Magnetic Reconnection Flux and Coronal Mass Ejection Velocity

Jiong Qiu[1,2,3] & Vasyl B. Yurchyshyn[1]

1. Big Bear Solar Observatory, New Jersey Institute of Technology 40386 N. Shore Ln., Big Bear City, CA, 92314-9672

2.Division of PMA, California Institute of Technology 1200 E. California Blvd., Pasadena CA 91125

3. current address: Physics Department, Montana State University Bozeman MT 59717-3840

qiu@physics.montana.edu

ABSTRACT

In this paper, we explore the relationship between the total reconnection flux ψ_{rec} estimated from flare observations and the velocity V_{cme} of Coronal Mass Ejections (CMEs) observed by Large Angle and Spectrometric Coronagraph Experiment (LASCO). Our study includes 13 events with varying magnetic configurations in source regions. It is shown that V_{cme} is proportional to ψ_{rec}, with a linear cross-correlation 89% and confidence level over 99.5%. This result confirms the importance of magnetic flux transferred by magnetic reconnection in the early stage of fast CMEs. On the other hand, the CME velocity and kinematic energy are probably independent of magnetic configurations of source regions.

Subject headings: Sun: activity – Sun: flares – Sun: coronal mass ejection – Sun: magnetic reconnection

1. INTRODUCTION

Magnetic reconnection is considered to play an important role in the early stage of many large-scale solar eruptions. In our previous studies on solar eruptive events consisting of Coronal Mass Ejections (CMEs), flares, and filaments, we found evident temporal correlation and magnitude scaling relationship between filament acceleration and the rate of magnetic reconnection inferred from flare observations (Qiu et al. 2004; Jing et al. 2005). However, a direct comparison between CME acceleration and reconnection rate is not conclusive, as in the studied events, CME observations by Large Angle and Spectrometric Coronagraph Experiment (LASCO) start at 2-3 solar radii, when the stage of fast acceleration is nearly terminated (Zhang et al. 2001). In this paper, we derive the total reconnection flux as the time integration of the reconnection rate, and compare it with the mean velocity of CME spanning from 2 to 30 solar radii as observed by LASCO C2 and C3. CMEs at this stage are just coming out of the fast acceleration phase and usually exhibit no acceleration or very small deceleration. Therefore, the mean CME velocity during this stage is close to the maximum CME speed. This approach will remove the very large uncertainties in determining the start times of CMEs and allow us to have a direct comparison between reconnection and kinematics of CMEs.

It should be noted that the amount of total reconnection flux is an important physical parameter interacting with the flux rope evolution. Independent of specific low-corona magnetic configurations of source regions, magnetic reconnection reconstructs the magnetic topology in a way that most probably helps diminish the tension force binding the flux rope plasma to the solar surface, thus enhances the upward motion of the flux rope. The amount of mass and magnetic flux exchanged between the flux rope and its ambient is not ignorable.

The reconnection rate can be inferred as $\varphi_{rec} = \frac{\partial}{\partial t}\left(\int B_n dA \right)$, where dA is the newly brightened flare area at each instant, and B_n is the normal component of magnetic fields encompassed by dA (Forbes & Lin 2000, and references therein). This relationship is valid given that the following assumptions hold. Magnetic flux is conserved from the photosphere to the corona. The photospheric magnetic fields are line-tied, or equivalently their evolution timescale is much longer than the reconnection timescale. Heating of lower-atmosphere during flares is an immediate response to magnetic reconnection at the corona, which transports energy downward. And the timescales of magnetic reconnection, energy transport, and heating of lower-atmosphere is shorter than the observation and/or measurement timescales. Realistically, the timescale of magnetic field evolution ranges from hours to days, and timescales of magnetic reconnection, energy transfer, and atmosphere heating range from a fraction of a second to a few seconds. Meanwhile, our observation or measurement timescale is from several seconds to 3 minutes. Therefore, the approach is suitable for our purpose of research.

