A STATISTICAL STUDY OF THE POST-IMPULSIVE-PHASE ACCELERATION OF FLARE-ASSOCIATED CORONAL MASS EJECTIONS

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ABSTRACT

It is now generally accepted that the impulsive acceleration of a coronal mass ejection (CME) in the inner corona is closely correlated in time with the main energy release of the associated solar flare. In this paper, we examine in detail the post-impulsive-phase acceleration of a CME in the outer corona, which is the phase of evolution immediately following the main impulsive acceleration of the CME; this phase is believed to correspond to the decay phase of the associated flare. This observational study is based on a statistical sample of 247 CMEs that are associated with M- and X-class GOES soft X-ray flares from 1996 to 2006. We find that, from many examples of events, the CMEs associated with flares with long-decay time (or so-called long-duration flares) tend to have positive post-impulsive-phase acceleration, even though some of them have already obtained a high speed at the end of the impulsive acceleration but do not show a deceleration expected from the aerodynamic dragging of the background solar wind. On the other hand, the CMEs associated with flares of short-decay time tend to have significant deceleration. In the scattering plot of all events, there is a weak correlation between CME post-impulsive-phase acceleration and flare decay time. The CMEs deviated from the general trend are mostly slow or weak ones associated with flares of short-decay time; the deviation is caused by the relatively stronger solar wind dragging force for these events. The implications of our results on CME dynamics and CME–flare relations are discussed.

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

1. INTRODUCTION

Coronal mass ejections (CMEs) are large-scale solar activities which can release a vast amount of plasma and magnetic flux into the outer space and cause interplanetary disturbances and geomagnetic storms near the Earth (Gosling 1993; Webb et al. 1994). Flares are viewed as strong energy release in the lower atmosphere of the Sun, where CMEs originate from but then depart from the Sun. The physical relationship between CMEs and flares has been a long-standing elusive issue in solar physics (Kahler 1992; Gosling 1993; Hundhausen 1999). Nevertheless, recent studies demonstrate that there is a strong physical connection between CMEs and flares. Zhang et al. (2001, 2004) studied the whole kinematic process of CMEs and found that those CMEs associated with flares usually undergo three distinct phases of evolution: the initiation phase, impulsive acceleration phase (mainly in the inner corona, \( \lesssim 3.0 R_\odot \)), and propagation phase (mostly in the outer corona). Furthermore, it was found that the three kinematic phases of CMEs coincide in time very well with the three phases of the associated flares: the pre-flare phase, flare main energy release phase or rise phase in soft X-ray (SXR), and flare decay phase, respectively (Zhang et al. 2001; Burkepile et al. 2004; Vršnak & Skender 2005). Recently, Temmer et al. (2008) analyzed the kinematics of two fast halo CMEs in the inner corona and found that there was a close connection between the acceleration profiles of the CMEs and the HXR light curves of the related flares. The almost synchronized temporal correlation between CME acceleration and flare flux increase indicates that both are driven by the same energy release process in the corona, especially within the impulsive phase. In other words, the dynamic evolution of these two phenomena may be different manifestation of the same energetic process, presumably via magnetic reconnection (Lin & Forbes 2000; Priest & Forbes 2002; Vršnak et al. 2004; Zhang & Dere 2006; Maričić et al. 2007; Temmer et al. 2008).

Therefore, there is no apparent cause–effect relation between them, i.e., they do not cause one another.

In statistical views, the more intensive the flares are, the greater the possibility of the flares being associated with CMEs is (Andrews 2003; Yashiro et al. 2005). Yashiro et al. (2006) studied the power-law indices of the frequency distribution of flares, and found that flares with CMEs have a harder index of distribution than that of flares without CMEs. Zhang & Golub (2003) found that flares associated with fast CMEs show clear footpoint-separating and two-ribbon brightening, while this feature appears less often in flares associated with slow CMEs or without CMEs. MacQueen & Fisher (1983) and recently St. Cyr et al. (1999) found that CMEs associated with flares or active regions have relatively higher speeds and tend to propagate with a constant speed or a negative acceleration in the outer corona, while ones associated with eruptive filaments have an initial slow speed and a positive acceleration in the outer corona. Using the latest CDAW CME catalog, Moon et al. (2002) also found similar results.

