IMPULSIVE ACCELERATION OF CORONAL MASS EJECTIONS. II. RELATION TO SOFT X-RAY FLARES AND FILAMENT ERUPTIONS

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ABSTRACT

Using high time cadence images from the STEREO EUVI, COR1, and COR2 instruments, we derived detailed kinematics of the main acceleration stage for a sample of 95 coronal mass ejections (CMEs) in comparison with associated flares and filament eruptions. We found that CMEs associated with flares reveal on average significantly higher peak accelerations and lower acceleration phase durations, initiation heights, and heights, at which they reach their peak velocities and peak accelerations. This means that CMEs that are associated with flares are characterized by higher and more impulsive accelerations and originate from lower in the corona where the magnetic field is stronger. For CMEs that are associated with filament eruptions we found only for the CME peak acceleration significantly lower values than for events that were not associated with filament eruptions. The flare rise time was found to be positively correlated with the CME acceleration duration and negatively correlated with the CME peak acceleration. For the majority of the events the CME acceleration starts before the flare onset (for 75% of the events) and the CME acceleration ends after the soft X-ray (SXR) peak time (for 77% of the events). In ~60% of the events, the time difference between the peak time of the flare SXR flux derivative and the peak time of the CME acceleration is smaller than ±5 minutes, which hints at a feedback relationship between the CME acceleration and the energy release in the associated flare due to magnetic reconnection.

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

Online-only material: color figures

1. INTRODUCTION

Solar flares and coronal mass ejections (CMEs) are the two most energetic phenomena in our solar system. Solar flares are abrupt releases of energy up to $10^{33}$ J within tens of minutes and can be observed in the whole electromagnetic spectrum from radio emission to γ-rays (e.g., Fletcher et al. 2011). CMEs are sporadic ejections of coronal material with velocities in the range of ~100–3000 km s$^{-1}$ (e.g., Yashiro et al. 2004; Gopalswamy et al. 2009). It is generally accepted that both CMEs and flares are different manifestations caused by magnetic reconnection in the solar corona, but the details of how both phenomena are related are still under investigation.

Various statistical studies using white-light coronagraphic observations showed positive correlations between the flare intensity and CME velocity (e.g., Moon et al. 2002; Vršnak et al. 2005; Yashiro & Gopalswamy 2009) or CME kinetic energy (Burkepile et al. 2004; Yashiro & Gopalswamy 2009). The temporal differences between the CME and the flare onset were found to be quite small. Michalek (2009) and Yashiro & Gopalswamy (2009) found a Gaussian distribution for the difference between the flare and CME onsets. According to Michalek (2009), the mean difference is 7 minutes. In these studies, linear back extrapolation of the CME height-time curve was used to estimate the CME start time. However, the CME onset times cannot be accurately determined by using only coronagraphic observations, which miss the early phase of the CME acceleration and propagation due to the occultor disk.

The CME kinematics typically shows three phases of evolution (Zhang et al. 2001). In the initiation phase, the CME rises with velocities of several tens of km s$^{-1}$, followed by an impulsive acceleration. Thereafter, the CME propagates with almost constant or slowly decreasing/increasing velocity depending on its interaction with the ambient solar wind (e.g., Gopalswamy et al. 2000). Recent case studies (e.g., Gallagher et al. 2003; Vršnak et al. 2004; Temmer et al. 2008) combined EUV images with coronagraphic observations to derive detailed CME acceleration profiles from the CME initiation close to the solar surface until its propagation beyond 15 $R_\odot$. In these events the CME acceleration profiles showed a good synchronization with the energy release in the associated flare, as evidenced in the hard X-ray (HXR) flux or soft X-ray (SXR) derivative. Marić et al. (2004) studied a set of 22 CME events associated with flares using SOHO EIT, MLSO Mark IV, and LASCO C2 and C3. They report correlations between various CME and flare parameters as well as a close synchronization between the CME acceleration and the flare SXR flux derivative for ≥50% of the events under study.

In Bein et al. (2011, hereafter Paper I), we presented statistics and correlations between various decisive CME parameters for a sample of 95 events: peak velocity, peak acceleration, acceleration duration, height at peak velocity, height at peak acceleration, and initiation height. To this aim we combined EUV images from the Extreme Ultraviolet Imager (EUVI; Wuelser et al. 2004) with COR1 and COR2 coronagraphic observations on board the STEREO mission. The high time cadence and the overlapping fields of view (FOVs) of the different STEREO instruments enabled us to derive detailed and continuous CME height-, velocity-, and acceleration-time profiles from the low corona up to about 15 $R_\odot$. Out of the 95 CMEs presented in Bein et al. (2011), 70 events could be associated with a Geostationary Operational Environmental Satellite (GOES) flare and 24 events with a filament eruption. Nine events are associated with both, a flare and a filament. In the present paper, we perform a statistical study on the relation between characteristic CME and flare parameters as well as on the temporal relationship between the two phenomena. We also study the characteristic CME parameters separately for events...
Figure 1. CME kinematics and GOES 1–8 Å soft X-ray flux for the CME–flare events that occurred on 2008 January 7 (left) and 2009 January 9 (right). The top panels show the measured CME height-time curve derived from STEREO EUVI (crosses), COR1 (triangles), and COR2 (asterisks) observations. The measurement errors (0.03 $R_\odot$ for EUVI, 0.125 $R_\odot$ for COR1, and 0.3 $R_\odot$ for COR2), which are in some cases smaller than the plot symbols, and the spline fit (solid line) are overplotted.

The second and third panels show the CME velocity and acceleration profiles, derived from numerical differentiation of the direct measurements (plot symbols) and the spline fit (solid line) to the height-time curve. The gray shaded area represents the error range of the spline fit. The bottom panels show the GOES flux (black solid line) and its derivative (red dashed line) of the associated flare.

