Kinetic properties of coronal mass ejections corrected for the projection effect in Cycle 23

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ABSTRACT
Using Howard et al.’s method, we investigate, before and after the projection correction, the speed and acceleration distributions for 1747 coronal mass ejections (CMEs) associated solely with flares (FL CMEs) and 631 CMEs associated solely with filament eruptions (FE CMEs) observed by the Large Angle and Spectrometric Coronagraph on board the Solar and Heliospheric Observatory (SOHO/LASCO) from 1996 September to 2007 September, corresponding to almost an entire solar cycle. The results show the following. (1) Before the correction, the speed distributions for FL and FE CMEs are statistically different from each other; after the correction, the speed distributions for FL and FE CMEs should also be statistically different from each other. (2) Before the correction, the acceleration distributions for FL and FE CMEs are statistically different from each other. However, after the correction, FL and FE CMEs should have quite similar acceleration distributions.

Key words: Sun: coronal mass ejections – Sun: filaments – Sun: flares.

1 INTRODUCTION
The question of whether there exist two different classes of coronal mass ejections (CMEs) has emerged as one of the main issues in CME research (Dryer 1996; Sheeley et al. 1999; Andrews & Howard 2001; Moon et al. 2004). 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 slower events were associated with eruptive prominences. Several years later, MacQueen & Fisher (1983) suggested that CMEs be classified into two types by analysing the height–speed plots of 12 loop-like CMEs observed with the Mauna Loa K-coronameter covering 1.2–2.4 R⊙. In their study, flare-associated CMEs showed higher speeds and little acceleration, whereas CMEs associated with eruptive filaments exhibited lower speeds and large acceleration.

The concept of two distinct CME classes is widely employed to interpret various aspects of CMEs (Dryer 1996; Sheeley et al. 1999; Andrews & Howard 2001; Low & Zhang 2002; Moon et al. 2002; Chen & Krall 2003; Moon et al. 2004). However, very recently, Yurchyshyn et al. (2005) found that the speed distributions for accelerating and decelerating CME events are nearly identical and to a good approximation they can be fitted with a single lognormal distribution. They pointed out that the lognormal distribution of the CME speeds suggests that the same driving mechanism of a non-linear nature is acting in both slow and fast dynamical types of CMEs. Then, Vršnak, Sudar & Ruždjak (2005) pointed out that the speed 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. A similar conclusion was drawn by Chen, Chen & Fang (2006). They found that CMEs associated solely with flares (FL CMEs) and CMEs associated solely with filament eruptions (FE CMEs) have quite similar speed distributions, with almost the same average values, which suggests that they are a continuum of events rather than two distinct types.

However, the aforementioned speed and acceleration of the CMEs are subject to the projection effect, especially for the CME events propagating far from the plane of sky (Yeh, Ding & Chen 2005). For halo CMEs, Xie, Ofman & Lawrence (2004) improved the cone model proposed by Zhao, Plunkett & Liu (2002) and developed a method to obtain the actual CME parameters. Michalek, Gopalswamy & Yashiro (2003) presented another technique to derive the corrected parameters of halo CMEs and statistically studied the characteristics of a sample of halo CMEs. It was found that after correction these halo CMEs have an average speed of 1080 km s⁻¹, and they are 20 per cent larger than the speeds measured in the plane of the sky. For non-halo CMEs, with the assumption that each CME is like a cone with the front described by an arc of a circle, Hundhausen, Burkepile & St. Cyr (1994), Leblanc et al. (2001) and Yeh et al. (2005) developed a method to correct the projection effect, and obtained the real CME speeds. Vršnak et al. (2007) considered three different CME cone models frequently used in CME studies and derived three corresponding formulae to relate the plane-of-sky
speed and the real speed. Recently, through considerations of CME trajectories in three-dimensional (3D) geometry, Howard, Nandy & Koepke (2008) devised a methodology to correct for the projection effect. Using this method, the corrected speed and acceleration can be obtained.