Nevertheless, the detailed relationship between the CME evolution following the impulsive acceleration phase and the properties of the flare decay phase has not been studied. Prior to LASCO, CMEs were commonly thought to propagate with nearly constant speed. Now we know that CMEs usually have a small acceleration or deceleration in the outer corona (about between 3.0 and 30.0 \( R_\odot \)) after they have been strongly accelerated in the inner corona (Andrews & Howard 2001; Neupert et al. 2001; Zhang et al. 2001; Gallagher et al. 2003; Shammugadass et al. 2003). But how this late evolution, dubbed as “post-impulsive-phase acceleration,” is related to flare characteristics is not clear, and therefore a detailed study on this issue is desirable. To quantify such evolution of CMEs, we introduce a fixed time window of 2 hr beginning at the peak
time of the associated flare to calculate the acceleration (details of methods given in the next section). It is noted that the post-impulsive-phase acceleration is likely related to the residual acceleration originally proposed by Chen & Krall (2003). Based on their theoretical flux-rope model, Chen & Krall (2003) specified the residual acceleration (different from the main acceleration) to the acceleration of the period that Lorentz self-force is decreased and the dragging force of solar wind starts to dominate. In the observational context, the residual acceleration was used by Zhang & Dere (2006) in a more general sense to refer to the observed velocity change of CMEs following the impulsive acceleration phase, which can be practically separated by the peak time of the associated SXR flares. In this paper, we investigate the post-impulsive-phase acceleration through both a case study of a variety of typical events and a statistical study as well. The main finding is that CMEs associated with long-decay flares tend to have positive post-impulsive-phase acceleration, and thus are more likely to reach a higher peak speed. In Section 2, we present the observations. Example events of diversified properties are presented in Section 3. Our statistical results on post-impulsive-phase accelerations are shown in Section 4. The more general relations between CMEs and flares are given in Section 5 followed by a summary and discussions in Section 6.

2. OBSERVATIONS AND DATA

In this study, we make use of CMEs observed during 1996–2006 by the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO). The two complementing LASCO coronagraphs, C2 and C3, have fields of view (FOVs) of 2.2–6.0 R⊙ and 4.0–30 R⊙, respectively. Flare data are from GOES satellites providing the full disk SXR emission from the Sun in 1–8 Å. The RHessi (Reuven Ramaty High Energy Solar Spectroscopic Imager; Lin et al. 2002) and Yohkoh Soft X-ray Telescope (SXT) provide the hard X-ray light curves for some of the flares studied in this paper. However, the hard-X-ray flare data do not enter the statistical study in this paper.

From 1996 to 2006, there are in total about 11,536 CMEs observed by LASCO according to the CDAW CME catalog, and 22,686 flares seen by GOES based on the NOAA flare catalog. Because of the sheer number, we limit our study only to major flares; these are 1425 M-class and 120 X-class flares—1545 in total. In order to find out only those flares associated with CMEs (the so-called eruptive flares), an easy and quick approach is to use the so-called time-window method, without resorting to inspecting images (Harrison 1995; Yashiro et al. 2005). The CME onset time is estimated through a backward extrapolation to the surface at 1.0 R⊙ from the height–time observations in coronagraph assuming a constant velocity. An association is assumed if a flare occurs within a certain time window centered at the estimated CME onset time, e.g., ±60 minutes. We find that this simple time-window method can make successful associations for most of the events (~85%). However, there is a certain percentage of wrong associations, which may not be acceptable for serious studies, e.g., the work presented in this paper and predicting CMEs from flare observations. The wrong associations arise from chance association, e.g., between a confined solar flare occurring on the front-side of the Sun and a CME occurring on the back-side of the Sun.

In this paper, we use a stricter method to associate flares and CMEs by visually inspecting the movies observed by LASCO and those by the Extreme-ultraviolet Imaging Telescope (EIT, also on board SOHO: Delaboudinière et al. 1995) one by one, although it is tedious and time consuming. In addition to its use in identifying the location of flares through transient brightening in a small compact patch, EIT data are also commonly used to identify the source region of CMEs through the signature of large scale dimming and/or wave, which are often prominent for major eruptions. The CME is taken to be associated with a flare if the temporal–spatial co-registration of transient flare brightening and the large-scale dimming on EIT images occurs, which is the most reliable way to associate flares and CMEs.

