On the CME velocity distribution

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ABSTRACT

Context. Coronal mass ejections (CMEs) are often categorized into flare-associated and filament-associated types, which logically is incomplete since there are many CMEs of the intermediate type.

Aims. With this new classification, this paper aims to reexamine whether flare-associated CMEs and filament eruption-associated CMEs have distinct velocity distributions and to investigate which factors may affect the CME velocities.

Methods. We divide the CME events observed from 2001–2003 into three types, i.e., the flare-associated type, the filament eruption-associated type, and the intermediate type. The magnetic environments of the source regions, e.g., the polarity orientation, the chirality of the filament, etc., are examined.

Results. Our results indicate that the P-value of the likelihood between the flare-associated and the filament eruption-associated CMEs is as high as 0.79, which strongly suggests that they are a continuum of events rather than two distinct types. For the filament eruption-associated CMEs, the speeds are found to be strongly correlated with the average magnetic field in the filament channel. It is also found that there is a slight tendency for the filaments with the minority chirality to have weaker magnetic fields, and hence the corresponding CMEs have smaller eruption speeds. A slight tendency is also found for the CMEs associated with non-active region filaments to have higher eruption speeds than those with active region filaments. However, the polarity orientation of the filament channel has little effect on the eruption speed.

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

1. Introduction

Coronal mass ejections (CMEs) often occur in association with solar flares and/or filament eruptions. By studying 16 CME events associated with large flares and 11 non-flare events observed by the white-light coronagraph on Skylab, Gosling et al. (1976) concluded that the faster events were almost always associated with flares and type II or IV metric radio bursts, whereas the slow events were associated with eruptive prominences. Several years later, MacQueen & Fisher (1983) analyzed the height-speed plots of 12 loop-like CMEs over the range 1.2–2.4 $R_\odot$ observed by the MK3 coronagraph at the Mauna Loa Solar Observatory and proposed the concept of two types of CMEs, i.e., flare-associated events that exhibit higher speeds (and show little acceleration with height) and filament eruption-associated events that exhibit slower speeds (and show strong accelerations). Sheeley et al. (1999) used a new method to construct height-time maps of CMEs that were observed by the Large Angle Spectrometric Coronagraph (LASCO) aboard the Solar and Heliospheric Observatory (SOHO). Similarly they classified CMEs into prominence-associated gradual CMEs with speeds in the range 400–600 km s$^{-1}$ and impulsive CMEs with speeds typically in excess of 750 km s$^{-1}$. The statistical analysis by Moon et al. (2002) with a large sample of CME events tended to be in favor of the concept of two distinct types of CMEs.

The concept of two types of CMEs has been discussed and employed widely (e.g., St. Cyr et al. 1999; Andrews & Howard 2001; Low & Zhang 2002; Chen & Krall 2003). However, very recently, Vršnak et al. (2005) presented a statistical analysis of 545 flare-associated CMEs and 104 non-flare CMEs in the heliocentric distance range of 2–30 $R_\odot$. They found that there is no distinct difference between filament-associated CMEs and flare-associated CMEs. A similar conclusion was drawn by Chen et al. (2005). With a sample of 4315 CME events, Yurchyshyn et al. (2005) also found that there was no evidence to support the claim on two distinct types of CMEs. More and more evidence tends to indicate that the physics in the two types of CMEs is the same, with only the evolution timescale changing for individual events (Cliver & Hudson 2002); i.e., for the flare-associated CMEs, their characteristic timescales, e.g., the Alfvén transit time, are shorter, so the CMEs reach a high speed more rapidly.

It should be noted that the traditional two-class classification (flare or filament association) is logically incomplete since quite a lot of filament eruptions are accompanied by two-ribbon flares (e.g., Munro et al. 1979; see Zhang et al. 2001b for a typical event), which historically led to the classical CSHKP model for two-ribbon flares. The validation of the traditional classification of CMEs was first questioned by Feynman & Ruzmaikin (2003), who presented a CME that combines contributions of a solar flare and an erupting filament. The analysis of this event and others led them to suggest that the apparent differences separating the two types of CMEs may be an observational effect, and all CMEs can be described by a single process as presented in Zhang et al. (2001a; see also Chen & Shibata 2000). Therefore, a complete classification should include the intermediate type of CMEs that are associated with both filament eruptions and flares. For completeness, we should also consider the possibility of events with no surface activity association, although most, if not all, of them would originate from the far side of the Sun. However, these events are ignored.

