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On the relation between the CMEs and the solar flares

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Abstract The aim of this paper is to study the relation between the coronal mass ejections, CMEs, and their associated solar flares. During the period from 1996 to 2010 there are 12,433 CMEs recorded by SOHO and 22,688 flare events observed by GOES. Under certain temporal and spatial conditions, we selected 776 CME–Flare associated events. We found that there is a good relation between the solar flare fluxes and their associated CME energies, where $R = 65\%$. In addition we found that 67% of the CME–Flare associated events ejected from the solar surface after the occurrence of the associated flare. Furthermore we found that the CME–Flare relation improved during the period of high solar activity. Finally, we have distributed the selected events depending on their flare class.

Introduction

CME ejected from the sun is one of the main solar phenomena. The Earth-directed CMEs are very important, since they can produce geomagnetic storms. Usually these CMEs are seen as Halo CMEs (Howard et al., 1982). The relation between CMEs and the other phenomena has been examined by many researches (e.g., Munro et al., 1979 and Kahler, 1992). Early measurements of the CMEs speeds have helped to advance our understanding of the physical processes in the solar corona. Wild et al. (1963) derived speed values 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 interplanetary medium. 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, 1974; MacQueen et al., 1974). It has been found that CMEs associated with large X-ray flares are likely to be fast and wide (Gosling et al., 1976), after comparing 16 CMEs associated with large flares and 11 non-flare CMEs observed by the Skylab coronagraph. MacQueen and Fisher (1983) analyzed six flare-associated CMEs and six non-flares with filament eruption observed by the MK3 coronagraph, and also they noticed that the former ones were faster, moving at nearly constant velocities where as the latter were slower, showing considerable accelerations. Hence they put forward the concept of two distinct classes of CMEs, the CME–Flare associated ones and the non-Flare CMEs. In the early 1980s, improved observations with the k-coronameter on Mouna Loa enabled MacQueen and Fisher (1983) to measure the speeds of 12-loop-like CMEs over the range of 1.2–2.4 R_S (where R_S is the solar radius). During the 1980s and as the SOLWIND and SMM coronagraphs observations observed thousands of CMEs from Earth's orbit, the statistical studies

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of CMEs have been improved. These CMEs 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).With the launch of the Large-Angle Spectrometric Observatory (SOHO) spacecraft in December 1995, the quality of the observations has improved again. Several years latter Andrews and Howard (2001) presented the height–time plots of several well-observed limb events, supporting the idea of the two CME classes. Recently, (Yashiro et al., 2002) made a comprehensive CME catalog that lists speeds and acceleration of 3217 CMEs observed by SOHO from 1996 to 2000. Vršnak et al. (2004) showed that the duration of the CME acceleration depends on the different phases of the solar flares. Early statistical studies (see, e.g., Munro et al., 1979) showed that ~40% of CMEs were associated with H-alpha flares and almost all flares (90%) with H-alpha ejecta were associated with CMEs. Thus the "mass motion" aspect of flares seems to be critical for a flare to be associated with CME. Flares have been classified (see, e.g. Pallavicini, 1977; Moore et al., 1999) as impulsive (short-duration (< 1 h), compact (10^{26}–10^{27} cm^3), low-lying (10^4 km)) gradual (long duration (h), large volumes (10^{28}–10^{29} cm^3), and great heights (10^5 km)). The probability of CME–Flare association increases with flare duration (Sheeley et al., 1983): 26% for duration < 1 h and 100% for duration > 6 h. It must be pointed out that some major flares associated with large-scale CMEs are not long-duration events (Nitta and Hudson, 2001; Chertok et al., 2004). Currently, there are three ideas about the flare–CME relationship: (1) flares produce CMEs (see, e.g., Dryer 1996), (2) flares are byproducts of CMEs (Hundhausen, 1999), and (3) flares and CMEs are part of the same magnetic eruption process (Harrison 1995; Zhang et al., 2001). Zhang et al. (2001) investigated four CMEs and compared their time evolution with GOES X-ray flares. They found that the CMEs started accelerating impulsively until the peak of the soft X-ray flare, consistent with an earlier result that flare-associated CMEs are in general faster than other CMEs (MacQueen and Fisher, 1983). There is also weak correlation (R = 0.53) between soft X-ray flare intensities and associated CME energies (Hundhausen, 1999; Moon et al., 2002). The fact that flares with H-alpha ejecta are closely related to CMEs suggests that we need to understand how the free energy in the eruptive region is partitioned between heating (soft X-ray flares) and mass motion (CMEs). The connection between flares and CMEs needs to be revisited especially because of the availability of high quality multiwavelength data on flares and CMEs.

In this paper, the relation between the coronal mass ejection (CME) and the solar flare is statistically studied by using a large sample of CME and flare events during the period from 1996 to 2010.