Among the 1545 major solar flares recorded by NOAA, 1246 events have both EIT and LASCO observations; the other 299 flares occurred in a period of either EIT or LASCO data gap (or both). For these 1246 flares, we find that 706 events (56.6%) are associated with CMEs, while the other 540 flares (43.4%) are confined. These confined flares will not be used in this study. Further, we eliminate those events with less than five effective snapshot observations during the 2 hr window of calculating the post-impulsive-phase acceleration (explained in the next paragraph). We also remove those events without effective C2 observations. In the end, we obtain 247 flare–CME pairs suitable for study in this paper.

To determine the magnitude of the post-impulsive-phase acceleration, we calculate the average acceleration within the fixed time window of 2 hr beginning at the peak time of the associated flare. While the post-impulsive-phase refers to the CME evolution, we have adopted the flare peak time as the proxy of the starting time of this CME phase. The starting time is difficult to determine directly from CME observations due to the poor cadence and the lack of inner coronal observations of LASCO (except for a small number of events). Further, we believe that this proxy is a reasonable one because of the temporal coincidence between CME kinematic evolutions and flare flux variations (e.g., Zhang et al. 2001). The average acceleration is obtained through the second-order polynomial fitting of the observed height–time measurements in this window. We believe that such an average acceleration value is an effective representation of the post-impulsive-phase acceleration of the CME, whereas its validity may need to be further demonstrated by using observations with higher cadence. As for the method of the fixed time window, we think that it is a good approach in characterizing relevant observation. In this approach, the beginning time of the post-impulsive-phase acceleration phase is uniform and well defined; that is the peak time of the associated flare. On the other hand, for this type of observational study of calculating an average property from a limited number of data points, one has to choose the most appropriate window. We think that the selection of a 2 hr window is reasonable; it is long enough to obtain a sufficient number of data points to make a second-order polynomial fitting to the CME height–time measurement, while it is short enough to differentiate the coronal effect on the dynamic evolution from the otherwise dominant solar wind effect on CME evolution in the later phase of the propagation in the LASCO FOV. Furthermore, we have checked the influence of different time windows on the data and find that there is always a weak correlation between the CME post-impulsive-phase acceleration and the associated-flare decay time. Therefore, similar results are obtained if a different time window is adopted. Note that the average acceleration through the fixed time window carries a much smaller error than the uncertainty inferred from any piecewise fitting method. In general, the
acceleration is much more difficult to calculate than the speed due to the nature of differentiation on discrete data points; the error bars in the acceleration values are significantly larger than those in the speed values (Zhang & Dere 2006; Yashiro et al. 2004). For one specific data point, the acceleration error could be comparable to the inferred acceleration value. However, the error in the average acceleration based on the second-order polynomial fitting of at least five observed height–time measurements becomes significantly smaller.

3. EXAMPLES

Before we show the statistical properties of CME post-impulsive-phase acceleration and flare decay time, we present in detail four individual events, two of which are of positive acceleration and the other two are of negative acceleration. The overall properties of these four events are summarized in Table 1, including CME velocity, impulsive acceleration, post-impulsive-phase acceleration, acceleration error, flare rise time, decay time, location, and peak intensity.

### Table 1
Properties of Four Typical CME–Flare Events

| Event       | Property | Velocity (km s⁻¹) | Im. Acc (km s⁻²) | Post. Acc (km s⁻²) (errors) | Rise (minutes) | Decay (minutes) | Location (deg) | Magnitude |
|-------------|----------|------------------|------------------|------------------------------|----------------|----------------|----------------|----------|
| 2001 Sep 24 | A-L      | 2402             | 455              | 64 (±58)                     | 66             | 31             | S16E23         | X2.6     |
| 2003 Nov 18 | A-L      | 1821             | 632              | 40 (±36)                     | 48             | 50             | S14E89         | M4.5     |
| 2004 Oct 20 | D-S      | 763              | 1589             | −71 (±37)                    | 8              | 5              | N11E68         | M2.6     |
| 2005 Aug 25 | D-S      | 1327             | 2453             | −129 (±41)                   | 9              | 5              | N09E80         | M6.4     |

### Notes.

a Magnitude of impulsive acceleration.

b Magnitude of post-impulsive-phase acceleration.