For this paper, we have selected a sample of CME events with their origins on the solar disk, and then divided the events...
into the following three types in order to reexamine the CME velocity distributions: (1) CMEs associated solely with filament eruptions (type FE for short); (2) CMEs associated solely with flares (type FL for short); and (3) CMEs associated with both filament eruptions and solar flares, i.e., the intermediate type. It should be kept in mind that for the type FE CMEs, we mean by “associated solely with filament eruptions” that there are no soft X-ray flares above B1.0 class recorded in the Solar-Geophysical Data (SGD) reports.

Regarding the diverse velocities of the CMEs, an important question is which factors determine the CME velocity. Hundhausen (1997) finds that there is a weak correlation between the apparent CMEs velocities and the peak flux of the associated flares. Similar weak correlation was confirmed by Yashiro et al. (2002) and Vršnak et al. (2005). With the projection effect corrected, Yeh et al. (2005), however, find that the already weak correlation becomes significantly weaker. A different conclusion was drawn by Burkepile et al. (2004), who analyzed 11 limb events observed by SMM satellite and find that the correlation between the kinetic energy of CMEs and the peak intensity of the associated Geostationary Operational Environmental Satellites (GOES) X-ray flares is stronger than was previously found. A promising result was recently shown by Qiu & Yurchyshyn (2005), who analyzed flare-associated CMEs to find that the CMEs' velocities are proportional to the total reconnection flux, which is equal to the total magnetic flux that is swept by flaring ribbons. Moreover, they tentatively suggest that the CME velocity is probably independent of the magnetic configuration of the source region, which requires further confirmation. In this paper, we choose the filament eruption-associated CME events (type FE) to examine the relationship between the CMEs velocities and the magnetic properties of the source region.

This paper is arranged as follows. The data selection and analysis are described in Sect. 2, the CME velocity distributions are presented in Sect. 3, the relation between CME velocities and the magnetic properties is investigated in Sect. 4, which is followed by discussions in Sect. 5.

2. Data selection and analysis

After the launch of the SOHO satellite in December 1995, the LASCO telescope (Brueckner et al. 1995) observed thousands of CMEs. Our data sample is limited to the years from 2001 to 2003, during which 4201 events were recorded in the CME catalog. Solar flares are routinely recorded in the SGD reports. Filament eruption events are collected by SGD and National Geophysical Data Center (NGDC). In addition, Big Bear Solar Observatory (BBSO) Hα data are searched for filament eruption events. Among the 4201 CMEs, 658 events are centered temporally by both SOHO/LASCO and BBSO observations.

Coronal dimming is widely believed to be the near-surface manifestation of CMEs (e.g., Hudson et al. 1996; Sterling & Hudson 1997; Harra & Sterling 2001), and the EUV Imaging Telescope (EIT; Delaboudiniere et al. 1995) dimming area is found to map the “foot-point” of the CME (Thompson et al. 2000; Harrison et al. 2003). To get a sample of CMEs originating in the front side, the EIT running-difference movies were examined carefully. Only the CMEs that are associated with EIT dimmings appearing almost in the same angular span during their propagation in the LASCO/C2 field of view were selected. In this way we get a sample of 286 front-side CME events. Then, the association of each CME with a filament eruption and/or solar flare was scrutinized. We determined the approximate onset times of the CMEs by linearly extrapolating the CME trajectory observed by LASCO/C2 to 0.5 $R_\odot$ from the solar disk center.

It was found that the impulsive phase of a solar flare is nearly coincident with the CME acceleration phase (Chen & Shibata 2000; Zhang et al. 2001). However, since the acceleration phase cannot be observed by LASCO for most events, we followed the conventional way of assuming that the acceleration phase of each CME is within a time window that is generally set to ±1 h, relative to the estimated CME onset time. Flare events higher than the B1 class in the SGD reports are searched during the time window. The flare that occurs during this time window and that is located within the angular span of the CME is considered to be associated with the CME (see Yeh et al. 2005 for details). For those CMEs with an angular span less than 20°, flares are searched within ±10° relative to the central position angle of the CME. Filament eruptions and CMEs have been found to start roughly at the same time (Gopalswamy et al. 2003). Since there is uncertainty in estimating the CME onset time, a time window of ±1.5 h relative to the above-estimated CME onset time was set to judge the association with a filament eruption.