Data sources and selection of events

We used 15,880 records of CMEs data (obtained from CME catalogue) observed by SOHO, during the period from 1996 to 2010. This CME data is available in the CDA website: http://cdaw.gsfc.nasa.gov/CME_list/catalog_description.htm.

This catalogue contains all CMEs manually identified since 1996 from the Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO) mission. LASCO has three telescopes C1, C2, and C3. However, only C2 and C3 data are used for uniformity because C1 was disabled in June 1998. At the outset, we would like to point out that the list is necessarily incomplete because of the nature of identification. In the absence of a perfect automatic CME detector program, the manual identification is still the best way to identify CMEs. This data base will serve as a reference to validate automatic identification programs being developed. We also used the X-ray flares data which measured and provided by Geostationary Operational Environmental Satellite (GEOS), during the same interval (1996–2010) with records of 25,688 flare events.

To select the CME–Flare associated events, we used two conditions, firstly the spatial condition, according to this condition, the CMEs when ejected from the sun, must be near to the flares locations on the solar surface. As shown in Fig. 1, suppose that F represents the location of the solar flare on the solar disc and N is the solar north pole. For CME–Flare associated events, and by solving the spherical triangle FPN in Fig. 1, the following condition must be hold:

$$|(\Psi_{\mathrm{CME}} - \Psi_{\mathrm{F}})| < \Phi, \tag{1}$$

where Ψ_{CME} is the position angle of the CME (the angle measured on the solar disk between the solar north pole and the line directed to the ejection of the CME), Ψ_{F} is the flare's position angle and Φ is the angular width of the CME as detected by SOHO.

We obtained both Ψ_{CME} and Φ from CME catalogue, while Ψ_{F} is not found directly in the flare data so to calculate Ψ_{F}; we used the flare latitude λ and longitude β. From spherical triangle of the heliocentric celestial sphere we can deduce:

$$\Psi_{\mathrm{Flare}} = \tan^{-1}[\sin\lambda/\tan\beta] \tag{2}$$

where, β is the solar flare latitude, λ is the flare longitude.

The second condition is the temporal condition which required that the detection time of the CMEs (when the CMEs ejected from the solar surface) must be simultaneous to the start time of the associated flares.

If a CME is launched from the flare site, it has to propagate distance 2 solar radii before it is detected. If we denote the propagation distance from the solar surface out to the first detection location with C2 detector with height h, and the

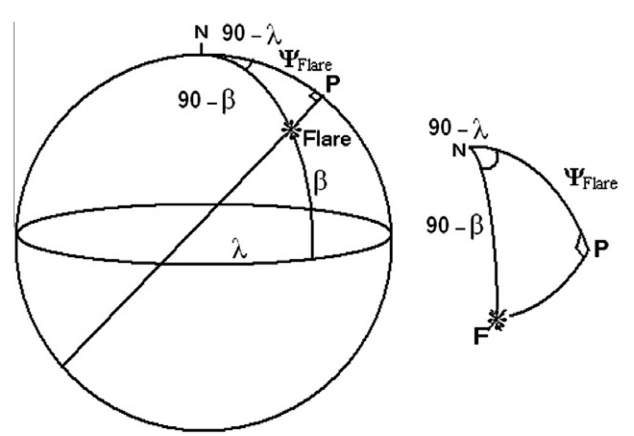

Fig. 1 Flare location on the solar disk.

CME is launched from the flare site with longitude l, we have the relation:

$$\sin(l) = 2/(1+h)$$

So the propagation distance is:

$$h = [2/\sin(l)] - 1$$

And the resulting detection delay is:

$$dt = h/V_{\mathrm{CME}}$$

Then we subtracted this time delay, dt, from each detection time of the CME events to be sure that the CMEs are simultaneous with the start time of the associated flares.

Fig. 2 shows a histogram of the CME–Flare time delay. Taking into account the spatial and temporal conditions, and picking up all the CMEs occurred between ±1 h the start time of their associated solar flare, we selected 778 CME–Flare associated events.

Results and discussion

CME–Flare energy correlation

To test our selection method by using the above temporal and spatial conditions, we study the linear relationship between the kinetic energy of CME, E_{CME}, and the intensity of the X-ray flare flux. First, we plot E_{CME} against X-ray flux according to the spatial condition only without any restriction to the temporal condition of CME motion and the result is shown in Fig. 3.

As shown in Fig. 3, it is obvious that only 2514 CME–Flare associated events can verify that condition of the 15,880 CMEs during the period of our study, and the linear correlation in this case is R_{corr} = (0.38). But when we apply both the spatial and temporal conditions the CME–Flare associated events falls from 2514 events to 778 events only. We found that the value of R_{corr}, increased in this case to be =(0.65) as shown in Fig. 4.