In this paper, using the method of Howard et al. (2008), we investigate, before and after the projection correction, the speed and acceleration distributions for 1747 FL CMEs and 631 FE CMEs observed by the Large Angle and Spectrometric Coronagraph on board the Solar and Heliospheric Observatory (SOHO/LASCO) from 1996 September to 2007 September.\(^1\)

## 2 THE METHOD

Using trigonometric considerations and the general 3D geometry, Howard et al. (2008) arrived at

\[
\frac{1}{R} = \sin \alpha \cot \epsilon + \cos \theta \cos \phi, \tag{1}
\]

where \(R\) is the deprojected distance of the measured point from the Sun (Howard et al. 2007), \(\epsilon\) is obtained from distance observed by SOHO/LASCO, distance in solar radii \(\sim 216\) (Howard et al. 2008), \(\phi\) is the longitude of the associated surface event and \(\theta\) is the latitude of CME. For each CME measurement, the observed central position angle (CPA) was converted to solar latitude, which was used in preference to the latitude of the associated surface event. This is because the associated surface events are more commonly associated with only one footpoint of the CME and therefore it may not be a true indicator of the ‘central latitude’ of the whole CME structure (Howard et al. 2008). In this paper, halo CMEs (with an apparent angular width of \(360^\circ\)) are excluded for which the CPAs cannot be determined. SOHO/LASCO has observed 394 halo CMEs from 1996 September to 2007 September, or 3.1 per cent of all the 12717 CMEs recorded.

Differentiating equation (1) with respect to time and assuming that CMEs propagate radially, Howard et al. (2008) obtained

\[
V_{3D} = \frac{dR}{dt} = R^2 \sin \alpha \csc^2 \epsilon \frac{de}{dt}, \tag{3}
\]

and

\[
A_{3D} = \frac{d^2R}{dt^2} = \frac{V_{3D}}{de/dt} \left( \frac{d \epsilon}{dt^2} \right) + 2V_{3D} \left[ \frac{V_{3D}}{R} - \cot \epsilon \frac{d \epsilon}{dt} \right], \tag{4}
\]

where

\[
\frac{de}{dt} = V_0 \sec \epsilon \tag{5}
\]

and

\[
\frac{d^2 \epsilon}{dt^2} = A_0 \sec \epsilon + V_0^2 \tan \epsilon \sec^2 \epsilon. \tag{6}
\]

Here, \(V_{3D}\) and \(A_{3D}\) are the corrected speed and acceleration, respectively, and \(V_0\) and \(A_0\) are the sky-plane projected speed and acceleration, respectively. It is noted that in the above formulae \(\epsilon\) should be deduced from certain procedures.

### 2.1 Determination of \(\epsilon\)

In this paper, we consider those CMEs that associate solely with flares (FL CMEs)\(^2\) or filament eruptions (FE CMEs).\(^3\) The Large Angle and Spectrometric Coronagraph (LASCO) instrument consists of a set of three nested coronagraphs with overlapping and concentric fields of view: C1 (1.1–3 \(R_\odot\)), C2 (2–6 \(R_\odot\)) and C3 (4–30 \(R_\odot\)). The C1 images, which have an unprecedented view of the low corona (Plunkett et al. 1997; Schwenn et al. 1997), provide key information on the early evolution of CMEs. C2 and C3 are traditional externally occulted white-light coronagraphs that observe Thomson-scattered visible light through a broad-band filter. Zhang et al. (2001) investigated the temporal relationship between CMEs and X-ray flares by making use of observations with the LASCO, which covers the corona from 1.1 to 30 \(R_\odot\) and found that the impulsive acceleration phase of a CME coincides very well with the rise phase of the accompanying soft X-ray flare. However, the telescope C1 was disabled in 1998 June, that is to say, the acceleration phase cannot be observed by LASCO for most CME events. Thus, we followed the conventional way of assuming that the acceleration phase of each CME is within a time window that is generally set to \(\pm 1\) h, relative to the estimated CME onset time. X-ray flare events higher than the B1.0 class in the Solar-Geophysical Data (SGD) reports are searched during the time window. The flare that occurs during this window and that is located within the angular span of the CME is considered to be associated with the CME. That is to say, the flare associated with the CME is determined with the following steps. (1) The CME onset times obtained by extrapolating the linear fit to the solar surface (height \(= 1\) solar radius) are adopted. (2) All X-ray flares within \(\pm 1\) h time window are selected from the SGD database, while only those flares that are located within the angular span of the CME are chosen for the candidate flares associated with the CMEs (Yeh et al. 2005). (3) If more than one candidate flare exists after the above steps, the one with the peak time closest to the CME onset time is uniquely determined as the flare associated with this CMEs (Yeh et al. 2005).