2. OBSERVATIONS AND MEASUREMENTS

In our previous studies, we evaluated the electric field of the reconnecting current sheet at the reconnection site, which reflects the reconnection rate per unit length along the current sheet with a 2D assumption. In this study, we only evaluate the reconnection rate φ_{rec} and its time integration $\psi_{rec} = \int \varphi_{rec}(t)dt$, which does not require the 2D assumption, thus avoids large uncertainties in evaluating the ribbon expansion velocities. Figure 1 illustrates how the newly brightened pixels are counted from consecutive flare images and mapped to the co-registered longitudinal magnetogram obtained by the Michelson Doppler Imager (MDI). Uncertainties stemming from this method are evaluated by artificially mis-aligning the magnetogram and flare monograms by 1-2 pixels, and by varying the cutoff value that outlines the edge of newly brightened patches. The former contributes to an error of no more than 10%, and the latter results in errors of 15-20%. Altogether they give about 30% errors. Since flare observations are obtained at Hα and UV wavelengths reflecting emission from the chromosphere or transition region, we evaluate B_n by extrapolating the photospheric longitudinal magnetic fields to 2000 km above the photosphere using a potential field assumption. Most flares in this study occur on the disk with an orientation cosine factor of around 0.8. Systematic errors include calibration uncertainties and projection effects in MDI magnetograms, and the potential field assumption in the extrapolation. These systematic uncertainties are more difficult to formulate and therefore not discussed in this paper. However, we do not expect them to amount to altering the measurements by more than half order of magnitude.

In this paper, 13 events are analyzed. All of them consist of fast Halo-CMEs observed by LASCO C2 and C3 and C- to X- class flares observed in Hα and UV wavelengths by Big Bear Solar Observatory (BBSO) and Transition Region And Corona Explorer (TRACE), respectively. Table I gives the information of the 13 events. Of these events, 4 were reported in earlier studies (Qiu et al. 2004; Jing et al. 2005, and references therein). Figure 2a gives the time profiles of the inferred reconnection rate derived in both the positive and negative magnetic fields for one event. In principle, reconnection rate derived from the positive and negative magnetic fields, or φ^+ and φ^-, should be identical, as equal amount of positive and negative magnetic fluxes participate in reconnection. But measurements do not always yield good balance between the positive and negative fluxes (e.g. Fletcher & Hudson 2001). Figure 2b shows the ratio of total reconnection fluxes in opposite polarities, $R = \psi^+_{rec}/\psi^-_{rec}$, for all the 13 events. Given the uncertainties involved in the measurements, cases with $R \approx 0.5 \sim 2$ can be regarded as of good balance. Only 2 events in this study exhibit large imbalanced fluxes ($R > 2$ or $R < 0.5$). In this paper, ψ_{rec} is given as the mean of ψ^+_{rec} and ψ^-_{rec}.

The CME velocity V_{CME} is obtained from LASCO on-line catalog[1]. It is computed from a linear fit to the height-time profile of the CME front measured in C2 and C3, i.e., with the assumption of constant CME speed. Errors in CME velocity measurements are about 10%

[1]see $http://cdaw.gsfc.nasa.gov/CME\_list/$ for more details

(Seiji Yashiro, private communication, 2005). Note that these measurements give the CME velocities projected in the plane of sky.

We also distinguish these events by magnetic configurations of their source regions. Specifically, 2 events occur in quiescent regions with diffused weak magnetic fields that resemble the standard bipolar 2D flare-CME picture, or the CSHKP model, (Forbes & Acton 1996, and references therein), and the other events take place in active regions with complicated strong magnetic fields, typically at or around sunspots. Half of the events are accompanied by erupting filaments, while in the rest of the events, although filaments are present in source regions, they are not disrupted. We also note that in some events, post-flare loops form above the undisrupted filaments (Figure 3), which provides clear evidence that magnetic reconnection proceeds above the filament. These configurations are distinguished so as to provide observational test to existing CME models, for example, catastrophe flux cancelation model (e.g. Forbes & Priest 1995) versus break-out model (e.g. Antiochos, DeVore, & Klimchuk 1999).

