Exploring the Role of Magnetic Reconnection in Solar Eruptive Events

Jiong Qiu
Physics Department, Montana State University, Bozeman MT 59717-3840, USA

Abstract. We summarize our recent progress in investigating the role of magnetic reconnection in solar eruptive events consisting of flares, Coronal Mass Ejections (CMEs), and/or Magnetic Clouds (MCs). The rate and total flux of magnetic reconnection in low-corona are inferred from flare observations and compared with kinematic properties and magnetic flux budget of erupting flux ropes. The results and their physical implications are discussed.

Keywords: Sun: activity–Sun: flares–Sun: coronal mass ejections–Sun: magnetic reconnection

1. Introduction

Flare observations in the past few decades have lent support to the so-called standard flare model, also widely known as CSHKP model (see Priest & Forbes 2000 for review). The model is most successful in interpreting multi-wavelength observations of dynamic two-ribbon flares, in which two flare ribbons in the chromosphere spread away from each other and from the magnetic polarity inversion line (PIL), accompanied by rising and cooling post-flare loops observed in the corona. These have been regarded as signatures of progressive magnetic reconnection in an organized manner at the corona and subsequent energy transport downward.

Based on the macroscopic picture of reconnection in the standard flare model, Poletto & Kopp (1989) first derived the coronal reconnection rate in terms of reconnecting electric field E_{rec} by tracing flare ribbon expansion in the chromosphere and compared E_{rec} with flare light curves. This practice is revived a decade later by a few groups employing new-generation flare observations (Isobe et al. 2002, 2005, Fletcher & Hudson 2001, Tarbell et al. 2003, Qiu et al. 2002, 2004, Fletcher et al. 2004, Jing et al. 2005, Qiu & Yurchyshyn 2005, Qiu 2006). Most recently, RHESSI observations of evolution of loop-top and foot-point hard X-ray sources provide another line of support to the idea that instantaneous energy release in flares is a direct response to coronal magnetic reconnection (Sui et al. 2004, Krucker et al. 2005).

We have inferred magnetic reconnection rate and total reconnection flux from lower-atmosphere flare observations and explored the role of magnetic reconnection in large-scale solar eruptive events. These are related in the following sections.

2. Magnetic Reconnection and Flare Energy Release

Forbes & Priest (1984) considered the instantaneous coronal magnetic reconnection rate $\varphi_{rec} \equiv \partial\Phi_{rec}/\partial t$ to be equivalent to the amount of magnetic flux encompassed by newly brightened flare patches in the lower atmosphere per unit time. In other words, $\varphi_{rec} = \partial(\int B_l dS_l)/\partial t$, where dS_l denotes the newly brightened area and B_l is the normal component of magnetic fields at the locations of flare patches in the lower atmosphere, which are believed to map the foot-points of field lines reconnecting at the corona. The relation reflects the conservation of magnetic flux from the coronal reconnection site to the lower-atmosphere energy deposit site and is suitable to describe magnetic reconnection rate in a general configuration. With a 2D approximation, i.e., when there is a translational symmetry along the current sheet (or the length of the flare ribbons), this relation is reduced to $E_{rec} = V_{rib} \times B_l$, where E_{rec} is the electric field in the coronal reconnecting current sheet and V_{rib} is the ribbon expansion velocity perpendicular to the current sheet or PIL.

We have inferred the magnetic reconnection rate in terms of both E_{rec} and φ_{rec} in half a dozen events and compared these measurements with flare non-thermal emissions (Qiu et al. 2004, Qiu 2006). The results show that the time profiles of independently measured E_{rec} and φ_{rec} are consistent with each other, both being temporally correlated with hard X-ray and/or microwave time profiles (though an exception case is also shown in Qiu 2006). The agreement between E_{rec} and φ_{rec} reflects valid approximation of the studied events to the 2D configuration, and the temporal correlation between reconnection rate and non-thermal emissions can be viewed as evidence of instantaneous energy release by reconnection.