(A color version of this figure is available in the online journal.)

2. DATA

The CME kinematics was derived from data of the STEREO/SECCHI instrument suite (Howard et al. 2008). The STEREO mission consists of two nearly identical spacecraft, STEREO-A, which moves ahead of the Earth, and STEREO-B, which moves behind the Earth. The SECCHI package consists of an EUVI, two coronagraphs (COR1 and COR2), and two Heliospheric Imagers (HI1 and HI2). For our study of the CME kinematics we combined data from EUVI, COR1, and COR2.

EUVI provides observations from the solar chromosphere and low corona in four different wavelengths with an FOV up to 1.7 $R_\odot$ (Wuelser et al. 2004). For our study we used primarily 171 Å observations with a time cadence as high as 75 s. In some cases it was only possible to track the CME in 195 Å observations with a default cadence of 10 minutes, but in some cases as good as 2.5 minutes. The high time cadence was necessary to derive detailed acceleration profiles of the CME initiation and impulsive acceleration phase. Observations in 171 Å and 195 Å were compared to 304 Å filtergrams to check if a filament eruption and/or flare were observed in association with the CME under study.

The inner coronagraph COR1 has an FOV of 1.4–4 $R_\odot$. For most events it has a nominal time cadence of 5 minutes, but in some cases it was also lower (20 minutes). The outer coronagraph COR2 has an FOV of 2.5–15 $R_\odot$ and an observing cadence of 30 minutes for the polarized brightness images, which were used in our study (Howard et al. 2008). The overlapping FOVs between EUVI and COR1 and between COR1 and COR2 made it possible to connect the same CME structure in all three instruments and thus to study the CME evolution continuously from its initiation close to the solar surface up to about 15 $R_\odot$. To compare the CME kinematics with the flare SXR evolution, we used GOES 1–8 Å flux measurements.

3. RESULTS

We studied 95 CMEs, which occurred between 2007 January and 2010 May, i.e., at the transition from solar cycle no. 23 to no. 24. For each event the full CME height, velocity, and acceleration profiles could be derived. For details on the methods applied we refer to Paper I. For each event, which was associated with a GOES flare, we compared the CME kinematics with the GOES SXR flux evolution and its derivative. Because of the temporal correlation between the HXR emission caused by flare-accelerated electron beams and the derivative of the SXR emission observed in many flare events (Neupert effect; Neupert 1968; Dennis & Zarro 1993; Veronig et al. 2002, 2005), we use the derivative of the GOES 1–8 Å flux as a proxy for the evolution of the flare energy release. Figures 1 and 2 show four...
representative events of our sample. The top panels show the CME height, the second panels the CME velocity, and the third panels the CME acceleration curve against time. In the bottom panels the GOES 1–8 Å flux and its derivative are plotted.

For each CME we derived the following characteristic parameters: (1) peak velocity $v_{\text{max}}$, (2) peak acceleration $a_{\text{max}}$, (3) acceleration phase duration $t_{\text{acc}}$, (4) first measured height $h_0$, (5) height at peak velocity $h_{v_{\text{max}}}$, and (6) height at peak acceleration $h_{a_{\text{max}}}$. We applied a spline fit to the CME height-time profile, and from its first and second derivative we derived $v_{\text{max}}$ and $a_{\text{max}}$, respectively. $a_{\text{max}}$ is given by the maximum value of the CME acceleration profile; $v_{\text{max}}$ is defined as the value of the velocity profile where the acceleration profile has decreased to 10% of its peak value. This definition is used in order to ensure that the peak velocity during the CME impulsive acceleration phase (Zhang et al. 2004) is calculated excluding the effect of the subsequent residual acceleration phase (for details see Paper I). The acceleration phase duration $t_{\text{acc}}$ was defined as the time difference between $t_{\text{acc, end}}$, the time when the acceleration profile has decreased to 10% of its maximum value, and $t_{\text{acc, start}}$, the time in the increasing phase of the acceleration when the profile has reached 10% of its maximum value. $h_0$, the first measured height in our height-time plots, is used as a rough estimate of the CME initiation height, because we measured the CMEs as soon as it was possible to observe them in the low corona. The heights $h_{v_{\text{max}}}$ and $h_{a_{\text{max}}}$ are defined as the heights where the CME reached its peak velocity ($v_{\text{max}}$) and peak acceleration ($a_{\text{max}}$). A detailed study of these CME parameters is presented in Paper I.

3.1. CME Characteristics in Dependence of Flare/Filament Association

We studied each CME parameter ($v_{\text{max}}$, $a_{\text{max}}$, $t_{\text{acc}}$, $h_0$, $h_{v_{\text{max}}}$, and $h_{a_{\text{max}}}$) separately for CMEs with/without associated flares and with/without associated filament eruptions. Figures 3–8 show the distributions of the different CME parameters for the whole sample of 95 events (gray histograms) together with the distribution for events associated with flares (colored histogram in the top panel) and for events associated with filament eruptions (colored histogram in the bottom panel). For each parameter we derived the arithmetic mean together with its standard deviation and the median and its absolute deviation, for the whole sample as well as separately for the samples with/without associated flares or filaments. The resulting values are summarized in Table 1. Because the distributions do not show a Gaussian behavior but have a tail toward high values, a lognormal distribution better describes their behavior (Limbert et al. 2001; Yurchyshyn et al. 2005; Bein et al. 2011). Thus, we also calculated the mean value $\mu$ and the standard deviation $\sigma$ of the natural logarithm of the different CME parameter distributions (Cowan 1998):