3.1. CME Positive Post-impulsive-phase-acceleration and Flare Long-decay Time

3.1.1. 2001 September 24 Event

The CME on 2001 September 24 is associated with a GOES X2.6 class flare. Figure 1 shows the velocity–time plot of the CME (broken lines with symbols) along with the GOES X-ray time profiles (solid line). The CME onset time, estimated through linear extrapolation of the height–time measurement, was at 10:21 UT while the associated flare started at 09:32 UT; there is a 49 minute difference between the two onset times. We argue that if inner corona observation were available, one would expect to find that the CME onset time coincide with the flare onset, probably within a few minutes. The time difference we find here is due to the usage of linear extrapolation assuming a constant speed in the inner corona, which is apparently an over-simplification of the true evolution involving significant acceleration from almost zero speed to the final speed (e.g., Zhang et al. 2001). The heliographic location of the flare was S16 E23, which is consistent with the CME feature position angle of 142°. The feature position angle is defined as the most distinguishable feature used to measure the height. Here, we use the feature position angle instead of the center position angle because the CME is a halo CME when it appears in the FOV of LASCO/C3. The CME first appeared in the FOV of the C2 image at 10:30 UT at a height of 3.3 R☉ from the disk center. As shown in Figure 1, the CME reached a velocity at about 2000 km s⁻¹ at the peak time of the flare. What is important of this event is that it continued to accelerate during 2 hr after the peak time of the flare, from about 2000 to 2500 km s⁻¹; during this period, the CME leading edge (LE) moved from about 3 R☉ to 25 R☉. The post-impulsive-phase acceleration during the fixed time window is about 64 m s⁻², as determined by the second-order polynomial fitting of the height–time measurements. On the other hand, the inferred CME impulsive acceleration during the impulsive acceleration phase is about 455 m s⁻², using the flare rise time as a proxy of the time of CME impulsive acceleration (Zhang & Dere 2006).

Note that the uncertainty of the CME speed comes mainly from the uncertainty in height measurements, which are estimated to be about 8 pixels in the original images, or about 0.10 and 0.47 R☉ for C2 and C3, respectively. In the same way, the uncertainty in height measurements also determined the acceleration uncertainty, which is ±58 m s⁻² for this event. The same uncertainties are used for other events discussed in this paper. We note that the uncertainties may be even larger than that determined for CME events with less sharp LEs. The flare peaked at 10:38 UT and ended at 11:09 UT with a decay time of 31 minutes; the ending time is defined by NOAA as the time of the half-maximum. The flare is apparently a long decay
flares as seen from the temporal profile of the SXR emission in Figure 1. The decay phase lasts longer than the radiation cooling timescale (about 20 minutes), so there must be the continuing energy released to delay the radiation cooling time. We believe that the observed post-impulsive-phase acceleration of this CME is related with the continuing energy release following the impulsive energy release phase known for such a long-decay flare. Continuing driving force is needed, not only to overcome the aerodynamic dragging force of the background solar wind, but also to further accelerate the CME.

3.1.2. 2003 November 18 Event

The CME on 2003 November 18 is another example of events showing positive post-impulsive-phase acceleration. It is a CME associated with a GOES M4.5 class flare (Figure 2). The estimated CME onset time from linear extrapolation is 9:43 UT and the associated flare started at 9:23 UT. The heliographic coordinate of the flare was S14 E89 and the feature position angle of the CME that was about 87°. The CME first appeared in the FOV of C2 at 9:50 UT at a height of 2.9 \( R_\odot \). As from Figure 2, the CME was continuously accelerated from about 1300 to 1900 km s\(^{-1}\) for 2 hr after the peak time of the flare. The post-impulsive-phase acceleration and its error of the CME are about 40 m s\(^{-2}\) and ±36 m s\(^{-2}\), respectively. The flare peaked at 10:11 UT and ended at 10:56 UT with a decay time of only 5 minutes. This event indicates that a CME, when associated with a short decay flare, lacks the continuing driving force and therefore suffers significant deceleration after the impulsive acceleration phase.

3.2. CME Negative Post-impulsive-phase-acceleration and Flare Short-decay Time

3.2.1. 2004 October 20 Event

Different from the previous two events, we show examples of CMEs with negative post-impulsive-phase acceleration, or deceleration following the impulsive acceleration phase. In Figure 3, we show a CME that occurred on 2004 October 20 and was associated with a GOES M2.6 class flare. The CME onset time was 10:32 UT and the associated flare started at 10:43 UT. The position of the flare was N11 E68. The center position angle and width of the CME were 68° and 123°, respectively. It is evident that the CME was decelerated from about 1100 to 700 km s\(^{-1}\) for 2 hr after the peak time of the flare, as seen from the velocity profile of the event in Figure 3. The post-impulsive-phase acceleration and its error of the CME are about –71 m s\(^{-2}\) and ±37 m s\(^{-2}\) in the fixed time window, respectively. The flare peaked at 10:51 UT and ended at 10:56 UT with a decay time of only 5 minutes. This event indicates that a CME, when associated with a short decay flare, lacks the continuing driving force and therefore suffers significant deceleration after the impulsive acceleration phase.

