release rate to become brighter hard X-ray sources that are locally confined. Scenario B advocates the 2D model at the cost of introducing another mechanism for particle redistribution along the arcade axis, which should then occur more commonly. Scenario C arguably is

![Fig. 6](https://example.com/fig6.png)

Fig. 6. A time sequence of the RHESSI 50-100 keV images. The peak flux in each image is labeled, and the green contours show flux at levels of 0.018, 0.02, and 0.022 photons cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. 6-12 keV image with yellow contours at levels of 50%, 70%, and 90% of its maximum flux. The white contours outline the TRACE 1600 Å ribbons. (Credit: Liu et al. 2007)
the most plausible because it requires an uncommon type of magnetic reconnection such as the sigmoid-to-arcade transformation seen in this event. This suggests that the ribbon-like hard X-ray structure may be associated with the sigmoid-to-arcade transformation.

### 3.7. Electric Field and Hard X-Ray Spectral Index

An important bi-product of the standard model is the particle acceleration because the strong electric field at the reconnection site will directly accelerate charged particles at least. There is no problem with the DC electric field in producing high enough particles because typical electric field strength is $10 \, \text{V cm}^{-1}$ along the X-line in two dimensions or a separator in three dimensions. This is not only much larger than the typical Dreicer field (of about $10^{-4} \, \text{V cm}^{-1}$) to overcome the Coulomb drag, but accelerates the charged particles to an energy high enough to account for the gamma rays and hard X-ray bursts as long as the field sustains a typical diameter of an active region. It is, however, conceivable that a charged particle would run only a small portion of the current sheet before deflected away from the CS, for which the size depends on the transverse magnetic component in the current sheet (Litvinenko 1996). What seems important from the observational viewpoint is whether the electric field deduced from the footpoint motions correlates with any particle acceleration features. Liu et al. (2008) investigated this problem using observations of 7 two-ribbon flares. The hard X-ray spectral index was calculated from the spectral data of RHESSI and Yohkoh/HXT, and the coronal reconnection...
rate, $uB$, was calculated from the Hα ribbon motions and line-of-sight magnetograms of the BBSO, Optical Solar Patrol Network (OSPA), and MDI/SoHO. One of their results is partly reproduced in Fig. 9, which shows an anti-correlation between the hard X-ray spectral index and the electric field. This result is, at least, consistent with the hypothesis that the DC electric field is a dominant mechanism that accelerates high-energy particles during solar flares. We should, however, note that DC field acceleration is not the only mechanism to be supported by the above result. Particle acceleration by shocks is also possible because slow-mode shocks are attached to the diffusion region and a fast-mode shock often exists below an outflowing reconnection jet (Tsuneta & Naito 1998). A highly turbulent environment may exist both in the diffusion region and in the outflowing jets and thus, may give rise to stochastic acceleration. Possible agents for stochastic acceleration are Alfvén waves from many reconnection sites for ion acceleration (Miller et al. 1997) and whistler waves for electron acceleration (Miller & Ramaty 1992; Hamilton & Petrosian 1992). All these competing mechanisms can also be enhanced at the time of a stronger reconnection. For this reason, it may be premature to conclude that the correlation should be taken as evidence for the DC field acceleration only.

3.8. Visibility of the Current Sheet

Although ribbon motions relative to the PIL provide a strong support for the standard reconnection model, they are only circumstantial. A cusp-shaped dimming region located above the post-flare arcade during the decay phase in EIT and a signature of chromospheric evaporation seen during the decay phase with the Coronal Diagnostic Spectrometer (CDS) onboard SOHO also provide a complementary view of the reconnection geometry and dynamics in the sun. It is, however, yet desirable to be able to image the reconnection site itself in the corona. The X-ray images obtained from the HXT and the SXT on Yohkoh have provided several features suggestive of a reconnection site in the corona including a hard X-ray source located above the soft X-ray loops (Sakao et al. 1992; Masuda et al. 1994; Bentley et al. 1994), cusp structures caused by either an X-type or a Y-type neutral line (Acton et al. 1992; Tsuneta et al. 1993; Doschek et al. 1995), and high-temperature plasma along the field lines mapping to the tip of the cusp (Tsuneta 1996). An X-ray piece of evidence for the formation of a large-scale current sheet in a flare was presented by Sui & Holman (2003) observed by the RHESSI on 2002 April 15. The hard X-ray features that they found would correspond to both ends of a Y-shaped magnetic configuration, with no features for the middle current sheet region itself. This is expected to some extent because the density there is not high enough to make it visible. Some of the cusp-shaped loops observed by Yohkoh have a linear, trunk-like feature which extends from the top of the cusp all the way down to the inner arch of the flare loop system. The hottest regions in the loop system, however, do not lie in the trunk feature but along the edges of the cusp formed by the outermost loop (Tsuneta 1996). Liu et al. (2010, 2011) reported the presence of a distinctly bright sharp EUV bright feature above the cusp-shaped flaring loop imaged during the flare rising phase with the EIT/SoHO, and identified it with the current sheet formed due to the stretch of a transequatorial loop system imaged during the flare rising phase with the EIT/SoHO. By identifying the current sheet with bright EUV features, we now have a comprehensive view of the reconnection geometry and dynamics in the solar corona as well as various reconnection signatures.