With these criteria, we find that in our sample of 201 front-side CMEs, 58 events are of type FE, 79 events are of type FL, and 64 events belong to the intermediate type.

3. Velocity distributions for different types of CMEs

Figure 1 shows the distributions of CME velocities for type FE (Fig. 1a), type FL (Fig. 1b), and the intermediate type (Fig. 1c), which are binned by 100 km s$^{-1}$. Since there are only 12 CME events with velocities higher than 1200 km s$^{-1}$ in our sample, these events are binned in the 1200–1300 km s$^{-1}$ interval. It should be noted that in this paper, just as in Vršnak et al. (2005) and Moon et al. (2002), there is no consideration of the projection effect on the CME velocities, which was found to underestimate the average velocity of CMEs by 30% by Yeh et al. (2005). Since the CME events have been selected without the bias in latitude and longitude, the projection effect is statistically equivalent for the three types of CMEs.

The profile of Fig. 1a is quite similar to that in Moon et al. (2002). The average speeds for the three types of CMEs are 526 km s$^{-1}$, 564 km s$^{-1}$, and 738 km s$^{-1}$, respectively. Thus, on average, type FL CMEs are slightly faster than type FE, while the intermediate type is significantly faster than they are. Although the distribution of the type FL CMEs has an evident tail in the high velocity range (e.g., >1000 km s$^{-1}$), its main peak appears at ~300 km s$^{-1}$, with a sub-peak at ~700 km s$^{-1}$. The distribution of the intermediate type of CMEs, which is strongly biased toward the high velocity range, has its peak at ~600 km s$^{-1}$ and a sub-peak at ~300 km s$^{-1}$.

A Kolmogorov-Smirnov test was performed on these distributions. It is found that the P-value is 0.79 for the likelihood of Figs. 1a and 1b. Since their average speeds are close to each other, the two distributions do not show distinct differences.

Despite the significant shift in the velocity axis, the P-value of the likelihood of the distribution profiles in Figs. 1a and 1c is even as high as 0.99.

The relative portions of the three types of CMEs at every 100 km s$^{-1}$ interval are shown in Fig. 2. It can be seen that the relative distributions of the three types are rather diffuse, though
there is a slight tendency for events at higher speeds to be mainly associated with solar flares, as reported by Vršnak et al. (2005).

4. What determines the CME velocity?

As discussed in the previous section, even with a logically complete classification, our results do not show distinct velocity distributions for the CMEs associated solely with filament eruptions and those associated solely with flares. Since CME velocities vary from tens to more than 2000 km s$^{-1}$, the problem of which factors determine the CME velocity still remains.

Since type FE CMEs have a similar velocity distribution to type FL, we investigated only the filament eruption-associated CME events (type FE) in order to examine the relationship between the CMEs velocities and the magnetic properties. The magnetograms observed by the Michelson Doppler Imager (MDI) aboard SOHO (Scherrer et al. 1999) are used to obtain the magnetic properties of the CME source regions. With 9 events close to the solar limb or with no corresponding magnetograms, 49 type FE CME events were investigated. The parameters of the magnetic field analyzed here include the average magnetic strength in one polarity of the filament channel ($\overline{B}$), the total unsigned magnetic flux ($\Phi$), polarity orientation of the filament channel (i.e., whether it is in accord with Hale’s law), whether the filament is within or outside an active region, and the chirality of the filament. To get the average magnetic strength in one polarity of the filament channel $\overline{B}$ and the total magnetic flux $\Phi$, we selected only the magnetic elements in the positive polarity area with the magnetic strength larger than a tenth of the maximum value in the same polarity area. Figure 3 shows an

Fig. 1. Histograms showing the velocity distributions for the three types of CMEs. a) CMEs only associated with filament eruptions (type FE); b) CMEs only associated with solar flares (type FL); and c) CMEs associated with both filament eruptions and solar flares (i.e., the intermediate type).

Fig. 2. Histogram showing the relative portions of the three types of CMEs in different velocity ranges with an interval of 100 km s$^{-1}$.