3.2.2. 2005 August 25 Event

The following is another example of CMEs of negative post-impulsive-phase acceleration. The fast CME was observed on 2005 August 25 and was associated with a GOES M6.4 class flare. The CME onset time was 4:16 UT and the associated flare started at 4:31 UT. N09 E80 was the site of the flare. The center position angle and width of the CME were 75° and 146°, respectively. The LE of the CME was very sharp and can be easily identified from the running-difference images. It had a velocity of about 2000 km s\(^{-1}\) when it appeared in the FOV of C2. The velocity profile of this CME in Figure 4 shows that the CME was decelerated from about 2000 to 1400 km s\(^{-1}\) in about 2 hr. The post-impulsive-phase acceleration and its error of the CME are –129 m s\(^{-2}\) and ±41 m s\(^{-2}\), respectively. The flare peaked at 04:40 UT and ended at 04:45 UT. The decay phase of the flare lasted only 5 minutes in the SXR temporal profile.

4. STATISTICS ON CME POST-IMPULSIVE-PHASE ACCELERATION AND FLARE DECAY TIME

Having presented examples of two distinct types of events, we now look into the statistical behavior. Figure 5 shows the
distribution of the post-impulsive-phase acceleration of CMEs versus the decay time of the associated flares for all the 247 events studied. As shown by the linear fitting line in Figure 5, there is a general trend that the longer the decay time of flares, the larger the post-impulsive-phase acceleration of CMEs. On the other hand, the correlation between CME post-impulsive-phase acceleration and flare decay time is rather poor. There is an apparent-wide scattering of the parameters in both dimensions. The acceleration varies in a wide range from $-150 \text{m s}^{-2}$ to $180 \text{m s}^{-2}$ and tends to change from negative to positive, with the decay time of the associated flares increasing. The fraction of CME events with positive post-impulsive-phase acceleration apparently increases as the decay time of the associated flare increases. The mean post-impulsive-phase acceleration of all events is negative at about $-11.9 \text{m s}^{-2}$, as indicated by the solid thin line in the figure.

For the sake of clarity of discussion, we divide the events into three different groups, as enclosed by the three rectangular boxes in the figure: positive-post-impulsive-acceleration CMEs with long-decay flares (acceleration-long, or A-L), negative-post-impulsive-acceleration CMEs with short-decay flares (deceleration-short, or D-S), and positive-post-impulsive-acceleration CMEs with short-decay flares (acceleration-short, or A-S). Apparently, there is a lack of CME events of deceleration with long-decay flares; those CMEs associated with long decay flares tend to have positive post-impulsive-phase acceleration, even though they have reached a high speed at the end of the impulsive acceleration. It is commonly believed that there is a continuing energy release during the decay phase of long duration flares. Therefore, this statistical result implies that the continuing energy release also related with the continuing acceleration of CMEs in the outer corona.

Nevertheless, for events with short flare decay times, the post-impulsive-phase acceleration could be either positive or negative. One would expect that the post-impulsive-phase acceleration tends to be negative for events associated with short-decay flares, since there is no further energy available for accelerating CMEs following the main energy release phase. However, we believe that the influence of solar wind dragging force makes the matter complex. It is known that the solar wind dragging force accelerates slow CMEs and decelerates fast CMEs; the magnitude depends on the relative velocity between the CME and solar wind, the drag coefficient, and the CME cross section size (Cargill 2004). Indeed, we identify that many positive-acceleration-short-decay events (A-S) are slow CMEs. These slow CMEs also tend to be narrow and weak. Because of the slowness of these events, the positive acceleration is likely caused by the dragging force of the background solar wind, instead of the continuing energy release that only occurs in A-L type events. Further, slow and narrow CME events often appear weak in brightness and thus fuzzy in morphology as seen in coronagraph images. As a consequence, it is usually hard to trace consistent features such as LEs for these event, leading to large error in the height–time measurements and thus larger error in the derived velocity.