4. CONCLUDING REMARKS

We have presented a review of magnetic reconnection studies from the perspective of solar physics, while other progress in understanding magnetic reconnection has occurred in space physics and laboratory experiments as well. A brief comparison of solar research results with those in the latter fields would be appropriate. Recently, the magnetic reconnection process in the Earth’s magnetosphere was studied with the data from the Time History of Events and Macroscale Interactions during Substorms (THEMIS). The outstanding results include the orientation, velocity, and structure of a reconnection region, electron diffusion signature, and asymmetric magnetic reconnection in
the dayside Earth magnetosphere as well as a moving dipolarization front after a substorm in the night side (e.g., Angelopoulos et al., 2008; Paschmann et al., 2013). It was then realized that the thickness of the current sheet is of the order of the ion gyroradius typically 100-200 km in the magnetosphere and 1000-2000 km in the magnetotail. In this case, the reconnection dynamics cannot be described by the conventional MHD theory of reconnection, and the two-fluid and kinetic approach should be used. NASA’s Magnetospheric Multiscale (MMS) mission is designed to address these required measurement capabilities, and science support for the mission is underway (Hesse et al., 2014).

Magnetic reconnection has also been studied experimentally in well-controlled, 2D laboratory plasma. For instance, an early result from the Magnetic Reconnection Experiment (MRX) at the Princeton Plasma Physics Laboratory (PPPL) was found to be both qualitatively and quantitatively consistent with the generalized Sweet-Parker model with the effective resistivity significantly enhanced over its classical values in the collisionless limit (Ji et al., 1999). Since then, more institutes participate in this type experiment to explore astrophysical problems in the laboratory. The latest result from the MRX team shows that 50% of the magnetic energy is converted to particle energy, of which two thirds are transferred to ions and the rest goes to electrons (Yamada et al., 2014). This can be regarded as an important step toward resolving one of the most important problems in magnetic reconnection physics.

Both space-borne and laboratory experiments can utilize in-situ measurements of local plasma flows and magnetic field change to directly address the kinetic physics of magnetic reconnections that are not accessible with solar observations. However, solar research has several advantages and merits of its own. First, solar magnetic reconnection can adequately be addressed with the MHD approximation as described in Section 2. Although not covered in this paper, many MHD-based theoretical concepts and tools have been developed to address the 3D nature of solar magnetic reconnection (Priest & Forbes, 2002; Hesse et al., 2005). Second, the sun’s proximity allows us to resolve the magnetic structure and its dynamic evolution through remote observations. Magnetic reconnection can be explored in other astrophysical settings such as stellar flares and star forming regions; however, spatially resolved observations are available only for the sun. Finally, the direct measurement of the coronal reconnection rate is envisioned under the standard model for two ribbon flares, as reviewed in Section 3. This has prompted numerous empirical approaches to understand solar magnetic reconnection.

In addition to its general contribution to this multidisciplinary science, solar research has its own goals as follows: (1) understanding how solar magnetic reconnection proceeds helps to explain not only flare energy release but also coronal heating and coronal mass ejecta. (2) By investigating the patterns of solar magnetic reconnection, we can learn how reconnection in large systems is connected to small structures such as multiple X-lines, plasmoids and plasma turbulence. (3) Solar patrol observations provide an opportunity to determine how impulsive and rapid reconnection develops in relatively quiescent plasmas. Especially, the ability to predict the onset of magnetic reconnection in nature is important in the context of the sun-earth connection because they affect the near earth environment. Currently, even higher quality solar data are accumulated provided by the Atmospheric Imaging Assembly (AIA), magnetograms from Helioseismic, and the Magnetic Imager (HMI) onboard the Solar Dynamic Observatory (SDO) which is replacing SoHO. With the ever-increasing imaging capabilities of solar instruments, solar magnetic reconnection will continue to be one of the most active research areas of astrophysics that pursues fundamental research in coordination with space plasma physics and laboratory plasma experiments.

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In the Solar corona, magnetic reconnection plays a crucial role in the acceleration of electrons and ions, leading to various phenomena such as flares and coronal mass ejections. The reconnection process involves the tearing of magnetic field lines and the creation of new magnetic field configurations. This process is often studied in the context of current sheet models, where the magnetic field lines are stretched and then released, leading to the formation of energetic particles.

The dynamics of magnetic reconnection are complex and involve a variety of physical processes. One of the key aspects is the role of non-ideal plasma effects, such as collisions and heat conduction, which can significantly affect the reconnection rate and the resulting particle distribution. Recent studies have focused on understanding the role of these effects in solar flares and coronal mass ejections.

Theoretical models of magnetic reconnection, such as the Sweet-Parker and Petschek reconnection models, have been instrumental in providing insights into the reconnection process. These models are based on the ideal MHD equations and have been successful in reproducing many of the observed features of solar flares.

Experimental studies of magnetic reconnection in laboratory plasmas and in the Earth's magnetosphere have also provided valuable insights. For example, experiments in the NASA's Magnetospheric Multiscale Mission have allowed researchers to study the reconnection process in real-time, providing new perspectives on the dynamics of magnetic reconnection.

Overall, the study of magnetic reconnection in the solar corona is a rich and active field of research, with many open questions and exciting opportunities for future discoveries.
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