Fig. 3. MDI longitudinal magnetogram superposed with the spine of the Hα filament (gray curve). The black contour lines correspond to the magnetic field level of a tenth of the maximum magnetic strength in this filament channel.
example where the filament location is superimposed on the magnetogram. The contour lines with the level of a tenth of the maximum magnetic field enclose several magnetic elements. Then $\Phi$ and $B$ are expressed as

\[ \Phi = \sum B_i S_i, \quad (1) \]
\[ B = \frac{\Phi}{\sum S_i}, \quad (2) \]

where the sum is taken over all the pixels in the enclosed patches, and $B_i$ and $S_i$ are the magnetic field strength and area corresponding to each pixel, respectively. Since only the longitudinal component of the magnetic field is observed by SOHO/MDI, we corrected the magnetic field by assuming that the local field near the solar surface is radial. The projection effect was also corrected for $S_i$. The chirality is an important parameter for characterizing the magnetic configuration of the filament. It was found that in each hemisphere there is a predominant chirality, i.e., sinistral for the southern hemisphere and dextral for the northern hemisphere (Martin et al. 1994; Pevtsov et al. 2003; Jing et al. 2004). The chirality of each filament in our data sample is judged from the Hα images observed by the BBSO and Paris Observatory (Meudon). In cases where the images are too diffuse to determine the chirality, a potential field extrapolation is used. In addition, the polarity orientation and the filament type (active region type versus non-active region type) are also distinguished. The interaction between the CMEs and the ambient solar wind is another factor that may affect the CMEs propagation velocities, which has been studied by Gopalswamy et al. (2000).

Figure 4 shows the scatter plots of the CME velocity ($V_{\text{CME}}$) versus the total magnetic flux ($\Phi$, left panel) and versus the average magnetic field strength ($B$, right panel) for the 49 filament-associated events. Although the plots show a linear limit for both $\Phi$ and $B$, we can see that the scatters in the left panel are a little more diffuse than those in the right panel. The corresponding linear correlation coefficients are 0.68 and 0.70, respectively, indicating that the average magnetic field $B$ may be a better parameter for predicting the CME velocity when a filament erupts.

In each of the three panels of Fig. 5, the scatter plots of $V_{\text{CME}}$ and $B$ are divided into two groups according to the polarity orientation of the filament channel (upper panel), whether the filament is rooted within or outside an active region (middle panel) and whether the chirality of the filament is of the predominant type or minority type (lower panel). It can be seen in Fig. 5a that the polarity orientation has little effect on $V_{\text{CME}}$. In Fig. 5b, although there is no dividing line separating active region and non-active region filaments, a slight tendency can be discerned for CMEs associated with non-active region filaments to erupt faster, especially those with relatively strong average magnetic strength (around $B = 60$ G). Finally, in Fig. 5c, there is also no dividing line between filaments with predominant and minority chiralities. However, it is seen that the filaments with the minority chirality are concentrated in the weaker magnetic field, hence a smaller $V_{\text{CME}}$ regime.

5. Discussions

Traditionally, CMEs are classified into two distinct types, i.e., slow CMEs that are associated with filament eruptions and fast CMEs associated with solar flares (e.g., Gosling et al. 1976; MacQueen & Fisher 1983; St. Cyr et al. 1999; Andrews & Howard 2001; Moon et al. 2002). Vršnak et al. (2005), however, point out that the velocity distributions of the two types show very similar characteristics. For both types, there is a significant fraction of CMEs showing a considerable acceleration or deceleration, and the two types have a comparable ratio of fast and slow CMEs. Their results are strongly suggestive of a continuum of events rather than supporting the existence of two distinct CME classes.

After noticing that such a bimodal classification is logically incomplete, we classified the CMEs observed by SOHO/LASCO from 2001–2003 into three types – those associated solely with filament eruptions (type FE), those associated solely with flares (type FL), and those associated with both filament eruptions and flares (the intermediate type) – and then reexamined the velocity distributions. We also examined the effects of the magnetic environments of the source regions on the CME velocities. The main results of our statistical study can be summarized as follows:

