Provided for non-commercial research and educational use only. Not for reproduction or distribution or commercial use.



This article was originally published in a journal published by Elsevier, and the attached copy is provided by Elsevier for the author's benefit and for the benefit of the author's institution, for non-commercial research and educational use including without limitation use in instruction at your institution, sending it to specific colleagues that you know, and providing a copy to your institution's administrator.

All other uses, reproduction and distribution, including without limitation commercial reprints, selling or licensing copies or access, or posting on open internet sites, your personal or institution's website or repository, are prohibited. For exceptions, permission may be sought for such use through Elsevier's permissions site at:

http://www.elsevier.com/locate/permissionusematerial



Journal of Atmospheric and Solar-Terrestrial Physics 69 (2007) 129-134



www.elsevier.com/locate/jastp

Magnetic reconnection in solar eruptive events of varying magnetic configurations

Jiong Qiu*

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

Received 5 April 2005; accepted 17 June 2006 Available online 5 December 2006

Abstract

We study the relationship between magnetic reconnection and acceleration of filaments and coronal mass ejections (CMEs) in different magnetic configurations. They occur in either quiet-Sun or active regions of either bipolar or multipolar magnetic fields, and are either or not accompanied by filament eruptions. The preliminary results of the case studies confirm the temporal correlation and magnitude scaling relationship between reconnection rate and acceleration in the early phase of eruptions. The results suggest no clear difference between events of different magnetic configurations. It is shown that the total reconnection flux, which is calculated to be 10^{21-22} Mx, is proportional to the average velocities of CMEs, suggesting the important role of magnetic reconnection in the early stage of solar eruptions. (© 2006 Elsevier Ltd. All rights reserved.

Keywords: Sun; Activity; Flares; Coronal mass ejection; Magnetic reconnection

1. Introduction

Previous studies have revealed an evident temporal correlation and magnitude scaling relationship between magnetic reconnection rate in the low corona and mass acceleration measured in coronal mass ejections (CMEs) or filament eruptions in a number of solar eruptive events (e.g. Zhang et al., 2001; Qiu et al., 2004; Jing et al., 2005). Such a phenomenological relationship may be explained by interaction between eruption and reconnection shortly after the onset of the disruption. On one hand, the upward motion of the magnetized

*Corresponding author at: Current address: Physics Department, Montana State University, Bozeman, MT 59717-3840, USA. Tel.: +14069947253; fax: +14069944458.

E-mail address: qiu@physics.montana.edu.

plasmas stretches the magnetic field lines below the flux rope, which serves to boost magnetic reconnection. On the other hand, magnetic reconnection changes the topology of the fields surrounding the flux rope and helps reduce the magnetic tension force that binds the flux rope to the solar surface, hence enhancing acceleration of the expulsion. However, the role of magnetic reconnection is not fully understood in different kinds of magnetic configurations in varying magnetic environments as described by several flare-CME models, such as the flux-rope model (e.g. Forbes and Priest, 1995) that envisages a bi-polar configuration and the break-out model (e.g. Antiochos et al., 1999) invoking a quadruple configuration. These models also show differences regarding whether the flux rope is preexistent before eruption or formed in situ by magnetic reconnection during the disruption, and

^{1364-6826/\$ -} see front matter © 2006 Elsevier Ltd. All rights reserved. doi:10.1016/j.jastp.2006.06.012

whether magnetic reconnection takes place below or above the magnetic flux structure to be hurled out. It remains unclear whether these varying surface and coronal conditions will result in significantly different flare–CME relationship (e.g. Low and Zhang, 2002). The issue will be examined observationally by detailed case studies.

2. Data and methods

In this study, we analyze a number of eruptive events well observed in several wavelengths by a few instruments. The rate of magnetic reconnection is derived and compared with the dynamical evolution of mass ejection in a variety of magnetic configurations. Three groups of altogether six events (Table 1) are included in this study. They are all associated with flares and fast Halo-CMEs, with or without filament eruptions. Events in group A comprise two-ribbon flares and erupting filaments that occur in weak bipolar magnetic fields (Fig. 1a). Group B includes events of more complicated flare ribbons and erupting filaments in active regions of strong multipolar magnetic fields (Fig. 1b). Group C events also take place in active regions of multi-polar magnetic fields. They exhibit complicated morphologies with more than two flare ribbons and undisturbed filaments between the ribbons (Fig. 1c). Specifically, in the M8.7 event on 2002 July 26, post-flare loops are formed above the undisturbed filament, indicating that magnetic reconnection takes place above the filament (Wang et al., 2004).