$$\sigma = \sqrt{\ln \left( \frac{\text{Var}(E)}{E^2} + 1 \right)}$$  \hspace{1cm} (1)

$$\mu = \ln(E) - \frac{\sigma^2}{2},$$  \hspace{1cm} (2)
Table 1
Statistical CME Parameters Derived for Different Subgroups

| Parameter          | All CMEs (95 Events) | With GOES Flare (70 Events) | Without GOES Flare (25 Events) | With Filament (24 Events) | Without Filament (71 Events) |
|--------------------|----------------------|-----------------------------|--------------------------------|---------------------------|-------------------------------|
| $v_{\text{max}}$ (km s$^{-1}$) | mean ± s | 526 ± 263 | 550 ± 268 | 459 ± 242 | 467 ± 227 | 546 ± 273 |
|                    | median ± mad | 460 ± 160 | 461 ± 150 | 393 ± 135 | 400 ± 121 | 461 ± 161 |
| $\mu$ ± $\sigma$ | 6.15 ± 0.22 | 6.20 ± 0.12 | 6.00 ± 0.25 | 6.04 ± 0.21 | 6.19 ± 0.22 |
| $a_{\text{max}}$ (m s$^{-2}$) | mean ± s | 757 ± 1034 | 896 ± 1148 | 367 ± 424 | 391 ± 380 | 880 ± 1152 |
|                    | median ± mad | 414 ± 246 | 556 ± 306 | 241 ± 134 | 266 ± 103 | 545 ± 321 |
| $\mu$ ± $\sigma$ | 6.10 ± 1.05 | 6.31 ± 0.97 | 5.48 ± 0.85 | 5.64 ± 0.66 | 6.28 ± 1.00 |
| $t_{\text{acc}}$ (minutes) | mean ± s | 44.6 ± 60.4 | 33.9 ± 30.2 | 74.4 ± 102.0 | 63.1 ± 102.3 | 38.3 ± 36.1 |
|                    | median ± mad | 29.0 ± 14.5 | 26.0 ± 13.5 | 33.0 ± 14.5 | 35.0 ± 17.0 | 26.0 ± 16.0 |
| $\mu$ ± $\sigma$ | 3.28 ± 1.04 | 3.23 ± 0.58 | 3.77 ± 1.06 | 3.50 ± 1.29 | 3.33 ± 0.64 |
| $h_0$ ($R_{\odot}$) | mean ± s | 0.24 ± 0.29 | 0.19 ± 0.24 | 0.40 ± 0.35 | 0.31 ± 0.33 | 0.22 ± 0.28 |
|                    | median ± mad | 0.14 ± 0.08 | 0.12 ± 0.06 | 0.27 ± 0.16 | 0.23 ± 0.17 | 0.14 ± 0.07 |
| $\mu$ ± $\sigma$ | −1.85 ± 0.88 | −2.17 ± 0.99 | −1.19 ± 0.57 | −1.56 ± 0.77 | −1.97 ± 0.93 |
| $h_{\text{max}}$ ($R_{\odot}$) | mean ± s | 0.53 ± 0.64 | 0.36 ± 0.37 | 0.99 ± 0.95 | 0.72 ± 0.87 | 0.46 ± 0.53 |
|                    | median ± mad | 0.26 ± 0.12 | 0.24 ± 0.10 | 0.52 ± 0.34 | 0.35 ± 0.21 | 0.26 ± 0.12 |
| $\mu$ ± $\sigma$ | −1.10 ± 0.90 | −1.38 ± 0.72 | −0.34 ± 0.65 | −0.79 ± 0.90 | −1.20 ± 0.84 |
| $h_{\text{vmax}}$ ($R_{\odot}$) | mean ± s | 1.56 ± 1.82 | 1.17 ± 1.48 | 2.26 ± 2.38 | 2.00 ± 2.42 | 1.28 ± 1.54 |
|                    | median ± mad | 0.78 ± 0.42 | 0.70 ± 0.35 | 1.05 ± 0.53 | 0.86 ± 0.40 | 0.76 ± 0.41 |
| $\mu$ ± $\sigma$ | −0.09 ± 0.94 | −0.32 ± 0.96 | 0.44 ± 0.75 | 0.24 ± 0.91 | −0.21 ± 0.90 |

Notes. Arithmetic mean with standard deviation, median with median absolute deviation (mad), and mean value $\mu$ with standard deviation $\sigma$ of the lognormal probability function of the following decisive CME parameters: peak velocity $v_{\text{max}}$, peak acceleration $a_{\text{max}}$, acceleration phase duration $t_{\text{acc}}$, height $h_0$ where the CME leading edge could be identified for the first time, height at peak acceleration $h_{\text{max}}$, height at peak velocity $h_{\text{vmax}}$. Mean, median, and $\mu$ of all these parameters were derived for the whole sample of events (Column 3) and for several subgroups: events with associated flares (Column 4), events for which no flare could be associated (Column 5), events with associated filament eruptions (Column 6), events for which no filament eruptions could be associated (Column 7).

Figure 3. Histogram of the CME peak velocity $v_{\text{max}}$ for the whole sample of 95 events (gray distributions in the top and bottom panels). In the top panel the $v_{\text{max}}$ distribution of CME events associated with a flare is overlaid in color; in the bottom panel the histogram of CME events associated with an erupting filament is overlaid. (A color version of this figure is available in the online journal.)

Figure 4. Same as Figure 3 but for the CME peak acceleration. (A color version of this figure is available in the online journal.)

with $\mu$ the mean value and $\text{Var}$ the variance of the quantity. In the following we use $\mu^* = e^\mu$ and $\sigma^* = e^\sigma$ as the median and multiplicative standard deviation of the lognormal probability function of the distribution (Limbert et al. 2001). The confidence interval of 68.3% is given by $e^{\mu \pm \sigma}$; $\mu$ and $\sigma$ are also summarized for each CME parameter in Table 1.