In the SGD reports, if the X-ray solar flare is correlated to an optical flare prior to 1997, the start time of X-ray solar flare is for the optical flare; for data after 1996, these start times of X-ray solar flares will be for the X-ray flares only. For Geostationary Operational Environmental Satellites (GOES) X-ray flare events, the event starts when four consecutive 1-min X-ray values have met all three of the following conditions: (1) all four values are above the B1.0 threshold; (2) all four values are strictly increasing and (3) the last value is greater than 1.4 times the value which occurred 3 min earlier. There is some uncertainty when the start time of X-ray solar flare is used. The peak time of X-ray solar flare is the time when the flux value reaches maximum. That is to say, we can accurately determine the peak time of X-ray solar flare. The discrepancy between the start time and the peak time of X-ray solar flare is only about 10 min, which is much less than the \(\pm 1\) h time window. Thus, we use flare peak time rather than start time.

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

\(^2\) The date of solar flare used here is available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES.

\(^3\) The date of filament eruption used here is available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FILAMENTS.
±1.5 h relative to the above-estimated CME onset time was set to judge the association with a filament eruption (Chen et al. 2006). It should be kept in mind that for FE CMEs, we mean ‘associated solely with filament eruptions’ that there are no soft X-ray flares above B1.0 class recorded in the SGD reports and vice versa. Given the projected speed, acceleration (V_0 and A_0), the observed distance and the CPA from the SOHO LASCO CME Catalogue, the longitude of the associated surface events (determined in Section 2.1) from the SGD data base, determine the corrected speed and acceleration (V_3D and A_3D) by using equations (3) and (4), respectively.

### 3 RESULTS

The minimum between Cycles 22 and 23 occurred in 1996 September (Harvey & White 1999), so we study the activity of CMEs from 1996 September to 2007 September. There are in total about 12717 CMEs observed by SOHO/LASCO in the interval from 1996 September to 2007 September. We select the CMEs that are associated solely with flares or filament eruptions in both timing and spatiality, as described in detail in Section 2.1. There are 1747 FL CMEs and 631 FE CMEs.

#### 3.1 Speed distributions of FL and FE CMEs

Before correction, we plot the speed distributions of FL and FE CMEs, shown in Fig. 1. The probabilities in 100 km s\(^{-1}\) intervals are obtained by dividing the number of CMEs in each bin by the total number of CMEs. All 28 FL CMEs and 10 FE CMEs with the sky-plane projected speed higher than 1200 km s\(^{-1}\) are binned in the 1200–1300 km s\(^{-1}\) interval. The average speed in each case is given.

![Figure 1](https://academic.oup.com/mnras/article-abstract/394/2/1031/1072908)

**Figure 1.** The speed distributions before correction for FL CMEs (top panel, vertical bars) and FE CMEs (bottom panel, vertical bars). All 28 FL CMEs and 10 FE CMEs with the sky-plane projected speed higher than 1200 km s\(^{-1}\) are binned in the 1200–1300 km s\(^{-1}\) interval. The average speed in each case is given.