It is also noted that the time profile of E_{rec} usually exhibits more variations as a result of both enlarged measurement uncertainties and errors, particularly in determining V_{rib}, and inhomogeneity in the coronal reconnection configuration, i.e., deviation of the real configuration from the ideal 2D assumption. The second effect is especially interesting noting that variations in E_{rec} are sometimes correlated with multiple non-thermal emission peaks (see Figure 3 in Qiu et al. 2004). This may be related to the long standing puzzle in two-ribbon flares, namely, the scarce observation of hard X-ray two-ribbons in spite of abundant Hα two-ribbons. It is usually understood as a consequence of inhomogeneous energy release or particle acceleration determined by the geometry of coronal magnetic fields, and observational effort is greatly needed to shed insight to this problem (e.g., Isobe 2002, Fletcher et al. 2004, Lee et al. 2005).

3. Acceleration and Formation of Magnetic Flux Ropes

The relationship between flares and CMEs has been in heated debate for decades, and recent observations have demonstrated that the timing relationship between flare emissions and velocities of *fast* CMEs is much closer than previously thought. Lately we further illustrated a temporal correlation and magnitude scaling relationship between early-stage flux rope acceleration and the rate of magnetic reconnection inferred from flare observations (Qiu et al. 2004; Jing et al. 2005). Figure 1a is reproduced from Qiu et al. (2004) and shows a most typical example with evidently correlated CME-filament acceleration profiles and reconnection rate. Note that in this figure, the filament height is measured from EIT coronal observations and from LASCO C2-C3 observations beyond the solar limb. Such temporal correlation argues for the importance of magnetic reconnection in the early-stage flux rope acceleration. Additionally, it is found that the CME travels much faster than the trailing filament, indicating expansion of the flux rope along with its eruption. Therefore, the difference height profiles between the filament, which is thought to reside at the bottom of the flux rope, and the CME, which refers to the front of the ejecting flux rope, provide useful information to study the expansion of the flux rope as shown in Figure 1b. In the standard configuration, coronal magnetic flux, amounting to 10^{21-22} Mx (Figure 1b), can be transported into the expanding flux rope through magnetic reconnection.

Our study also reveals a weak magnitude scaling pattern between the maximum reconnection rate and filament acceleration (Jing et al. 2005). The relationship with CME acceleration is not conclusive, because CMEs at the major acceleration stage are not observed. We take an alternative approach (Qiu & Yurchyshyn 2005; Qiu 2006) by comparing the time integrated reconnection rate, i.e., the total reconnection flux, with velocities of CMEs observed by LASCO C2 and C3. Most CMEs observed at this stage no long exhibit acceleration, thus their average velocities during this stage reflect the maximum velocities they have gained by acceleration ever since the take-off. We present the result of 18 events (including the 13 events shown in Qiu & Yurchyshyn 2005) in Figure 2a showing that the total reconnection flux Φ_{rec} is scaled with CME velocities V_{cme}, with a cross-correlation coefficient of 0.73

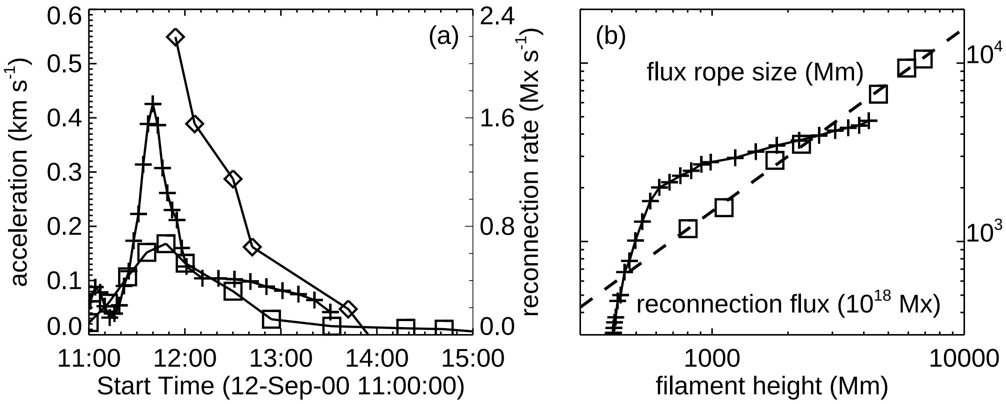

Figure 1. (a) Time profiles of CME (diamond) and filament (square) acceleration (left scale) and reconnection rate (cross; right scale). (b) Estimated flux rope size and instantaneous reconnection flux versus the filament height. The dashed line gives the least-square fit to the flux rope size versus filament height in logarithmic scale.

in linear scale or 0.75 in logarithmical scale. This result provides an indirect evidence that the greater reconnection rate is related to the larger CME acceleration. Noteworthily, in this figure, events with or without filament eruptions do not exhibit different patterns, indicating that the total reconnection flux is crucial in the kinematics of flux ropes regardless of specific source region configurations.