To check if the CME distributions with/without associated flares and with/without associated filament eruptions, respectively, come from the same continuous distribution (null hypothesis), we used the Kolmogorov–Smirnov test (e.g., Young 1977; Sachs 1997). This test is nonparametric, i.e., it
is not necessarily required to know the type of distribution (e.g., Gaussian, lognormal, exponential). A test statistic $D$ is calculated by

$$D = \max \left| \frac{F_1}{n_1} - \frac{F_2}{n_2} \right|,$$

with $F_1$ and $F_2$ the cumulative distribution functions of both subsamples and $n_1$ and $n_2$ the number of events in each sample. $D$ is then compared with

$$D_\alpha = K_\alpha \sqrt{\frac{n_1 + n_2}{n_1 \cdot n_2}},$$

where $K_\alpha$ can be found in tables for different significance levels $\alpha$. $\alpha$ represents the probability that we wrongly reject the true hypothesis or accept the false hypothesis (Essenwanger 1976). If $D > D_\alpha$, the null hypothesis can be rejected, i.e., both subsamples do not come from the same population.

### 3.1.1. CME–Flare Relation

For 70 events out of our sample of 95 CMEs, we could identify an associated GOES class flare. Figure 9 shows the distribution of the GOES classes of the associated flares, which were not partially occulted (61 events): 9 events are associated with an A-class flare, 27 with a B-class flare, 20 events with a C-class flare, and 5 events with an M-class flare. None of the CME events under study are associated with an X-class flare.
In the upper panels of Figures 3–8 the distributions of CMEs associated with flares (70 events) are overplotted in color. On average, the CME peak velocity $v_{\text{max}}$ is higher for events associated with flares than for those with no flare association. Assuming a lognormal distribution, we find $\mu^* = 490_{-117}^{+95}$ km s$^{-1}$ for events associated with flares and $\mu^* = 406_{-59}^{+50}$ km s$^{-1}$ for events with no flare association. All CMEs, which reached a velocity higher than 1000 km s$^{-1}$, are associated with a flare. These results are in accordance with former studies. Burkepile et al. (2004), who measured the average velocity of 111 limb CMEs observed with the Solar Maximum Mission coronagraph/polarimeter, found mean values of $566 \pm 67$ km s$^{-1}$ for CMEs with and $444 \pm 59$ km s$^{-1}$ for CMEs without associated flares. Vršnak et al. (2005) analyzed the CME mean velocity and the velocity at a distance of 3 $R_\odot$ of CMEs using LASCO data and found for the flare-associated CME sample higher mean values than for the whole sample of CMEs. However, the Kolmogorov–Smirnov test applied to our sample does not show a clear distinction of both subsamples up to a significance level of 0.2.

For the CME peak acceleration $a_{\text{max}}$ the differences in mean values and median values for events associated with flares and events with no flare association are even higher than for the velocities (see Table 1). We find a more than twice as high $\mu^* = 551_{-904}^{+343}$ m s$^{-2}$ for events with flare-association than for CMEs without a flare, $\mu^* = 240_{-321}^{+137}$ m s$^{-2}$. Although the range of $a_{\text{max}}$ values for flare-associated CMEs is large ($77–6781$ m s$^{-2}$), all events that reached a peak acceleration higher than $1600$ m s$^{-2}$ (9 events out of our sample of 9 CMEs) were associated with a flare. The Kolmogorov–Smirnov test, shows for the parameter $a_{\text{max}}$ at a significance level of 0.05 that both distributions (with/without associated flare) do not come from the same population.

For the acceleration phase duration, we found $\mu^* = 25.3_{-22.0}^{+11.2}$ minutes for events with associated flares, compared to the $\mu^* = 43.8_{-82.5}^{+28.6}$ minutes for events with no associated flare. All CMEs with $t_{\text{acc}} \leq 14$ minutes were associated with a flare. Applying the Kolmogorov–Smirnov test, it can be shown that both distributions do not come from the same population at a 0.10 significance level.

The measured CME height parameters $h_0$, $h_{\text{max}}$, and $h_{\text{amax}}$ are on average smaller for CMEs associated with flares than for CMEs with no flare (see Table 1). $\mu^*$ of $h_0$ and $h_{\text{max}}$ are more than twice as high for events with no flare than for events with an associated flare. For $\mu^*$ of $h_{\text{amax}}$ the differences between these subgroups are lower (ratio $\sim 1.32$). The Kolmogorov–Smirnov test showed for all height parameters that both subgroups do not come from the same population at a significance level of 0.10 for $h_0$, 0.15 for $h_{\text{max}}$, and even 0.05 for $h_{\text{amax}}$.

### 3.1.2. CME–Flament Relation

Twenty-four out of 95 CMEs were associated with an erupting filament. In the bottom panels of Figures 3–8 the distributions of these events are overplotted in color. Events that could be associated with filaments showed lower $v_{\text{max}}$ than events without filament eruptions. For the former group we find $\mu^* = 420_{-78}^{+40}$ km s$^{-1}$, whereas for the latter group of CMEs we obtain $\mu^*$ of $v_{\text{max}}$ of $531_{-134}^{+107}$ km s$^{-1}$. Burkepile et al. (2004) found no significant difference between both subgroups for the mean velocity of $\sim 520$ km s$^{-1}$.