![Figure 2](https://academic.oup.com/mnras/article-abstract/394/2/1031/1072908)

**Figure 2.** The speed distributions after correction for FL CMEs (top panel, vertical bars) and FE CMEs (bottom panel, vertical bars). All 32 FL CMEs and 22 FE CMEs with the corrected speed higher than 2200 km s\(^{-1}\) are binned in the 2200–2300 km s\(^{-1}\) interval. The average speed in each case is given.

The results of \(\chi^2\) test are given in Table 1. The average speeds before correction for FL and FE CMEs are 455.8 ± 5.8 and 451.7 ± 10.3 km s\(^{-1}\), respectively. The error represents the uncertainty in the average \(\sigma/(n)^{1/2}\), where \(\sigma\) is the standard deviation and \(n\) is the number of data points.

Table 1. The results of \(\chi^2\) test.

<table>
<thead>
<tr>
<th></th>
<th>(\chi^2)</th>
<th>(P)</th>
<th>Reduced (\chi^2)</th>
<th>Degrees of freedom</th>
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<tbody>
<tr>
<td>Speed distributions of FL and FE CMEs</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Before the correction</td>
<td>20.5</td>
<td>0.058</td>
<td>1.70</td>
<td>12</td>
</tr>
<tr>
<td>After the correction</td>
<td>29.0</td>
<td>0.14</td>
<td>1.31</td>
<td>22</td>
</tr>
<tr>
<td>Before the correction (natural logarithm)</td>
<td>49.8</td>
<td>0.36</td>
<td>1.05</td>
<td>47</td>
</tr>
<tr>
<td>After the correction (natural logarithm)</td>
<td>60.1</td>
<td>0.43</td>
<td>1.01</td>
<td>59</td>
</tr>
<tr>
<td>Acceleration distributions of FL and FE CMEs</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Before the correction</td>
<td>30.4</td>
<td>0.046</td>
<td>1.60</td>
<td>19</td>
</tr>
<tr>
<td>After the correction</td>
<td>13.5</td>
<td>0.81</td>
<td>0.71</td>
<td>19</td>
</tr>
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</table>

Then, we correct the projection effect and obtain the real speeds of 1747 FL CMEs and 631 FE CMEs, as described in detail in Section 2, and plot the speed distribution after the correction of FL and FE CMEs, shown in Fig. 2. All 32 FL CMEs and 22 FE CMEs with the corrected speed higher than 2200 km s\(^{-1}\) are binned in the 2200–2300 km s\(^{-1}\) interval. It is found that, after the correction, the speed distributions for FL and FE CMEs are statistically different from each other at 94.2 per cent confidence levels. The result of \(\chi^2\) test is collected in Table 1. The average speeds after correction for FL and FE CMEs are 679.3 ± 13.0 and 712.2 ± 24.5 km s\(^{-1}\), respectively. That is to say, the FE CMEs are slightly faster than the FL CMEs.

Before and after the correction, we also plot the probability distributions of both FL and FE CMEs versus the natural logarithm of their speeds, shown in Figs 3 and 4. A \(\chi^2\) test is also performed on these distributions. It is found that, before correction, the
The distributions of natural logarithm of speeds for FL and FE CMEs are statistically different from each other at 64 per cent confidence levels ($\chi^2 = 49.8$, with degrees of freedom $= 47$ and probability $P = 0.36$) and, after the correction, the distributions of natural logarithm of speeds for FL and FE CMEs are statistically different from each other at 57 per cent confidence levels ($\chi^2 = 60.1$, with degrees of freedom $= 59$ and probability $P = 0.43$). These confidence levels are low. However, we can conclude that, before and after the correction, FL and FE CMEs do not show similar distributions of natural logarithm of speeds.