3. RESULTS

Figure 4 shows the scatter plot of V_{CME} versus ψ_{rec} for the 13 events analyzed. A proportionality between V_{CME} and ψ_{rec} is evident in this figure. The linear cross-correlation is computed to be 89% for the 13 pairs of data, yielding a confidence level of greater than 99.5%. Considering the imbalance between positive and negative reconnection fluxes from the measurements, we can also compare the larger, rather than the mean, of ψ_{rec}^{+} and ψ_{rec}^{-} with V_{CME}. Such slightly deduces the degree of correlation by 1 percentage. This is to say, greater amount of reconnection flux is related to larger CME velocities out of the fast acceleration stage.

Note that events with greater amount of reconnection flux as well as larger CME velocities do not necessarily originate from complicated active regions with strong magnetic fields. For example, for the events on 2000 September 12 and 2002 November 24, the source regions are dominated by very simple bipolar fields, the maximum magnetic field strength being no more than 400 G. The magnitudes of reconnection rate as well as acceleration are not very large. But the durations of reconnection and acceleration are very long, giving rise to rather large mean CME velocities at ~1000-1500 km s^{-1}. In comparison, some events occur in much stronger magnetic fields with maximum field strength over 1000 G, but the durations of acceleration and reconnection are short, leading to mean CME velocities around 1000 km s^{-1}, comparable to the events in simple and weak field regions. The couple of events with relatively slow CMEs (V_{CME} < 1000 km s^{-1}) in this study originate from active regions.

That both the magnitude and duration of CME acceleration are important properties is also suggested by a recent independent research (Zhang 2005) investigating kinematic behavior of several tens of CMEs observed from LASCO C1 to C3.

Furthermore, events associated with and without erupting filaments are distinguished by dark and grey symbols in Figure 4. However, they do not appear to be two populations in the scatter plot. Therefore, at least at this level, the specific magnetic configuration does not play a significant role. These results substantiate the suggestion by Qiu et al. (2004); Qiu (2005) that CME velocities, and consequently the kinematic energy of CMEs, might not depend on particular magnetic configurations in source regions.

The measured ψ_{rec} amounts to 10^{21-22} Mx. These values should be regarded as the lower-limits of the total amount of magnetic flux participating in magnetic reconnection, as the numerical method takes into account relatively strong brightenings in flare core regions. However, reconnection flux involved in other than core regions is negligible, as remote brightenings usually occur in weak magnetic fields and are transient in comparison with flares in core regions.

4. CONCLUSION

We find a scaling relationship between velocities of CMEs, observed by LASCO C2 and C3, and total reconnection flux, amounting to 10^{21-22} Mx, evaluated from flare observations for 13 events analyzed in this paper. The result confirms the importance of magnetic reconnection in the early stage of CMEs. The events in our analysis occur in source regions with different magnetic configurations, however, this cannot be distinguished in the velocity-flux plot. This result indicates that the specific magnetic configuration might not be important in generating CMEs with certain speeds, and CME kinematic energies are likely independent of magnetic configurations in low corona.

In general, dynamics of solar ejecta are believed to be determined by the Lorentz and pressure forces (Vršnak 1990; Chen 1996), the former being related to the amount of magnetic flux confined in the erupted field. Research thus far has been conducted to explore relationship between magnetic flux measured in-situ in magnetic clouds and dynamics of solar ejecta. Dal Lago et al. (2001) and Owens & Cargill (2002) reported that the intensity of the magnetic fields in magnetic clouds is related to the turbulence velocity of solar wind. Earlier, Lindsay et al. (1999) concluded that Interplanetary Magnetic Fields (IMFs) with larger maximum magnitudes are associated with high speed CMEs. Very recently, Yurchyshyn et al. (2004, 2005) found that the magnitudes of hourly averaged B_z component and the total

IMF B_{tot} are both scaled with the speed of CMEs launched around the solar disk center. Our study, for the first time, illustrates the relationship between the CME velocity and magnetic flux transferred between the flux rope and its ambient fields on the Sun's surface by means of magnetic reconnection. A significant amount of the reconnection flux is expected to become part of the expanding flux rope, which travels into the interplanetary space.