Similar to the CME–flare association, the differences in the mean and median values for $a_{\text{max}}$ are more significant than for $v_{\text{max}}$. CMEs that could be associated with filaments showed lower $a_{\text{max}}$, with $\mu^*$ of $281_{-254}^{+136}$ m s$^{-2}$. None of these events reached $a_{\text{max}}$ higher than $1600$ m s$^{-2}$; 75% have $a_{\text{max}} < 400$ m s$^{-2}$. CME events without associated filament eruption show $\mu^*$ of $543_{-337}^{+305}$ m s$^{-2}$, i.e., the difference between these two subgroups is about a factor of two. $a_{\text{max}}$ was the only parameter for which the Kolmogorov–Smirnov test suggested that both distributions (filament/non-filament associated events) do not come from the same population at a significance level of 0.05.

For the CME acceleration duration $t_{\text{acc}}$ we found $\mu^*$ of $33.1_{-24.00}^{+78.00}$ minutes for events with associated filaments and $\mu^*$ of $27.8_{-24.74}^{+42.00}$ minutes for events with no filament association. Because filament eruptions are correlated to CMEs with larger $a_{\text{max}}$, it is not surprising that they are also correlated to events with longer $t_{\text{acc}}$, due to the strong negative correlation between $a_{\text{max}}$ and $t_{\text{acc}}$ (see Vršnak et al. 2007; Bein et al. 2011).

All CME height parameters $h_0$, $h_{\text{max}}$, and $h_{\text{amax}}$ have on average larger values for CMEs associated with filament eruptions than for CMEs without filament eruptions (Table 1). The differences in the median values of the lognormal distribution are about a factor of 1.5.

Considering the mean and median values of CME parameters, we found higher values for $v_{\text{max}}$ and $a_{\text{max}}$ and smaller values for $t_{\text{acc}}$, $h_0$, $h_{\text{max}}$, and $h_{\text{amax}}$ for events with associated flares than for those with no flare. This effect is smallest for the CME peak velocity. The differences in the mean and median values show that CMEs associated with flares tend to have a more impulsive and intense acceleration and start from lower heights in the corona. CMEs that could be associated with an erupting filament behave oppositely. Their mean and median values of $v_{\text{max}}$ and $a_{\text{max}}$ are lower than for CMEs with no erupting filament, and the mean and median values of $t_{\text{acc}}$, $h_0$, $h_{\text{max}}$, and $h_{\text{amax}}$ are higher, when a filament eruption was associated. The Kolmogorov–Smirnov test shows for all CME parameters except $v_{\text{max}}$, that the distributions of flare/non-flare-associated events do not come from the same population. Considering filament/non-filament events, the Kolmogorov–Smirnov test shows a distinction between both distributions only for $a_{\text{max}}$.

### 3.2. Relationship between CME and Flare Parameters

We analyzed the scaling of the GOES peak flux $F_{\text{SXR}}$ and the GOES SXR rise time $t_{\text{SXR}}$ with the characteristics of the associated CMEs, i.e., $v_{\text{max}}$, $a_{\text{max}}$, $t_{\text{acc}}$, $h_0$, $h_{\text{max}}$, and $h_{\text{amax}}$, and calculated their dependency in logarithmic space. For these correlations we only considered those 61 (out of 70) flare events that were not partially occulted from Earth view. The
correlations are in general weak. Figures 10 and 11 show four representative correlations.

We used a bootstrap method (Efron 1979) within a Monte Carlo algorithm to estimate the standard error of our calculated correlation coefficients (Efron & Tibshirani 1986). A bootstrap sample is constructed by randomly drawing with replacement from the original data pairs, with the bootstrap sample having the same number of entries as the original sample. Such bootstrap samples are constructed 1000 times, and for each bootstrap sample the correlation coefficient is calculated. The mean value plus standard deviation of all 1000 calculations is used as a robust measure of the correlation coefficient and its standard error.

We found a positive correlation between $F_{\text{SXR}}$ and $v_{\text{max}}$ of $c = 0.32 \pm 0.13$ (bottom panel of Figure 10), i.e., CMEs that were associated with flares with higher SXR flux tend to reach higher peak velocities. This is consistent with the results from Maričić et al. (2007), who analyzed the correlation between SXR flares and CMEs for a set of 18 events, including B- to X-class flares, finding $c = 0.52$. The power-law dependency between $F_{\text{SXR}}$ and $v_{\text{max}}$ of our study can be expressed by

$$v_{\text{max}} = 10^{0.318 \pm 0.18} F_{\text{SXR}}^{-0.08 \pm 0.03}. \quad (5)$$

The correlation between $F_{\text{SXR}}$ and $a_{\text{max}}$ is $c = 0.28 \pm 0.12$ (see the top panel of Figure 10), i.e., CMEs with high peak accelerations tend to be associated with flares of high GOES SXR flux. Maričić et al. (2007) also found a positive correlation between these two parameters with a correlation coefficient of $c = 0.60$. We found a power-law dependency of

$$a_{\text{max}} = 10^{0.62 \pm 0.38} F_{\text{SXR}}^{-0.14 \pm 0.06}. \quad (6)$$

We determined the SXR rise time $t_{\text{SXR}}$ from the derivative of the GOES flux curves as the time difference between the start of the increase and the maximum of the SXR derivative, which was possible for 57 events. The distribution of the time differences is shown in Figure 12. The GOES SXR rise time $t_{\text{SXR}}$ and CME parameters (Figure 11) do not yield distinct correlations. The highest correlation coefficient was obtained for the relation between $t_{\text{SXR}}$ and the CME acceleration duration, $c = 0.37 \pm 0.15$. The power-law dependency between these two parameters can be expressed as

$$t_{\text{acc}} = 10^{1.09 \pm 0.39} t_{\text{SXR}}^{-0.40 \pm 0.13}. \quad (7)$$

Between $a_{\text{max}}$ and $t_{\text{SXR}}$ we found a negative correlation with $c = -0.32 \pm 0.15$ and a power-law dependency of

$$a_{\text{max}} = 10^{0.02 \pm 0.48} t_{\text{SXR}}^{-0.43 \pm 0.16}. \quad (8)$$

Figure 10. CME peak velocity (top) and peak acceleration (bottom) against the GOES peak flux of the associated flare. A double logarithmic space is used for the plot and the calculation of the correlation coefficient $c$, which is annotated in each panel. The regression line is overplotted in red.