The average speeds after correction for FL and FE CMEs are 32.8 and 36.5 per cent larger than the corresponding sky-plane projected speeds consistent with Michalek et al. (2003) and Yeh et al. (2005). Before the correction, the average speeds of FL and FE CMEs are close to each other consistent with Chen et al. (2006). However, after the correction, the FE CMEs are slightly faster than the FL CMEs. The speed distributions before the correction for FL and FE CMEs are statistically different from each other; after the correction, the speed distributions for FL and FE CMEs should also be statistically different from each other. This finding implies that, statistically, there is a physical distinction between FL and FE CMEs.

### 3.2 Acceleration distributions of FL and FE CMEs

Before and after the correction, we plot the acceleration distributions of FL and FE CMEs, shown in Figs 5 and 6. The median accelerations before correction for FL and FE CMEs are 0.20 and 0.80 m s$^{-2}$, respectively. After the correction, the median accelerations for FL and FE CMEs are 0.25 and 1.0 m s$^{-2}$, respectively. From the median acceleration in each case, we find that, before and after the correction, the acceleration distribution of FE CMEs is somewhat shifted to positive values. Then we inspect, before and after the correction, whether the acceleration distributions for FL and FE CMEs have a statistically significant difference or not. The method used here is also the $\chi^2$ test. Before the correction, the acceleration distributions for FL and FE CMEs are statistically different from each other at 95.4 per cent confidence levels ($\chi^2 = 30.4$, with degrees of freedom $= 19$ and probability $P = 0.046$). However, after the correction, FL and FE CMEs have quite similar acceleration distributions at 81 per cent confidence levels ($\chi^2 = 13.5$, with degrees of freedom $= 19$ and probability $P = 0.81$).

### 4 CONCLUSIONS AND DISCUSSION

In this paper, using the method on the basis of trigonometric considerations and the general 3D geometry to correct the projection effect for speed and acceleration of CMEs (Howard et al. 2008), we study the speed and acceleration distributions of CMEs before and after correction. 1747 FL CMEs and 631 FE CMEs from 1996 September to 2007 September are selected for this statistical study, which requires that there is solely a flare-association or filament eruption-association. The main results of our statistical study can be summarized as follows. (1) Before the correction, the speed distributions for FL and FE CMEs are statistically different from each other; after the correction, the speed distributions for FL and FE CMEs are not statistically different from each other at 64 per cent confidence levels ($\chi^2 = 49.8$, with degrees of freedom $= 47$ and probability $P = 0.36$) and, after the correction, the distributions of natural logarithm of speeds for FL and FE CMEs are statistically different from each other at 57 per cent confidence levels ($\chi^2 = 60.1$, with degrees of freedom $= 59$ and probability $P = 0.43$). These confidence levels are low. However, we can conclude that, before and after the correction, FL and FE CMEs do not show similar distributions of natural logarithm of speeds.

The average speeds after correction for FL and FE CMEs are 32.8 and 36.5 per cent larger than the corresponding sky-plane projected speeds consistent with Michalek et al. (2003) and Yeh et al. (2005). Before the correction, the average speeds of FL and FE CMEs are close to each other consistent with Chen et al. (2006). However, after the correction, the FE CMEs are slightly faster than the FL CMEs. The speed distributions before the correction for FL and FE CMEs are statistically different from each other; after the correction, the speed distributions for FL and FE CMEs should also be statistically different from each other. This finding implies that, statistically, there is a physical distinction between FL and FE CMEs.
CMEs should also be statistically different from each other. Before the correction, the average speeds of FL and FE CMEs are close to each other. But, after the correction, the FE CMEs are slightly faster than the FL CMEs. (2) Before the correction, the acceleration distributions for FL and FE CMEs are statistically different from each other. However, after the correction, FL and FE CMEs should have quite similar acceleration distributions.

