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Relationship between CME velocities and X-ray fluxes of associated flares

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Abstract Coronal mass ejection (CME) velocities have been studied over recent decades. We present a statistical analysis of the relationship between CME velocities and X-ray fluxes of the associated flares. We study two types of CMEs. One is the FL type associated only with flares, while the other is the intermediate type associated with both filament eruptions and flares. It is found that the velocities of the FL type CMEs are strongly correlated with both the peak and the time-integrated X-ray fluxes of the associated flares. However, the correlations between the intermediate type CME velocities and the corresponding two parameters are poor. It is also found that the correlation between the CME velocities and the peak X-ray fluxes is stronger than that between the CME velocities and the time-integrated X-ray fluxes of the associated flares.

Key words: Sun: coronal mass ejections (CMEs) — Sun: flares — Sun: filaments

1 INTRODUCTION

As a kind of large-scale solar eruption, coronal mass ejections (CMEs) carry a lot of material and energy from the corona and cause interplanetary disturbances and geomagnetic storms. CME velocities vary from tens to more than 2000 km s^{-1}, but it is still unknown which factors are most important for determining the CME velocity. This has been a hot topic in the CME research field over recent decades. Some authors believed that there is a physical link between CMEs and flares (Zhang et al. 2001; Neupert et al. 2001), which indicates that the impulsive acceleration of the CMEs coincides very well with the flare's rising phase. The acceleration of CMEs ceases near the peak time of the soft X-ray flares. Shanmugaraju et al. (2003) showed that the peak acceleration of the CME occurs during the eruptive phase of the associated flares. Zhang et al. (2004) found that there was a close temporal correlation between the CME velocity and the soft X-ray flux of the associated flare in the acceleration phase, and the CME acceleration and the derivative of the X-ray flux have a temporal correlation as well.

By analyzing the CMEs observed by the Solar Maximum Mission (SMM) satellite, Hundhausen (1997) studied the relationship between the CME kinetic energy and the peak X-ray fluxes of the associated flares observed by the Geostationary Operational Environmental Satellite (GOES; Donelly & Unzicker 1974), and found a weak correlation between them, with the correlation coefficient being 0.53. Vršnak et al. (2005) studied 545 flare-associated CMEs observed by the Large Angle Spectrometric Coronagraph (LASCO) aboard the Solar and Heliospheric Observatory (SOHO), and also found a weak correlation between the two parameters. Yashiro et al. (2002) got a similar result with the observations of SOHO/LASCO from 1996 to 2001. The CME velocities used in these studies are only the apparent speeds projected on the plane of sky. After the projection effect was corrected, Yeh et al. (2005) found that the correlation between the CME's velocities and the peak X-ray fluxes of the associated flares becomes weaker. However, through analyzing 24 limb CMEs observed by the SMM satellite, Burkepile et al. (2004) obtained a different conclusion and found that the correlation between the CME's kinetic energy and the soft peak X-ray fluxes of flares is stronger than that previously reported. A similar conclusion was drawn by Moon et al. (2003), who also found a good correlation between the CME velocities and the GOES peak X-ray fluxes of the associated flares in two carefully selected sets of CME/flare events. By correcting the projection effect, Moon et al. (2002) analyzed the flare-associated CMEs observed from 1996 to 2000, and found a weak correlation between the time-integrated X-ray fluxes of limb flares and the associated CME velocities, where the correlation coefficient is 0.47. Other authors studied the relation between the parameters of the magnetic field and the CME velocities. Qiu & Yurchyshyn (2005) found a strong correlation between the total reconnection flux estimated from flare observations and the velocities of CMEs. Su et al. (2007) found that both the magnetic flux of the flaring active region and the change of shear angle of the foot points of the flare showed the most significant correlations with the velocities of CMEs.

Many authors concluded that a weak correlation exists between the CME's velocities and the peak (or the time-integrated) X-ray fluxes of the associated flares (e.g., Hundhausen 1997; Vršnak et al. 2005; Yashiro et al. 2002; Yeh et al. 2005; Moon et al. 2002). We consider that there are two reasons for these poor correlations. First, about half of the observed CMEs originate from the back side of the Sun. It is possible that some CME events originate from the back side of the Sun, and flares and/or filaments break out at the same time on the solar disk. In these events, the CMEs and flares are mismatched. Second, some flare-associated CMEs may have been associated with filament eruptions at the same time in the previous studies.

Note that about half of the observed CMEs originate from the back side of the Sun, and these events do not have an association with surface activity. Considering this reason, our previous study (Chen et al. 2006, hereafter Paper I) selected a sample of CME events with their origins on the front side of the Sun, and found that the CMEs, which were associated only with filament eruptions, had velocities that are strongly correlated with the average magnetic field and the total magnetic flux in the filament channel. In order to study the relationship between the CME velocities and the GOES X-ray flux of the associated flares, we select two types of CMEs studied in Paper I. One is the FL type associated only with flares and the other is the intermediate type associated with both filament eruptions and solar flares.