We infer the rate of magnetic reconnection in terms of electric field (E_c) in the reconnection current sheet and the rate of magnetic flux (φ_c) convected into the reconnection diffusion region at the corona by tracking flare ribbon expansion and magnetic fields they sweep through (Forbes and Lin, 2000; Qiu et al., 2004 and references therein). E_c and φ_c are determined independently by applying different numerical algorithms to observations. Measurement of φ_c does not rely on the 2D and bi-polar assumption and is a general description of reconnection rate. Integration of φ_c over time also yields the total magnetic flux involved in the reconnection during the early stage of solar eruptions.

To study flare ribbon evolution, we use H α observations from Global H α network run by the Big Bear Solar Observatory (BBSO) and UV observations by Transition Region and Corona Explorer (TRACE), which have a 30–60 and 30–90 s cadence, respectively. Filaments are observed in H α images and EUV images by Extreme ultraviolet Imaging Telescope (EIT) on-board Solar and Heliospheric Observatory (SoHO), as well as white-light images by Large Angle and Spectrometric Coronagraph Experiment (LASCO) on-board the SoHO.

Some of the events in Table 1 were reported in earlier studies (Qiu et al., 2004; Jing et al., 2005). In this paper, they are analyzed differently. First, as flare ribbons are observed in the chromosphere or transition region, we use longitudinal magnetic fields that are extrapolated to 2000 km above the photosphere. Second, filaments are tracked both on the solar surface from chromosphere and coronal observations and as well as above the solar limb from LASCO observations. Furthermore, for valid comparison of flares and CMEs, only events with CME observation time close to the flare onset time are selected, the time difference ranging from 15 to 37 min. In all these events, the first frame of CME observation is obtained at 2–3 solar radii by LASCO C2.

Table 1 Events information

Event date	Region	Flare time (GOLES)	Filament eruption	CME^{a}		
				Time	Height (solar radius)	Velocity (km s ⁻¹)
2000-09-12 (A)	QS	11:31/12:13/13:13	Yes	11:54	2.83	1550
2002-11-24 (A)	QS	20:14/20:29/20:57	Yes	20:30	3.74	1077
2001-10-19 (B)	AR	16:13/16:25/16:43	Yes	16:50	2.78	970
2000-11-24 (B)	AR	21:43/21:59/22:12	Yes	22:04	2.95	1000
2002-07-26 (C)	AR	20:51/21:12/21:29	No	22:06	2.89	818
2003-10-29 (C)	AR	20:37/20:49/21:01	No	20:54	2.92	2019

^aCME information is retrieved from LASCO CME on-line catalog at http://lasco-www.nrl.navy.mil/cmelist.html.



3. Results

Fig. 2 shows the temporal evolution of magnetic reconnection rate and flare light curves for the six events. Similar to previous studies (Qiu et al., 2004), there is generally a good temporal correlation between the flare impulsive emission and magnetic reconnection rate. For the event on 2002 November 24, the displacement between the peaks of reconnection rate and hard X-ray light curves may be caused by large projection effects in the longitudinal magnetograms as this event occurs relatively close to the limb. A close temporal correlation between mass acceleration and reconnection rate is also shown in all events (Fig. 3). This can be viewed from several aspects. First, fast acceleration of filaments and/or CMEs coincides with peaking magnetic reconnection rate in five out of six events. Second, the acceleration duration is longer in events with long duration flares (e.g. group A events in Fig. 3). It is also seen that, in all events, CME acceleration ceases after the impulsive phase of the flare.

Therefore, the observed good temporal correlation between flare impulsive emission, magnetic reconnection rate, and mass acceleration is independent of magnetic configuration of the events. In all these events occurring either in simple bipolar magnetic fields or complicated multipolar fields, fast acceleration of CME and filament plasmas takes place before the end of impulsive flare emission.

The magnitudes of reconnection rate and filament and CME acceleration are compared. For the four events in groups A and B, the linear crosscorrelation between filament acceleration and reconnection rate in terms of either E_c or φ_c is greater than 90%, confirming the magnitude scaling relationship reported in our earlier studies.

It is difficult to derive the magnitude of CME acceleration, because in most events, CME acceleration has ceased when it is first observed by LASCO C2. For lack of early stage observations of CMEs, we assume that pronounced CME acceleration coincides with significant magnetic reconnection. The mean CME acceleration is then estimated

Fig. 1. Snapshots of three groups of events with flares and filaments observed at H α and UV wavelengths, magnetograms, and CMEs and/or filaments observed by LASCO. Arrows indicate filaments visible in LASCO images.



