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# CME–flare association during the 23rd solar cycle

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**Abstract**

The relation between coronal mass ejections (CMEs) and solar flares are statistically studied. More than 10,000 CME events observed by SOHO/LASCO during the period 1996–2005 have been analyzed. The soft X-ray flux measurements provided by the Geostationary Operational Environmental Satellite (GOES), recorded more than 20,000 flares in the same time period. The data is filtered under certain temporal and spatial conditions to select the CME–flare associated events. The results show that CME–flare associated events are triggered with a lift-off time within the range 0.4–1.0 h. We list a set of 41 CME–flare associated events satisfying the temporal and spatial conditions. The listed events show a good correlation between the CME energy and the X-ray flux of the CME–flare associated events with correlation coefficient of 0.76.


*Keywords:* Solar wind; Coronal mass ejections; Solar flares

## 1. Introduction

Early measurements of the CME speeds have helped to advance our understanding of the physical processes in the solar corona. Wild et al. (1963) derived speeds of 500–1000 km/s from their observations of metric type II bursts and they concluded that these flare associated bursts were produced by shock waves moving out through the corona. In the late 1960s and early 1970s, white-light coronagraph observations from OSO-7 satellite and the Skylab space station provided the opportunity to measure the speeds of CMEs directly (Brueckner, 1973; MacQueen et al., 1974). Gosling et al. (1976) found speeds in the range 100–1200 km/s with an average of ~470 km/s. They found that the fast CMEs were associated with flares while type II bursts; the slow events; were associated with eruptive prominences. In the early 1980s, improved observations with the k-coronameter on Mauna Loa enabled MacQueen and Fisher (1983) to measure the speeds of 12 loop-like CMEs over the range of 1.2–2.4 RS. During 1980s and as the SOLWIND and SMM coronagraphs observations observed thousands of CMEs from the Earth orbit; the statistical studies of CMEs have been improved. These mass ejections were compared with soft X-ray bursts (Sheeley et al., 1983); coronal type II bursts (Sheeley et al., 1984; Kahler et al., 1985), interplanetary shocks (Sheeley et al., 1985; Schwenn, 1986) and interplanetary type II bursts (Cane et al., 1987). MacQueen and Fisher (1983) introduced the concept of two distinct classes of CME stating that flare associated events are being accelerated impulsively at low heights. Presently, the concept of two distinct classes is widely employed to interpret various aspects of CMEs (e.g., Sheeley et al., 1999; Moon et al., 2002; Chen and Krall, 2003).

With the launch of the Large-Angle Spectrometric Observatory (SOHO) spacecraft in December 1995, the quality of the observations has been improved; which enabled many authors to study the CME–flare correlation. Gopalswamy et al. (2004) used 44 CME–flare associated events to study the relationship between the CME speed,

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X-ray flare flux and active region area from 1997 to 2002. The correlation coefficients of their results are listed in Table 1. Lin and Jun (2004) found that the correlation between the CMEs and solar flares depend on the stored energy in the relevant magnetic structure, which is available to drive CME. In this paper, we try to study statistically the correlation between the CME and the solar flare by using a large sample of CME and flare events during the 23rd solar cycle.

## 2. Data selection

The analysis is based on two data sets including CMEs and solar flare events. The initial CME sample consists of 10,230 events observed by LASCO in the time period 1996–2005. The CME data is listed in the CDAW website (http://cdaw.gsfc.nasa.gov/CME_list). The soft X-ray flux measurements provided by GOES recorded 21,348 flare events in the same time period in the 1–8 Å channels. The data is listed in NOAA website (http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarflares.html#xray). The Space Environment Centers classifies flares upon their X-ray intensity. X-ray flare classification is based on a flare's maximum output power according to the order of magnitude of the peak burst flux ($I$) measured at the Earth in the 0.1–0.8 Å band as listed in Table 2.

In the same way, the CME events can be classified according to their kinetic energies into five levels within the range $10^{28}$–$10^{31}$ ergs as listed in Table 3.