The CME catalog is generated and maintained by the Center for Solar Physics and Space Weather, the Catholic University of America in cooperation with the Naval Research Laboratory and NASA. SoHO is a project of international cooperation between ESA and NASA. TRACE is a NASA Small Explorer (SMEX) mission. We acknowledge using data from the Global High Resolution Hα Network, operated by Big Bear Solar Observatory, New Jersey Institute of Technology. JQ is supported by NASA grant NNG04GF07G and NSF grant ATM-0454606. VY is supported by NSF grants ATM-9903515, ATM-0205157, and NASA grant NAG5-9682.

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Table 1: Flare and CME information

Date	Source Region	Flare Magnitude[a]	Erupting Filament	Reconnection Flux[b] (10^{21} Mx)	CME Velocity[c] (km s^{-1})
1998-11-05	AR	M8.3	yes	3.3±0.5	1118
2000-09-12	QS	M1.0	yes	3.7±0.6	1550
2000-11-24	AR	X1.0	yes	1.5±0.3	1000
2001-10-19	AR	X1.6	yes	2.6±0.5	970
2002-11-24	QS	C6.4	yes	1.8±0.8	1077
2003-10-28	AR	X17.0	yes	17.3±2.1	2459
1998-04-29	AR	M6.8	no	3.7±0.4	1374
2001-09-28	AR	M3.3	no	3.9±0.4	846
2002-03-20	AR	C4.0	no	1.4±0.3	603
2002-07-26	AR	M8.7	no	2.5±0.8	818
2003-10-29	AR	X10.0	no	10.2±1.0	2029
2004-11-07	AR	X2.0	no	5.4±0.7	1759
2005-05-13	AR	M8.0	no	6.2±0.4	1689

[a]according to GOES categorization of flares

[b]Magnetic fields measured from MDI are multiplied by a scaling factor of 1.56 (Berger & Lites 2003).

[c]obtained from *http://cdaw.gsfc.nasa.gov/CME_list/*

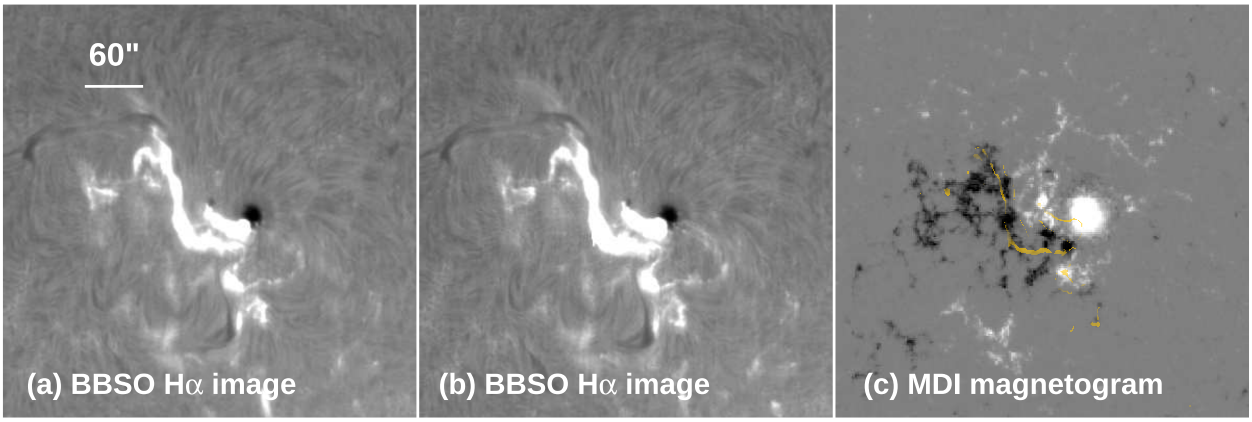

Fig. 1.— (a-b) Snapshots of a flare observed at Hα in consecutive time frames. (c) MDI longitudinal magnetogram (gray scale) superposed with the newly brightened pixels (gold symbols) measured from (a) and (b).