(A color version of this figure is available in the online journal.)

Figure 11. CME acceleration duration (top) and peak acceleration (bottom) against the flare SXR rise time. The correlation coefficient $c$ (calculated in double logarithmic space) and the regression line are overplotted.

(A color version of this figure is available in the online journal.)
i.e., CMEs with high peak accelerations are preferentially associated with flares, which show short SXR rise times.

One possible explanation for the weak flare–CME correlations we obtained is the lack of strong flare events in our sample, which contains only a few M-class flares and no X-class flares due to the solar activity minimum condition in the period under study (2007–2010). Since we cover only low energetic flares due to the solar activity minimum condition in the period under study (2007–2010), we obtained the lack of strong flare events in our sample, which contains only a few M-class flares and no X-class flares due to the solar activity minimum condition in the period under study (2007–2010).

To circumvent this effect, we calculated the mean and median values of the CME parameters separately for each GOES class plotted against the mean GOES flux in each subgroup. The correlation coefficient $c$ (calculated in logarithmic space) is annotated in each panel.

![Figure 12. Distribution of the rise time $t_{\text{SXR}}$ of the GOES SXR flares.](image)

**Table 2**

| Class  | $v_{\text{max}}$ (mean $\pm$ s) | $a_{\text{max}}$ (mean $\pm$ mad) | $t_{\text{acc}}$ (mean $\pm$ mad) | $h_0$ (mean $\pm$ mad) | $h_{\text{max}}$ (mean $\pm$ mad) | $h_{\text{max}}$ (mean $\pm$ mad) |
|--------|---------------------------------|-----------------------------------|-----------------------------------|------------------------|-----------------------------------|-----------------------------------|
| A-class| 501 $\pm$ 258                  | 461 $\pm$ 221                    | 32.6 $\pm$ 15.6                  | 0.22 $\pm$ 0.19        | 0.16 $\pm$ 0.28                  | 0.31 $\pm$ 0.33                  |
| B-class| 532 $\pm$ 257                  | 460 $\pm$ 135                    | 28.9 $\pm$ 24.1                  | 0.19 $\pm$ 0.27        | 0.41 $\pm$ 0.28                  | 0.23 $\pm$ 0.08                  |
| C-class| 609 $\pm$ 301                  | 530 $\pm$ 200                    | 25.2 $\pm$ 15.7                  | 0.14 $\pm$ 0.19        | 0.31 $\pm$ 0.32                  | 0.22 $\pm$ 0.10                  |
| M-class| 754 $\pm$ 340                  | 710 $\pm$ 122                    | 29.9 $\pm$ 17.7                  | 0.27 $\pm$ 0.39        | 0.58 $\pm$ 0.58                  | 0.27 $\pm$ 0.13                  |

Figure 13 shows these mean values for $v_{\text{max}}$, $a_{\text{max}}$, and $t_{\text{acc}}$ plotted against the mean GOES flux of each subgroup. In this representation a clear trend is noticeable that CMEs, which reach higher peak velocities, are correlated with flares with higher GOES peak flux (top panel in Figure 13), consistent with former studies. Moon et al. (2002) analyzed 3217 LASCO CMEs that were associated with flares and compared the median value of the CME speeds derived from the whole sample, from CMEs associated with flares $>$C1, and from CMEs associated with flares $>$M1. When considering the whole sample, the authors found the lowest median value, whereas CMEs that were associated with flares $>$M1 showed the largest median value for the CME speed distribution. Vršnak et al. (2005) compared the velocities between B and C flare-associated CMEs with the velocities of M- and X-class flare-associated CMEs and found that the mean value of the M- and X-class flare-associated events is about 1.4 times the mean value of the other subgroup.

![Figure 13. Mean value of the CME peak velocity $v_{\text{max}}$ (top), acceleration $a_{\text{max}}$ (middle), and acceleration duration $t_{\text{acc}}$ (bottom) for each GOES class plotted against the mean GOES flux in each subgroup. The correlation coefficient $c$ (calculated in logarithmic space) is annotated in each panel.](image)

3.3. Flare–CME Temporal Relationship

We studied the relative timing of the CME acceleration phase and the flare energy release in order to investigate possible temporal synchronizations between these two phenomena. From the CME observations we derived the start ($t_{\text{acc, start}}$), peak ($t_{\text{acc, peak}}$), and end time ($t_{\text{acc, end}}$) of the CME acceleration. From the GOES flare observations we derived the start and peak time of the 1–8 Å SXR flux as well as the peak of the 1–8 Å flux derivative. For this study we used only flare events that were not partially occulted and for which a peak in the derivative of the GOES flux could be derived. This was the case for 57 out of 70 flare–CME pairs.