Traditionally, CMEs are classified into two distinct types, i.e. slow CMEs that are associated with filament eruptions (large acceleration) and fast CMEs associated with solar flares (little acceleration) (Gosling et al. 1976; MacQueen & Fisher 1983; Sheeley et al. 1999; Andrews & Howard 2001; Low & Zhang 2002; Moon et al. 2002; Chen & Krall 2003; Moon et al. 2004). However, recently, Yurchyshyn et al. (2005) found that the lognormal distribution of CME speed for accelerating and decelerating CME events are nearly identical. Then, Chen et al. (2006) also found that FE and FL CMEs have quite similar speed distributions, which suggests that they are a continuum of events rather than two distinct types. Here, we note that our result is, before correction, the speed distributions for FL and FE CMEs are statistically different from each other. The discrepancy should be due to the different time intervals considered: Yurchyshyn et al. (2005) analysed the distribution of CME’s speeds in the interval from 1996 to 2001; Chen et al. (2006) analysed CME events observed from 2001 to 2003, i.e. the ascending time and the maximum period of Cycle 23, respectively, while we analysed the interval from 1996 September to 2007 September, almost a complete solar cycle. However, the aforementioned speed of CMEs are subject to the projection effect. Thus, our result – after the correction, the speed distributions for FL and FE CMEs should also be statistically different from each other – indicates that there is physical distinction between FL and FE CMEs.

In general, the dynamics of solar ejecta are believed to be determined by the Lorentz and pressure forces (VeSiǎk 1990; Chen 1996; Yurchyshyn et al. 2005). The Lorentz force is related to the amount of magnetic flux confined in the erupted field. Qu & Yurchyshyn (2005) found, by studying flare-associated CMEs, that the speed of CMEs is linearly proportional to the total magnetic flux that is swept by flare ribbons. Similarly, the results of Chen et al. (2006) indicate that, for the filament-associated CMEs, the speed of CMEs is also roughly linearly correlated with the total magnetic flux in the filament channel. However, they found that the correlation between the speed of CMEs 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 Carmichael, Sturrock, Hirayama, Kopp & Pneuman (CSHKP) model (Svestka & Cliver 1992; Yashiro et al. 2008). The model requires that a flare occurs just underneath an erupting filament which eventually becomes the core of the CME associated with the flare. That is to say, 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 speed is roughly linearly proportional to $B$ (Chen et al. 2006). Of course, the aforementioned speed of CMEs is the projected speeds of CMEs. Our conclusion is that the projected speeds of FL and FE CMEs, as two groups, are close to each other and consistent with the result of Chen et al. (2006). However, after the correction, the FE CMEs are slightly faster than the FL CMEs.

It must be pointed out that the usage of associated surface events may introduce a source of error in this work. Flare locations are straightforward, as flares are little more than point sources on the Sun. Filaments, however, often have extended sizes/lengths on the solar disc, and usually only their central locations are listed. This means that if most flares are at a footpoint of the CME and if most filaments span the entire length of the CME, then the filament locations might be more accurate or at least done differently than for the flares. When we apply the assumption that the latitude of CME is that of the CPA for FL CMEs and is that of central location of filament for FE CMEs, we can also obtain the results: after the correction, the acceleration distributions for FL and FE CMEs should be statistically different from each other; FL and FE CMEs do not show similar distributions of natural logarithm of speeds; the FL and FE CMEs should have quite similar acceleration distributions. Of course, the results of $\chi^2$ test have a slight change, these results are shown in Table 2. However, the average speeds after correction for FL and FE CMEs are $679.3 \pm 13.0$ and $675.5 \pm 20.8$ km s$^{-1}$. That is to say, the latitude of CME for correction may be sufficient to produce corrected speeds that are slightly higher for the FE CMEs than the FL CMEs. We expect that 3D observations with Solar Terrestrial Relations Observatory (STEREO) will confirm our results and determine the relationship between corrected speeds of FL and FE CMEs. But, we cannot know why, before the correction, the acceleration distributions for FL and FE CMEs are statistically different from each other, however, after the correction, FL and FE CMEs should have quite similar acceleration distributions.

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<td>59</td>
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<tr>
<td>After the correction</td>
<td>11.7</td>
<td>0.89</td>
<td>0.61</td>
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