## 3. Data filtering

The data is filtered under certain temporal and spatial conditions to select the CME–flare associated events. In order to associate flares to CME, we select flare events that occurred within the temporal window $\Delta t = T_{\mathrm{CME}} - \mathrm{T}_{\mathrm{F}}$, where $T_{\mathrm{CME}}$ time of first occurrence of the CME by LASCO and $T_{\mathrm{F}}$ triggering time of associated X-ray flare flux detected by GOES. The value of $T_{\mathrm{F}}$ was set to the flare start time $T_{\mathrm{FS}}$, flare maximum time $T_{\mathrm{FM}}$ and flare end time $T_{\mathrm{FE}}$. Applying the temporal conditions only to the detected 10,230 CME, the number of events was reduced to 942 CME–flare associated events by setting the maximum temporal window $\Delta t = \pm 2.5$ h.

The spatial condition requires that the position angle of the flare ($\Psi_{\mathrm{F}}$) is nearly close to the position angle ($\Psi_{\mathrm{CME}}$) spanned by the CME. The flare's position angle is calculated in the heliographic coordinates ($\lambda, \beta$) according to the following equation:

$$\Psi_F = \tan^{-1}(\sin\lambda / \tan\beta) \quad (1)$$

where $\lambda$ is the heliographic longitude of the flare's active region on the Sun's surface and $\beta$ its heliographic latitude. To correlate a CME event to a flare event, the position angle of the flare has to be within the position angle spanned by the CME, therefore, the condition $\Phi \leqslant |\Psi_{\mathrm{CME}} - \Psi_{\mathrm{F}}|$ was adapted in our selection criteria, where ($\Phi$) is the observed angular width of CME.

Applying the spatial condition only to the detected 10,230 CME, the number of events was reduced to 524 CME–flare associated events.

Table 1
The relationship (with correlation coefficient $R$) between the CME speed, X-ray flare flux and active region area according to Gopalswamy et al. (2004).

| Correlation between | | $R$ |
|---|---|---|
| X-ray flare flux | Active region area | 0.60 |
| CME speed | X-ray flare flux | 0.36 |
| Active region area | CME speed | 0.11 |

Table 2
Flare classification according to their flux.

| Flare type | Flare flux (erg cm$^{-2}$ s$^{-1}$) |
|---|---|
| B | $I < 10^{-3}$ |
| C | $10^{-3} < I < 10^{-2}$ |
| M | $10^{-2} < I < 10^{-1}$ |
| X | $10^{-1} < I$ |

Table 3
CME classification levels according to their energy.

| CME level | Energy of CME (erg) |
|---|---|
| L1 | $E < 10^{28}$ |
| L2 | $10^{28} < E < 10^{29}$ |
| L3 | $10^{29} < E < 10^{30}$ |
| L4 | $10^{30} < E < 10^{31}$ |
| L5 | $E \geqslant 10^{31}$ |

## 4. Results and discussion

The time deviation between the occurrence of the flare and the lift-off time of the CME associated events was calculated to estimate the most proper temporal conditions. Fig. 1 represents a histogram of the time deviation ($\Delta t = T_{\mathrm{CME}} - \mathrm{T}_{\mathrm{FS}}$) as a function of the number of CME–flare associated events. The figure shows that most of the CME–flare associated events are located within the time interval 0.4 h $\leqslant \Delta t \leqslant$ 1 h, which is adopted as a temporal condition in our selection criteria.

Vrsnak et al. (2004) estimated roughly the lift-off time of CME, by using the linear back-extrapolation of its trajectory. They found that the time interval between the starting of the flare and the lift-off time of CME associated event occurred within the range $-1$ h $< \Delta t <$ 1 h. There is difference of about 0.8 h in the lower limit of $\Delta t$ between our results and that of Vrsnak et al. (2004).

Applying the temporal conditions ($T_{\mathrm{F}} = T_{\mathrm{FS}}$) and spatial conditions to the data set; we obtain 224 CME–flare associated events as plotted in Fig. 2. The figure shows the correlation between the CME energy and the X-ray flux of the CME–flare associated events with correlation coefficient ($R = 0.52$). Changing the temporal condition