The top panels of Figure 14 show the histograms of the time differences between the GOES flare start times and the start of

![Figure 14. Histograms of the time differences between the GOES flare start times and the start of](image)
the associated CME acceleration. For the distribution on the left-hand side the differences expressed in minutes were used, whereas the values on the right-hand side were normalized by the CME acceleration duration. For the time differences we found a mean value of $4.9 \pm 10.2$ minutes and a median of $4.6 \pm 6.3$ minutes. The distribution shows that the values are confined to within about $\pm 20$ minutes (93% of the events lie within this interval). In 75% of the cases, the CME acceleration starts before the rise of the flare SXR flux. Considering the normalized values, the time differences are smaller than $\pm 0.5$ for 77% of the events and smaller than $\pm 0.25$ for 44%. Maričić et al. (2007) also found that for the majority of the events the CME acceleration starts before the SXR flare with a mean value of $23 \pm 30$ minutes (for a set of 18 events containing a significant fraction of gradual events). This mean value is larger than in our study, but the time delays normalized by $t_{acc}$ are quite similar in both studies, with a mean value of $0.17 \pm 0.71$ in our study and $0.14 \pm 0.20$ in Maričić et al. (2007).

In the middle panels of Figure 14 we compare the end of the CME impulsive acceleration phase $t_{acc\_end}$ with the GOES SXR flare peak time, which relates to the end of the impulsive flare energy release phase. We found that for the majority of the events (77%), the GOES peak occurred earlier than $t_{acc\_end}$. The
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Table 3
Statistical Parameters Derived for Characteristic CME–Flare Time Differences

| Time Delay                                                                 | Minimum  | Maximum | Arithmetic Mean ± Standard Deviation | Median ± Mad |
|---------------------------------------------------------------------------|----------|---------|-------------------------------------|-------------|
| GOES flare start time − tacc_start (minutes)                              | −17.3    | 32.6    | 4.9 ± 10.2                          | 4.6 ± 6.3   |
| (GOES flare start time − tacc_start)/tacc                                 | −1.58    | 3.26    | 0.17 ± 0.71                         | 0.17 ± 0.20 |
| GOES flare peak time − tacc_end (minutes)                                 | −71.5    | 21.5    | −9.3 ± 15.8                         | −6.5 ± 7.5  |
| (GOES flare peak time − tacc_end)/tacc                                    | −1.08    | 2.83    | −0.13 ± 0.69                        | −0.33 ± 0.20|
| GOES der. peak time − tacc_peak (minutes)                                 | −31.5    | 23.0    | 1.29 ± 8.63                         | 1.00 ± 4.00 |
| (GOES der. peak time − tacc_peak)/tacc                                    | −0.63    | 1.17    | 0.09 ± 0.38                         | 0.02 ± 0.18 |

Notes. Statistical parameters (minimum value, maximum value, arithmetic mean, standard deviation, median, and median absolute deviation) for time delays between characteristic CME and flare times: time difference between the start of the GOES flare and the start of the CME acceleration tacc_start (differences expressed in minutes in the first row, values normalized by the CME acceleration time tacc in the second row), time delay between the GOES flare peak time and the end of the CME acceleration phase tacc_end (delays expressed in minutes in the third row, normalized values in the fourth row), and time difference between the peak time of the GOES derivative and the peak time of the CME acceleration tacc_peak (delays expressed in minutes in the fifth row, normalized values in the sixth row).

mean value of the distribution is −9.3 ± 15.8 minutes and the median −6.5 ± 7.5 minutes. For some gradual CMEs (tacc > 50 minutes), the delay between flare peak and acceleration end can be > 30 minutes (three events). At the right-hand side the normalized difference between the GOES peak flux and tacc is plotted. The distribution shows an asymmetric behavior with a tail at positive values and a distinct mode in the range of −0.5 to −0.3. For 65% of the events, the normalized time differences are between −0.7 and −0.1.

The time difference between the peak of the GOES 1–8 Å flux derivative and the CME acceleration peak (bottom left panel of Figure 14) is found to be small. The distribution does strongly peak around zero; for the mean value we obtained 1.3 ± 8.6 minutes, for the median 1.0 ± 4.0 minutes. Maričić et al. (2007), who used the logarithmic derivative of the SXR GOES flux, found a mean value of 2.7 ± 14 minutes, consistent with our findings. In 81% of the events, we found a difference smaller than ±10 minutes and for 58% of the events it is smaller than ±5 minutes. Only one event of our study showed a time delay > 20 minutes. Sixty-five percent of the normalized values (distribution shown at the right-hand side of Figure 14) lie within ±0.25. The statistical parameters for the time differences described above are summarized in Table 3.

These findings provide strong evidence that the timing of the flare energy release and the CME dynamics (acceleration) are well synchronized, supporting previous results from case studies (e.g., Zhang et al. 2004). Recent studies also analyzed the relationship between the flare HXR emission and the CME acceleration peak, finding that the flare HXR peak occurs close in time with the maximum CME acceleration (Temmer et al. 2008, 2010; Cheng et al. 2010; Berkebile-Stoiser et al. 2012).

4. SUMMARY AND CONCLUSION

Based on a sample of 95 CME events, we present a statistical study on various characteristic CME parameters and their relation to flares. CMEs that are associated with flares show on average higher peak velocities (vmax), higher peak accelerations (amax), shorter acceleration phase durations (tacc), lower heights at peak velocity (hmax), lower heights at peak acceleration (hmax), and lower initiation heights (h0). The ratio between the median values of the lognormal probability functions of both subgroups is about a factor of two. Only for vmax is the ratio significantly smaller (~1.1), most probably due to the small range of vmax values. Due to the anticorrelation between amax and tacc and the relation vmax ≈ amax · tacc, the range for vmax is smaller than for the other two quantities; it basically covers only one order of magnitude. Although we found clear differences in the mean and median values of the two subgroups, there exist also events associated with flares that have low vmax and amax values and high tacc, hmax, hmax, and h0. For instance, the smallest measured amax value for a CME with flare was 77 m s⁻², and the highest measured value for a CME without flare was 1577 m s⁻². The Kolmogorov–Smirnov test suggested a distinction between both distributions (flare/nonflare-associated events) for every CME parameter (except for vmax) at 0.05–0.15 levels of significance. The clearest distinctions were found for amax and hmax at a 0.05 level of significance.