This paper is arranged as follows: the data analysis and results are described in Section 2 and following it is the discussion in Section 3.

2 DATA ANALYSIS AND RESULTS

In Paper I, we found that 79 CME events can be regarded as the FL type and 64 as the intermediate type in our samples of 201 front-side CMEs. Considering that the X-ray flux of the minor flare is possibly influenced by the background, we select CME events associated with flares whose importance is higher than the C1 class. The velocities of CMEs are obtained from the CME catalog [1], and X-ray fluxes of flares are derived from the observational data from the GOES satellite.

62 FL type and 58 intermediate type CME events were finally selected as our samples. Using these events, we study the relationship between the CME velocities and the peak X-ray fluxes ($F_{\rm p}$) and the time-integrated X-ray fluxes ($F_{\rm t}$) of the associated flares. The $F_{\rm p}$ is obtained from the importance of the flares as reported in the Solar-Geophysical Data (SGD). The $F_{\rm t}$ is the GOES X-ray flux integrated over flaring time from the flare onset to its end, and the onset and end time of solar flares are collected from the SGD database.

Figure 1 shows the scatter plots of the FL type (left panel) and the intermediate type (right panel) CME velocities versus the peak X-ray fluxes $F_{\rm p}$ of the associated flares. The FL type CME velocities

[1] *http://cdaw.gsfc.nasa.gov/CME_list*

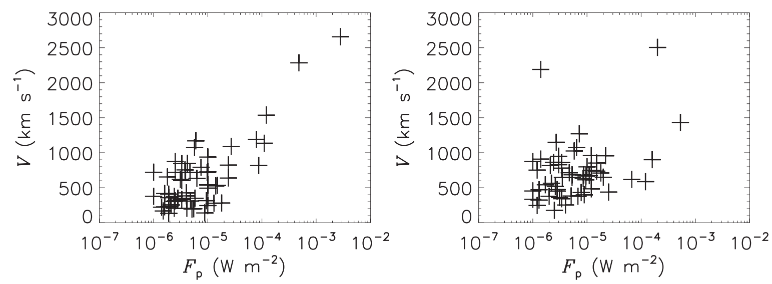

Fig. 1 *Left*: scatter plot of the FL type CME velocities versus the peak X-ray fluxes of the associated flares; *right*: scatter plot of the intermediate type CME velocities versus the peak X-ray fluxes of the associated flares.

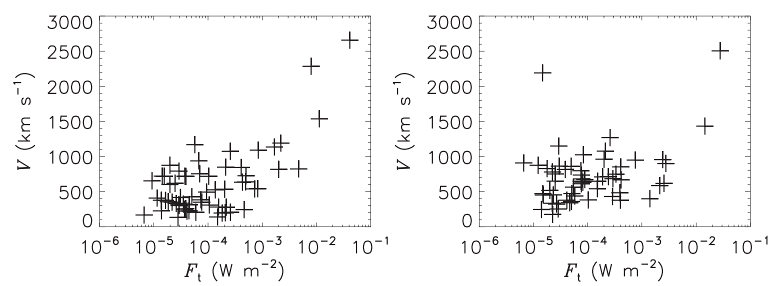

Fig. 2 *Left*: scatter plot of the FL type CME velocities versus the time-integrated X-ray flux of the associated flares; *right*: scatter plot of the intermediate CME velocities versus the time-integrated X-ray flux of the associated flares.

are strongly correlated with the peak X-ray fluxes, and this correlation is stronger than that for the intermediate type CMEs. The corresponding linear correlation coefficients for both types are 0.78 and 0.35, respectively. The left panel result is consistent with the result of Moon et al. (2003), where they studied four homologous CME events and four well-observed limb events and concluded that there is a very good correlation between the CME velocities and the peak X-ray fluxes of the associated flares. Burkepile et al. (2004) also found a similar result. The right panel result is consistent with the results of Hundhausen (1997), Vršnak et al. (2005), Yashiro et al. (2002) and Yeh et al. (2005). They also found weak correlations between the CME velocities (or kinetic energy) and the peak X-ray fluxes of the associated flares.