In Figure 6, we show a similar scattering plot as in Figure 5 but use only events with fast CME speed ($>800 \text{ km s}^{-1}$) and wide CME angular width ($>60^\circ$). The general trend between CME post-impulsive-phase acceleration and flare decay time becomes more distinct than that in Figure 5. In essence, we want to argue that, for major fast and wide CMEs, the CMEs associated with long decay-time flares tend to be further accelerated in the outer corona, overcoming the slowing-down effect of solar wind dragging on fast CMEs. The CMEs associated with short decay-time flares tend to be decelerated in the outer corona, but may gain positive acceleration due to the solar wind dragging if the initial speed is slow.

5. GENERAL STATISTICAL RELATIONS BETWEEN CME AND FLARE PROPERTIES

In this section, we describe the more general relations between CMEs and flares from a statistical point of view. In Figure 7, we show the scattering plots between CME velocity and various flare parameters, including rise time, total duration, peak flux, and total flux (or fluence). We find that the velocities of
CMEs show almost no correlation, or are weak at best, with the rise times or the total durations of the associated flares. However, there is a certain positive correlation between CME velocity and flare peak flux. This correlation has been noted before (Moon et al. 2002, 2003). The linear-fitting formula between CME velocity $V$ (km s$^{-1}$) and flare peak flux $F$ (W m$^{-2}$ s$^{-1}$) can be expressed as $V = 474.0 \log F + 2922.2$.

It is interesting that the best correlation is found between CME velocity and total flare flux or fluence; the total flux here is simply calculated through the product of the peak flux and rise time, which is controlled by the radiation cooling and also the thermal conduction to the cooler chromosphere, is only about 20 minutes (Forbes et al. 1989; Isobe et al. 2002). The impulsive acceleration coincides well with the main energy release of the associated flare (Zhang et al. 2001; Gallacher et al. 2003; Vršnak et al. 2004; Temmer et al. 2008). In this paper, we further find that the post-impulsive-phase acceleration of CMEs may be also physically related with the continuing energy release. In particular, CMEs tend to have positive post-impulsive-phase acceleration if the associated flares have a long decay phase; this kind of flares is often called long duration event (LDE). When flare decay times are short, accompanying CMEs may have mixed response, possibly with positive or negative post-impulsive-phase acceleration from event to event.

We argue that the positive post-impulsive-phase acceleration of LDE events is driven by the continuing magnetic reconnection occurring during the flare decay phase. It is widely accepted that the main energy release phase of a solar flare is driven by magnetic reconnection in the inner corona. When a flare has a long decay phase, continuing magnetic reconnection is also needed to explain the lasting thermal emission. Without the continuing energy release, the typical thermal energy decay time, which is controlled by the radiation cooling and also the thermal conduction to the cooler chromosphere, is only about 20 minutes (Forbes et al. 1989; Isobe et al. 2002). The correlation coefficient obtained here is larger than that obtained for a larger sample of events by Yashiro et al. (2004).

Finally, we show the histogram distribution of the CME/flare parameters used in this study (Figure 9). Their overall statistical properties, including minimum value, maximum value, average value, medium value, mode (or the value at maximum distribution), and standard deviation are summarized in Table 2. The mean velocity of 747 km s$^{-1}$, for the 247 major events studied in this paper, is larger than the value of 684 km s$^{-1}$ obtained by Moon et al. (2002). The mean impulsive acceleration of these CMEs is 939 m s$^{-2}$, whereas the post-impulsive-phase accelerations are limited to a small range centered near zero and the mean post-impulsive-phase acceleration is $-11.9$ m s$^{-2}$, being almost consistent with the results of Zhang & Dere (2006).

**6. SUMMARY AND DISCUSSIONS**

We have studied the statistical kinematic properties of major-flare-associated CME events occurred between 1996 and 2006, with a focus on the post-impulsive-phase acceleration. It has been well known that a typical flare-associated CME usually has a strong and impulsive acceleration in the inner corona, and that the impulsive acceleration coincides well with the main energy release of the associated flare (Zhang et al. 2001; Gallacher et al. 2003; Vršnak et al. 2004; Temmer et al. 2008). In this paper, we further find that the post-impulsive-phase acceleration of CMEs may be also physically related with the continuing energy release. In particular, CMEs tend to have positive post-impulsive-phase acceleration if the associated flares have a long decay phase; this kind of flares is often called long duration event (LDE). When flare decay times are short, accompanying CMEs may have mixed response, possibly with positive or negative post-impulsive-phase acceleration from event to event.