CMEs that are associated with erupting filaments show on average smaller vmax and amax and larger tacc, hmax, hmax, and h0. These trends are the opposite of those for the flare association. The ratio between the mean and median values of both subgroups is somewhat smaller than for the flare association. Again we found the smallest ratio between the median values μ⁺ of vmax (1.1). The μ⁺ of amax and hmax showed the highest ratio with 1.9. For tacc, hmax, and h0 we found ratios between 1.2 and 1.5. But there exist also CMEs associated with filament eruptions that have high vmax and amax values and low tacc, hmax, hmax, and h0. For example, the highest measured amax value for a CME that was associated with an erupting filament was 1561 m s⁻², while the smallest value for a CME event with no erupting filament was 35 m s⁻² (the second lowest value of the whole distribution). Both of these events were not associated with a flare. The Kolmogorov–Smirnov test did not show a clear distinction between both subgroups. Only for amax did the test suggest that both distributions do not come from the same population at a 0.05 level of significance.

The correlations obtained between vmax, amax, and tacc with the GOES peak flux F_SXR and the SXR rise time t_SXR of the associated flare were low. We found a weak positive correlation between the CME acceleration duration tacc and the flare rise time t_SXR (c = 0.37 ± 0.15) and a weak negative correlation between amax and t_SXR (c = −0.32 ± 0.15). Correlations between vmax and amax with F_SXR were c = 0.32 ± 0.13 and c = 0.28 ± 0.12, respectively. If the events are averaged and binned into the different GOES classes, the correlations are much more distinct. The mean values in each GOES class show an increasing trend for vmax and amax, and a decreasing trend for tacc with higher GOES flux.

For the majority of the events (75%) we found that the CME acceleration starts before the SXR flare onset, which is...
consistent with the findings of Maričić et al. (2007), suggesting that the flare is a consequence of the eruption. Similar to our study, these authors also found about one-fourth of the events for which the onset of the associated flare occurred before the CME acceleration started. They explained these cases by a superposition of two flares, a confined flare in the pre-eruption stage, which releases only a part of the stored magnetic energy, and a second flare, beginning after the CME acceleration onset and causing a prolongation of the first flare in the full-disk integrated SXR light curve. The CME is associated with the second flare, but because of the superposition, the flare start is measured from the first one. To test this hypothesis, we checked the SXR curves for all events for which the CME acceleration start was after the flare onset and found indeed in 11 out of 14 events evidence of a second SXR peak, confirming their suggestion. Three. Figure 15 shows two representative examples. The top panels show the CME acceleration profile, the bottom panels the GOES SXR flux together with its derivative. We marked the two possible SXR peaks by arrows. Assuming that we have a superposition of two subsequent flares, we would also measure erroneous SXR start times and, as a result, too long $t_{\text{SXR}}$. This misidentification would also influence our correlation negatively. To test this, we correlated $t_{\text{SXR}}$ again with $t_{\text{max}}$ and $t_{\text{acc}}$ considering only events for which the CME acceleration starts before the flare onset and found indeed distinctly higher correlation coefficients (Figure 16, $c = 0.59 \pm 0.12$ and $c = -0.50 \pm 0.14$) than for the whole sample (shown in Figure 11, $c = 0.37 \pm 0.15$ and $c = -0.32 \pm 0.15$). Thus, a superposition of two subsequent flares and more complex structures are probably a reason for the weak correlations and may account for a considerable number of events where the flare seems to start before the eruption.

For the majority of the events (77%) we found that the end of the CME acceleration occurred after the SXR peak. Especially long duration flares reach a certain point when they become too weak to compensate cooling of the hot plasma. As a result, the SXR curve decreases although the energy release in the flare may still be going on.

For 81% of the events the time delay between the CME acceleration peak and the peak of the GOES SXR flux derivative, which is a proxy for the flare energy release rate, was smaller than $\pm 10$ minutes, for 58% smaller than $\pm 5$ minutes. This high synchronization hints at a feedback relationship between the CME and the flare energy release (Lin 2004; Zhang & Dere 2006; Maričić et al. 2007; Temmer et al. 2008, 2010; Reeves & Moats 2010). There are basically two forces acting on a

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This is a significantly higher rate than in the total sample of events, in which about 20% showed a double SXR peak.

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**Figure 15.** CME acceleration (top) and GOES SXR curve (bottom) from the events observed on 2009 October 25 (left) and 2008 March 23 (right). In both events the CME acceleration starts after the flare onset, which may be related to an overlap of two flares. Arrows mark two SXR maxima indicating two possible flare maxima. (A color version of this figure is available in the online journal.)

**Figure 16.** Same as Figure 11 but only for events where the CME acceleration starts before the flare. (A color version of this figure is available in the online journal.)
flux rope in equilibrium, an upward-directed magnetic pressure and a downward-directed magnetic tension of the overlying magnetic field. When the magnetic structure loses equilibrium, it starts rising and a current sheet is formed below it, where magnetic reconnection takes place (Priest & Forbes 2002). The reconnection reduces the tension of the overlying field and enhances the magnetic pressure at the bottom part of the flux rope due to additional poloidal flux, providing the upward acceleration of the rope (Vršnak 2008). The upward motion of the rope leads to elongation of the current sheet and a more efficient reconnection, thus enhancing the acceleration. On the other hand, more efficient reconnection means also a more powerful energy release in the CME-associated flare, which directly relates the dynamics of the eruption and the energy release in the flare.

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