Figure 2 shows scatter plots of the FL type (left panel) and the intermediate type (right panel) CME velocities versus the time-integrated X-ray fluxes $F_{\rm t}$ of the associated flares. The time-integrated X-ray fluxes $F_{\rm t}$ of the associated flares are strongly correlated with the FL type CME velocities and the correlation coefficient is 0.66. However, the intermediate type CME velocities are poorly correlated with the time-integrated X-ray fluxes $F_{\rm t}$ of the associated flares, and the correlation coefficient is 0.37. The result of the right panel is consistent with the result of Moon et al. (2002), in which they also found a weak correlation between the CME velocities and the time-integrated X-ray fluxes of the associated limb flares.

From Figures 1 and 2, it can be seen that the FL type CME velocities are more strongly correlated with the peak X-ray fluxes $F_{\rm p}$ than the time-integrated X-ray fluxes $F_{\rm t}$ of the associated flares.

Moreover, the average velocities of the CMEs are calculated. For the FL type events, the average velocity is about 471 km s^{-1}, and this value is 662 km s^{-1} for the intermediate type. It seems that the CMEs associated with both filament eruptions and flares eject out faster than the events only associated with flares.

3 DISCUSSION

Some authors concluded that a weak correlation exists between the CME velocities and the peak (or the time-integrated) X-ray fluxes of the associated flares (e.g., Hundhausen 1997; Vršnak et al. 2005; Yashiro et al. 2002; Yeh et al. 2005; Moon et al. 2002). However, others found a strong correlation between them (e.g., Burkepile et al. 2004; Moon et al. 2003). Considering that some flare-associated CMEs originated from the back side of the Sun or were associated with concurrent filament eruptions in previous studies, we study two types of CMEs, which are only associated with flares (FL type) and are associated with both filament eruptions and solar flares (intermediate type). First, we studied the relation between the two types of CME velocities and the peak X-ray fluxes of the associated flares. Second, we studied the relation between the two types of CME velocities and the time-integrated X-ray fluxes of the associated flares. The main results can be summarized as follows:

1. There are strong correlations between the FL type CME velocities and both the peak and the time-integrated X-ray fluxes of the associated flares.
2. The intermediate type of CME velocities are poorly correlated with both the peak and the time-integrated X-ray fluxes of the associated flares.
3. The linear correlation between the velocities and the peak X-ray fluxes is stronger than that between the velocities and the time-integrated X-ray fluxes of the associated flares for the FL type CMEs.

Consistent with Moon et al. (2003) and Burkepile et al. (2004), these results show that there are strong correlations between the FL type CME velocities and both the peak and the time-integrated X-ray fluxes of the associated flares. Previous studies concluded that there is a weak correlation between the CME velocities and the peak X-ray fluxes (e.g., Hundhausen 1997; Vršnak et al. 2005; Yashiro et al. 2002; Yeh et al. 2005) or the time-integrated X-ray fluxes (Moon et al. 2002) of the associated flares. Two reasons may cause the weak correlation: one may be mismatching between back-side CMEs with the front-side flares, the other is flare-associated CMEs associated with concurrent filament eruptions in previous statistical studies.

CMEs and their associated flares have a strongly coupled relationship but do not cause one another. They are two different manifestations of the same magnetic process in the corona (e.g., Harrison 1995; Zhang et al. 2001; Priest & Forbes 2002). Qiu & Yurchyshyn (2005) found a strong correlation between the CME velocities and the total reconnection flux estimated from the associated flare observations. In Paper I, we found that there is a strong correlation between the CME velocities and the magnetic field flux in the filament channel. These results are consistent with the classical CSHKP model, which supposes that magnetic reconnection occurs below a filament or flux rope and the upward reconnection outflow pushes the filament or flux rope to erupt. The FL type CME velocities were influenced mainly by the magnetic reconnection. However, for the intermediate type of CME velocities, the condition is more complex, and filament eruptions also contribute to CME velocities. In some events, the gravity of filaments drag the ejecta and slow down CMEs. However, in other events (such as the events caused by kink instability), filaments carry a lot of free energy, and the energy is released during the eruptions. As the filaments stretch out, the CMEs are speeded up. Because of the complexity of filament eruptions, the velocities of these events become more disperse than those of CMEs associated only with flares. The average velocity of the intermediate type of CME is higher, which implies that in most events, the integrated effect of a filament eruption for a CME is pushing out the ejecta. In our future work, we will make an effort at understanding the relationship between filament eruptions and the acceleration process of CMEs.

Many of the X-ray flares associated with CMEs have long duration, and the bulk of the integrated X-ray flux occurs after the peak X-ray emission (Burkepile et al. 2004). However, studies suggest that the CME is accelerated near the flare onset time and prior to the bulk of the X-ray emission (e.g., Zhang et al. 2001; Zhang et al. 2002). Therefore, it is easy to understand why the CME velocities are more strongly correlated with the peak X-ray fluxes than the time-integrated X-ray fluxes of the associated flares for the FL type.

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