The correlation coefficient obtained here is larger than that obtained for a larger sample of events by Yashiro et al. (2004). The mean impulsive acceleration of these CMEs is 939 m s$^{-2}$, whereas the post-impulsive-phase accelerations are limited to a small range centered near zero and the mean post-impulsive-phase acceleration is $-11.9$ m s$^{-2}$, being almost consistent with the results of Zhang & Dere (2006).
The idea of continuing reconnection has also been supported by observations of long-lasting post-flare loops (Schmieder et al. 1995, 1996; Czaykowska et al. 1999; Sheeley et al. 2004; Kołomanński 2007). The observed rising motion of post-flare loops, as well as the observed separation motion of flare ribbons, are well explained by the reconnection model that these observed motions are driven by systematic rising of the reconnection point in the corona. The observed down-flows above post-flare arcades in the long-duration flares also support the idea of continuing reconnection (Mckenzie 2000; Sheeley et al. 2004). Similar connection between ribbon separation motion and coronal magnetic reconnection also occurs in the main energy release phase (Qiu et al. 2004, 2005). Nevertheless, there must be certain differences between the reconnection during the main energy release phase and that during the decay phase. Isobe et al. (2002) found that in the decay phase the reconnection rate, and also the energy release rate, was about one-tenth of that in the rise phase. Therefore, it is reasonable to argue that the impulsive CME acceleration is driven by the fast reconnection in the impulsive phase, while the post-impulsive-phase CME acceleration is caused by the slow reconnection after the impulsive phase.
Chen et al. (2000, 2006) and Chen & Krall (2003) devised an analytic flux rope model to explain CME's main and residual accelerations. It seems that the residual acceleration in the context of the Chen's model is similar to the post-impulsive-phase acceleration discussed in this paper, especially in terms of their magnitude and timing relative to that of the main phase. They showed that the main acceleration is attained before the CME reaches a critical height (below 2–3 \( R_\odot \)), and is then followed by the residual acceleration. The main acceleration phase is dominated by the Lorentz self-force through the injection of the poloidal magnetic flux of the flux rope, while the residual acceleration is dominated by the solar wind aerodynamic dragging force (Chen & Krall 2003). On the other hand, in the scenario of magnetic reconnection models, the CME impulsive acceleration is driven by the fast reconnection. It is a kind of runaway tether-cutting reconnection, not only cutting off the field lines tied to the photosphere and lessening the restraint of the overlying field, but also rapidly increasing the magnetic pressure below the flux rope due to an added poloidal flux (Moore et al. 2001; Zhang & Dere 2006). When the runaway tether-cutting reconnection ceases, the impulsive acceleration stops. However, for the CME associated with a long decay flare, even though it has departed from the Sun and may have already moved to as far as several solar radii from the Sun, the reconnection process may continue; it is most evident in the formation of the post-eruption loop arcades. The continued reconnection may further drive the CME and thus produce the positive post-impulsive-phase acceleration of the CME. Note that the difference between the impulsive acceleration and the post-impulsive-phase acceleration may be mainly their different reconnection rates. A question may arise with respect to how to connect the positive post-impulsive-phase acceleration in the outer corona with the reconnection site close to the surface of the Sun. A possible explanation is that the reconnection magnetic fields are overlying fields surrounding the CME LE in the outer corona but are stretched up open in the low corona. Therefore, the post-impulsive-phase acceleration of the CME in the outer corona and the energy release of the associated flare in the decay phase are different manifestations of the slow magnetic reconnection following the fast magnetic reconnection.

On the other hand, when the associated flare is of short duration, one does not expect continuing reconnection and thus continuing acceleration of the CME. Indeed, about half CMEs with short-duration flares have suffered deceleration in the outer corona, or negative post-impulsive-phase acceleration. Nevertheless, many CMEs associated with short-duration flares have also showed positive post-impulsive-phase acceleration. Detailed investigation shows that these CMEs tend to be slow, narrow, and weak. It is likely that the positive acceleration is caused by the solar wind dragging force, which acts as a positive driving force when the embedded object is slower. The full dynamic evolution of a CME shall involve not only the various Lorentz forces caused by current-carrying magnetic fields, but also the solar wind dragging force. For those fast CME events associated with long decay flares, even though the solar wind dragging force is a decelerator of CMEs, the positive Lorentz force caused by continuing magnetic reconnection is able to overcome the dragging and further accelerating the already-fast CMEs. This scenario helps explain why certain number of CMEs are extremely fast.

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