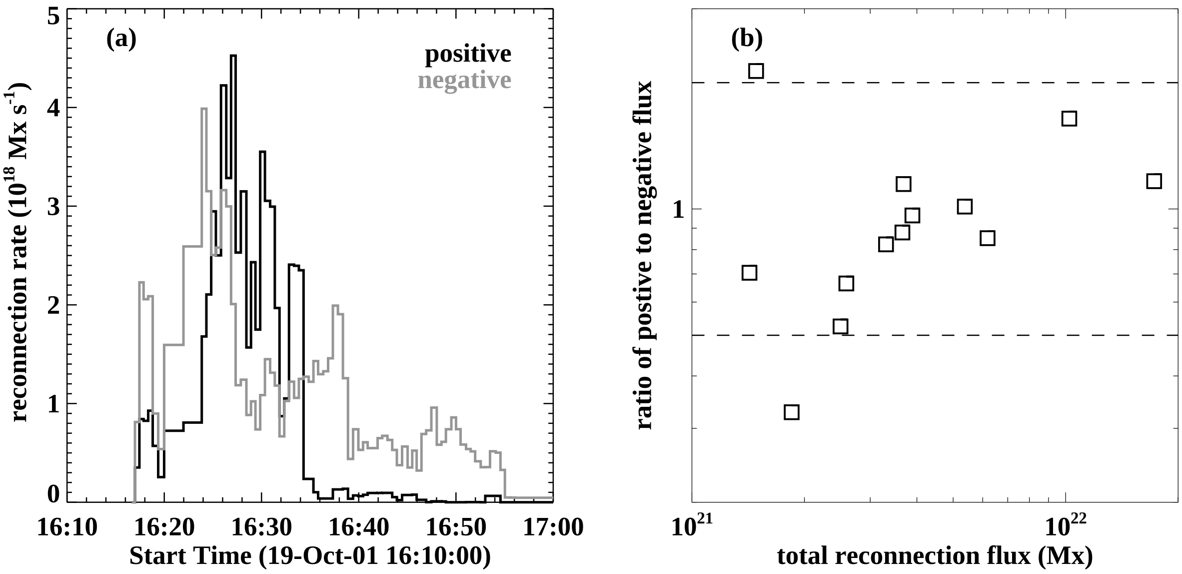

Fig. 2.— (left) magnetic reconnection rate derived in positive and negative magnetic fields for one flare event. (right) the ratio (R) of total reconnection flux derived in positive magnetic fields to that in negative magnetic fields for 13 events. Dashed lines indicate $R = 0.5, 2$.

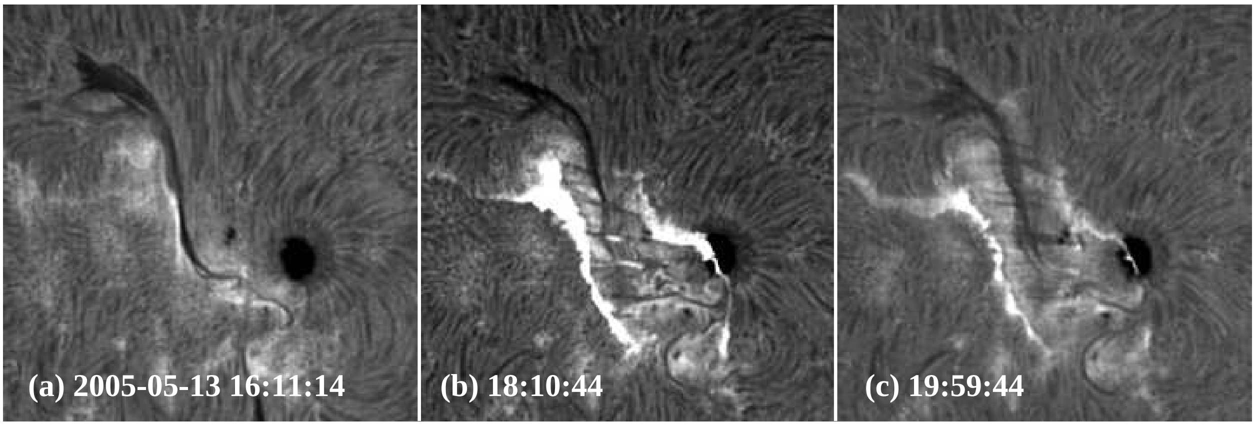

Fig. 3.— Snapshots of pre-flare (a) and post-flare (b-c) images taken at Hα showing the undisrupted filament between flare ribbons and post-flare loops formed above the filament.