The total reconnection flux involved in the early stage of flux rope eruption bears more significance than its impact on the kinematics of flux ropes, as solar magnetic flux may be also transported via reconnection into the erupting magnetic flux, contributing to interplanetary magnetic flux budget. Magnetic flux ropes observed at 1 AU are called Magnetic Clouds (MCs), and a few compelling cloud-fitting models have utilized the in-situ MC magnetic field and/or plasma measurements to retrieve important parameters, such as magnetic structure, flux, and helicity, of these interplanetary flux ropes (Riley et al. 2004). We apply the Grad-Shafranov cloud-fitting algorithm (Hu & Sonnerup 2002) to in-situ MC observations by ACE, and compare the computed magnetic flux inside MCs with the total reconnection flux for events in which association between flares, CMEs, and MCs is identified. As shown in Figure 2b (reproduced from the results by Qiu & Hu 2006), this new study yields a proportionality between the total reconnection flux and poloidal component of MC flux with their ratio being close to unity, suggesting that the magnetic flux budget in the interplanetary flux rope is highly relevant to low-corona magnetic reconnection in the

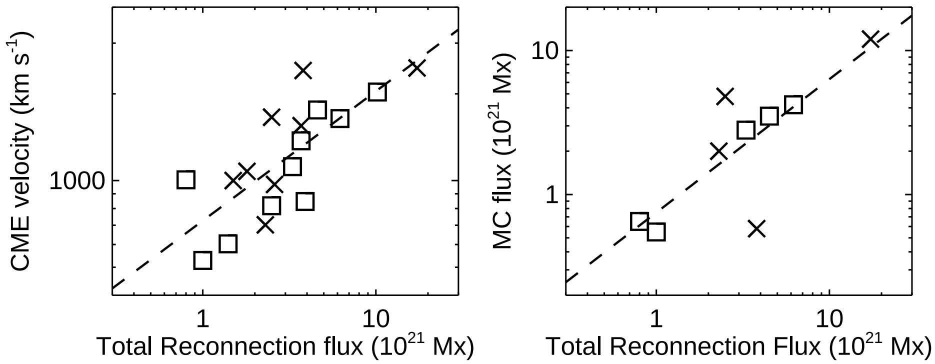

Figure 2. (a) Velocities of CMEs versus total reconnection flux for 18 events. The cross and square symbols indicate events with and without filament eruption, respectively. (b) Poloidal magnetic cloud flux versus total reconnection flux in low-corona for 9 events. In both panels, the dashed line gives the least-square fit to the data pairs in logarithmic scale.

studied events. The poloidal component of MC flux is equivalent to the amount of twisted magnetic flux inside the flux rope, thus the revealed relation implies that the helical structure of magnetic flux ropes in these events be largely *formed in-situ* by magnetic reconnection other than *pre-existing* in the solar atmosphere before expulsion of the flux rope into interplanetary space (Qiu & Hu 2006; Longcope et al. 2006).

4. Summary

Magnetic reconnection is believed to govern flare energy release at all levels, and evolution of flares in the lower atmosphere can be utilized to infer the rate of magnetic reconnection in the corona. Such measurements have been performed by a number of groups, confirming that flare energy release in terms of radiation is an instantaneous response to magnetic reconnection. Our recent observations have also revealed a temporal correlation between magnetic reconnection rate inferred from flare observations and kinematic evolution of erupting magnetic flux ropes in the early stage of eruption. In about one and a half dozen events with the association between flares, CMEs, and/or MC identified, the total reconnection flux is found to be proprotional to the CME velocities as well as the poloidal magnetic flux computed from the in-situ measurements of MC properties. These provide observational evidence of the important role of low-corona magnetic reconnection in large-scale solar eruptive events, in that magnetic reconnection not only interacts with early-stage acceleration of flux ropes, but may also contribute to formation of the helical structure of interplanetary magnetic flux ropes in those strong, fast, and most geo-effective events that are closely associated with solar flares. These results await confirmation by further studies on large data samples.

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