1. With the new classification, it is found that the types FE and FL CMEs have quite similar velocity distributions (with the P-value being 0.79 in the Kolmogorov-Smirnov test), with almost the same average values;
2. the CME velocity varies roughly linearly with the average magnetic field. Thus, the average magnetic field in the filament channel can be used to predict the CME velocity when a CME originates in the channel;
3. there is a slight tendency for the filaments with the minority chirality to have weaker magnetic fields, hence the corresponding CMEs have smaller eruption speeds. A slight tendency is also found for the CMEs associated with non-active region filaments to have higher eruption speeds than those with active region filaments. However, the polarity orientation of the filament channel has little effect on the CME speed.
Consistent with Vršnak et al. (2005) and our preliminary work in Chen et al. (2005), the results in this paper indicate that types FE and FL CMEs have quite similar velocity distributions and are, therefore, a continuum of events. There is no solid foundation to classifying the CMEs into two physically distinct types according to the association with filament eruptions or flares. CMEs may be due to the same process as the accompanied flares, but manifested at different scales (Harrison 1995; Priest & Forbes 2002).

Several factors have contributed to reaching the conclusion of the existence of two types of CMEs by early research. The first, as pointed out by Vršnak et al. (2005), is that the samples used by them were too small to be statistically reliable. The second factor is that some prominences are rooted behind the solar limb. For these events, the low-lying flares cannot be observed. Yet another factor is that some CMEs are associated with soft X-ray (SXR) giant arcades (Hiei et al. 1993), which are physically the same as solar flares but cannot be detected by GOES satellites (Shibata 1996). As a result, the giant arcade-associated events are often categorized into the non-flare CMEs. For instance, the 1997 January 6 CME event, which was widely claimed not to be associated with any flare, was shown to correspond to a GOES A-class flare by Wu et al. (2002). Recently, Zhou et al. (2003) studied 197 front-side halo CMEs and found that all the CMEs were accompanied by local brightenings in the CME source regions in EIT images, although some brightenings may correspond to only ~10% enhancement. Theoretical modeling also indicates that a low reconnection rate, which could result in weak brightening, may allow the eruption of the flux rope system (Lin & Forbes 2000).

As the relation between the CME velocities ($V_{\text{CME}}$) and flare intensities remains controversial, Qiu & Yurchyshyn (2005) found, by studying flare-associated CMEs, that $V_{\text{CME}}$ is linearly proportional to the total magnetic flux that is swept by flare ribbons. Similarly, the results in this paper indicate that, for the filament-associated CMEs, $V_{\text{CME}}$ is also roughly linearly correlated with the total magnetic flux in the filament channel. However, we found that the correlation between $V_{\text{CME}}$ and the average magnetic field in the filament channel is better. Such a result is consistent with Lindsay et al. (1999), who find that the interplanetary magnetic fields with larger maximum magnitudes are associated with high-speed CMEs. It is also consistent with the classical CSHKP model, where magnetic reconnection is supposed to occur below a filament or flux rope. The upward reconnection outflow, which moves with the Alfvén speed at the inflow region, pushes the filament or flux rope to erupt. Since the Alfvén speed is proportional to the magnetic field strength, it is not surprising that the CME velocity is roughly linearly proportional to $B$. Compared with the total reconnection flux used in Qiu & Yurchyshyn (2005), the average magnetic field has a practical advantage in forecasting space weather since it is a quantity that can be measured before the eruption occurs.

Since the formation of the heliospheric pattern of the filaments is not understood well (Mackay 2005), our result that the filaments with the minority chirality have weaker magnetic fields, so smaller eruption speeds, may provide some hints for constructing the models of filaments with different chiralities. That non-active region filaments have higher eruption speeds than active region filaments may be explained by the fact that active region filaments are confined by the strong bipolar magnetic field, while non-active region filaments, especially the so-called type B filaments (Tandberg-Hanssen 1995), are often nested in regions with a quadrupolar magnetic field. Such a configuration is more favorable to these eruptions than the bipolar magnetic configuration (Forbes et al. 1994).

It is noted in passing that the P-value of the likelihood between the velocity distributions of the type FE and the intermediate type of CMEs is as high as 0.99, with the latter shifted toward the high-velocity range by about 200 km s$^{-1}$. As a filament erupts, the condensed mass, which is supposed to be hosted by magnetic dips, would partly drain down along the magnetic field to the chromosphere, and the mass drainage was proposed as able to accelerate the erupting flux rope (e.g., Tandberg-Hanssen 1974; Low 2001). Two facts – the average speeds of the type FE and type FL CMEs are almost identical, and the intermediate type CMEs have a higher average speed than the type FL CMEs – may imply that actually the mass drainage plays an
important and less appreciated role in the acceleration of the filament-related CMEs.

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