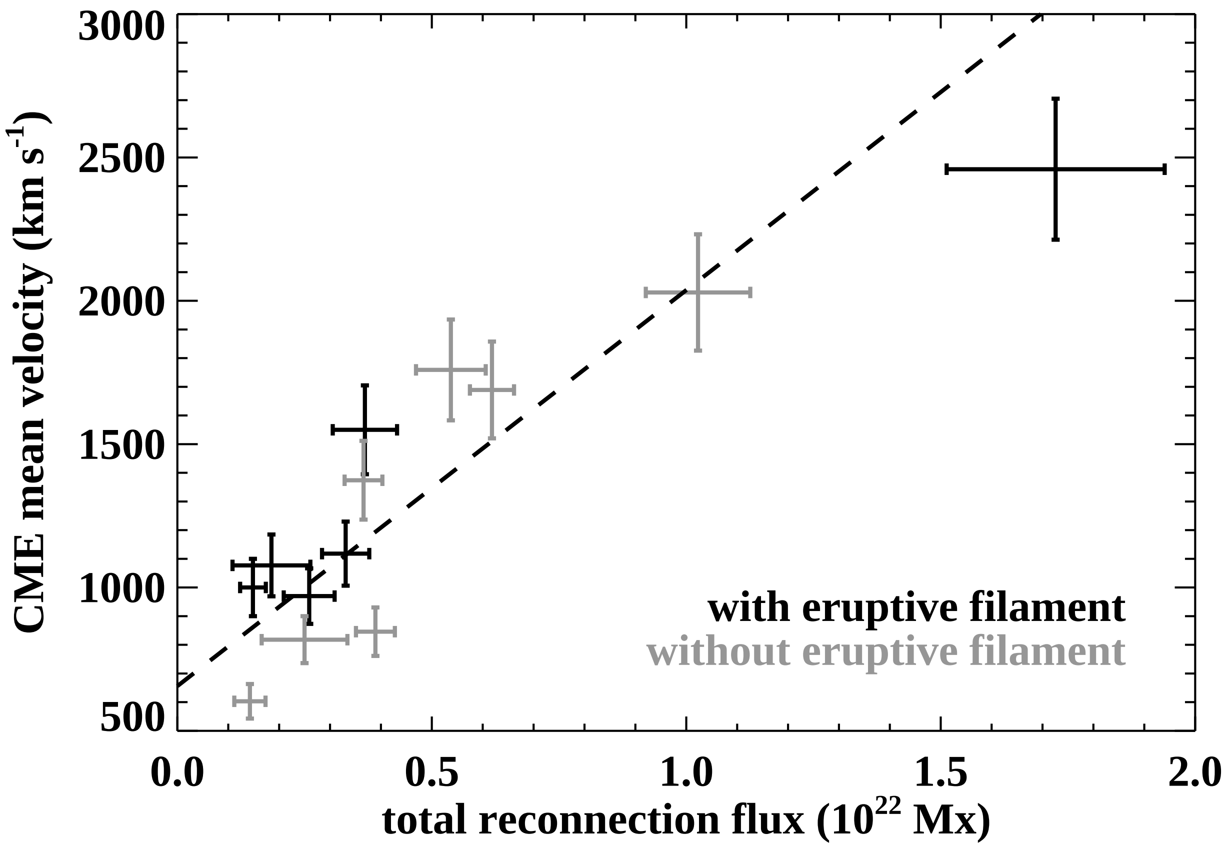

Fig. 4.— Scatter plot of CME velocities versus total reconnection flux for 13 events. Dark and grey colors indicate events associated with erupting and non-erupting filaments, respectively. The dashed guide line shows the least-squared linear fit to the data points.