Fig. 2. Evolution of magnetic reconnection rate E_c (thick solid line) in units of V cm⁻¹ (left scale) and φ_c (thin solid line) in units of Mx s⁻¹ (right scale) and flare impulsive emission (dotted line) normalized arbitrarily. Unless specified, the flare light curves are represented by soft X-ray time derivatives.

by dividing the CME velocity measured from C2–C3 observations by the reconnection time scale. Fig. 4a shows that the mean CME acceleration is also scaled with the reconnection rate with \sim 90% cross correlation.

Equivalently, Fig. 4b shows that the total reconnection flux integrated over the duration of reconnection is proportional to the CME velocity shortly after the fast acceleration stage. As an example, the events in group A occurred in weak magnetic fields with the maximum field strength of

200 G. The magnitude of the flares and the peak acceleration of filaments and CMEs are an order of magnitude smaller than other events in strong field regions. However, in these events, both reconnection and acceleration proceed for a long duration, leading to the CME velocity greater than some active region events. This result indicates the importance of the total reconnection flux in the kinematics and energetics of CMEs. On the other hand, the specific magnetic configuration is probably not important.



Fig. 3. Time evolution of CME (thin solid line) and filament (thin dashed line) acceleration in units of km s⁻² (left scale) and reconnection rate φ_c (thick solid line) in units of Mx s⁻¹ (right scale).

4. Summary

In this study, we investigate the relationship between magnetic reconnection and mass acceleration in solar eruptive events of a variety of magnetic configurations. The results confirm the good temporal correlation between reconnection rate and mass acceleration when an erupting filament is used as the proxy of mass ejection in the early stage of eruption. In general, fast acceleration of CMEs also takes place during the flare impulsive phase when magnetic reconnection rate is the greatest. With the events studies, it is shown that the CME velocity out of the fast acceleration stage is proportional to the total reconnection flux, which amounts to 10^{21-22} Mx, indicating that CME acceleration is also scaled with the magnitude of reconnection rate. These results suggest the important role of magnetic reconnection in the dynamical evolution of mass ejections. Importantly, we find that such observationally determined reconnection–acceleration relationship is independent of magnetic configurations of source regions, such as weak bipolar magnetic fields or multi-polar active regions, and regardless of whether CMEs are accompanied by filament eruptions or not, or



Fig. 4. (a) Reconnection rate vs CME acceleration; (b) total reconnection flux vs CME velocity. Straight lines indicate the least-square linear fit to the data points.

whether reconnection may take place above or below the flux rope.

Further research is to be conducted to elucidate different situations related to pre-existing and insitu formed flux ropes, and how the reconnection configuration may affect the partition between the radiative energy released in flares and the kinematical energy carried by erupting filaments and CMEs.

Acknowledgments

This work is supported by NSF Grant ATM-0603789 and NASA Grant NNG06GA37G.

References

Antiochos, S.K., DeVore, C.R., Klimchuk, J.A., 1999. A model for solar coronal mass ejections. Astrophysical Journal 510, 485–493.

- Forbes, T.G., Lin, J., 2000. What can we learn about reconnection from coronal mass ejections? Journal of Atmospheric and Solar-Terrestrial Physics 62, 1499–1507.
- Forbes, T.G., Priest, E.R., 1995. Photospheric magnetic field evolution and eruptive flares. Astrophysical Journal 446, 377–389.
- Jing, J., Qiu, J., Lin, J., Qu, M., Xu, Y., Wang, H., 2005. Magnetic reconnection rate and flux-rope acceleration of two-ribbon flares. Astrophysical Journal 620, 1085–1091.
- Low, B.C., Zhang, M., 2002. The hydromagnetic origin of the two dynamical types of solar coronal mass ejections. Astrophysical Journal 564, L53–L56.
- Qiu, J., Wang, H., Cheng, C.Z., Gary, D.E., 2004. Magnetic reconnection and mass acceleration in flare-coronal mass ejection events. Astrophysical Journal 604, 900–905.
- Wang, H., Qiu, J., Jing, J., Spirock, T.J., Yurchyshyn, V., Abramenko, V., Ji, H., Goode, P.R., 2004. Evidence of rapid flux emergence associated with the M8.7 flare on 2002 July 26. Astrophysical Journal 605, 931–937.
- Zhang, J., Dere, K.P., Howard, R.A., Kundu, M.R., White, S.M., 2001. On the temporal relationship between coronal mass ejections and flares. Astrophysical Journal 559, 452–462.