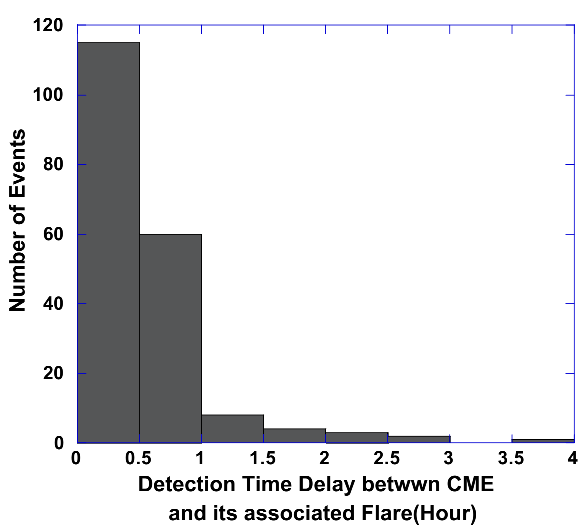

Fig. 2 Histogram of the CME–Flare time duration.

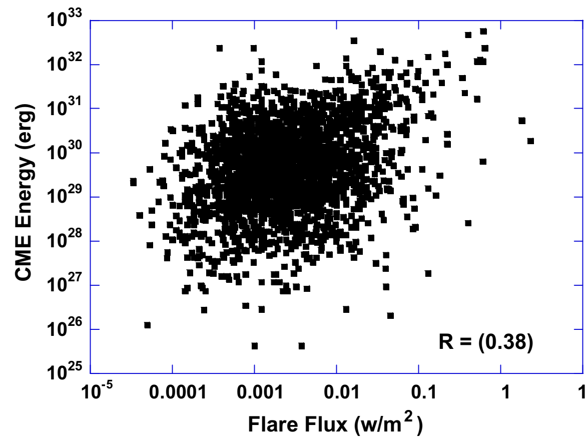

Fig. 3 CME–Flare correlation without the position angle condition.

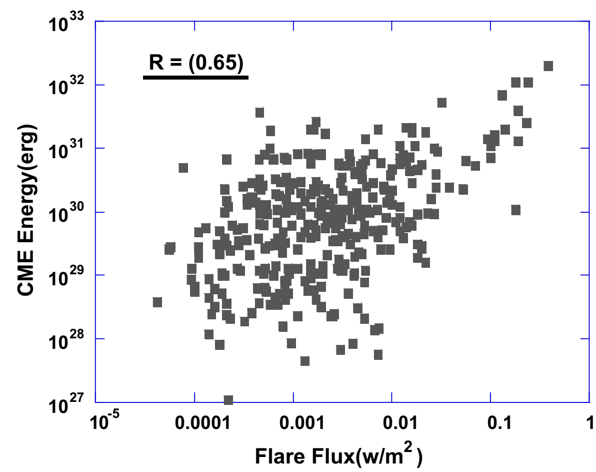

Fig. 4 CME–Flare correlation according to the temporal and spatial conditions.

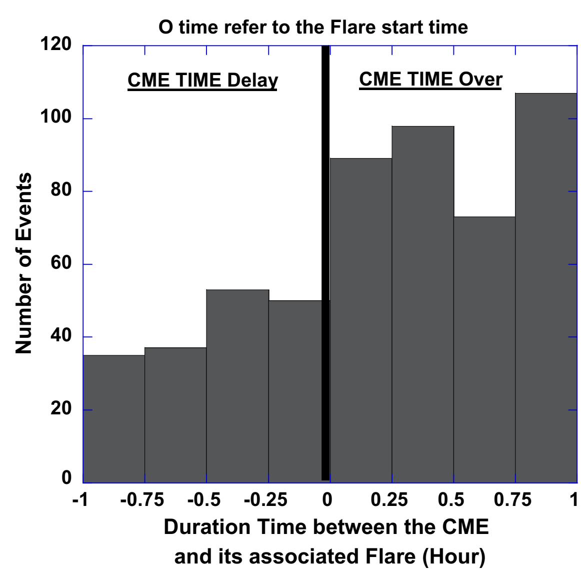

Fig. 5 Histogram of the interval time from start time of the flare.

The CME lift-off time

In Fig. 5, we divided the selected 778 CME–Flare associated events in two groups with respect to the flare start time as a reference level (CME time over events and CME time delay events) to study the effect of the CME-lift off time on the dependence of CME–Flare relationship. From Fig. 5, we found that 67% of the 778 CME–Flare associated events (530 events) are CME time over events and this maintain the idea that flares produce CMEs as suggested by (Dryer et al., 1996), not the idea that flares are byproducts of CMEs as postulated by (Hundhausen, 1999).

The relationship between the CME energies and their associated solar flare flux of each group is found in Fig. 6.

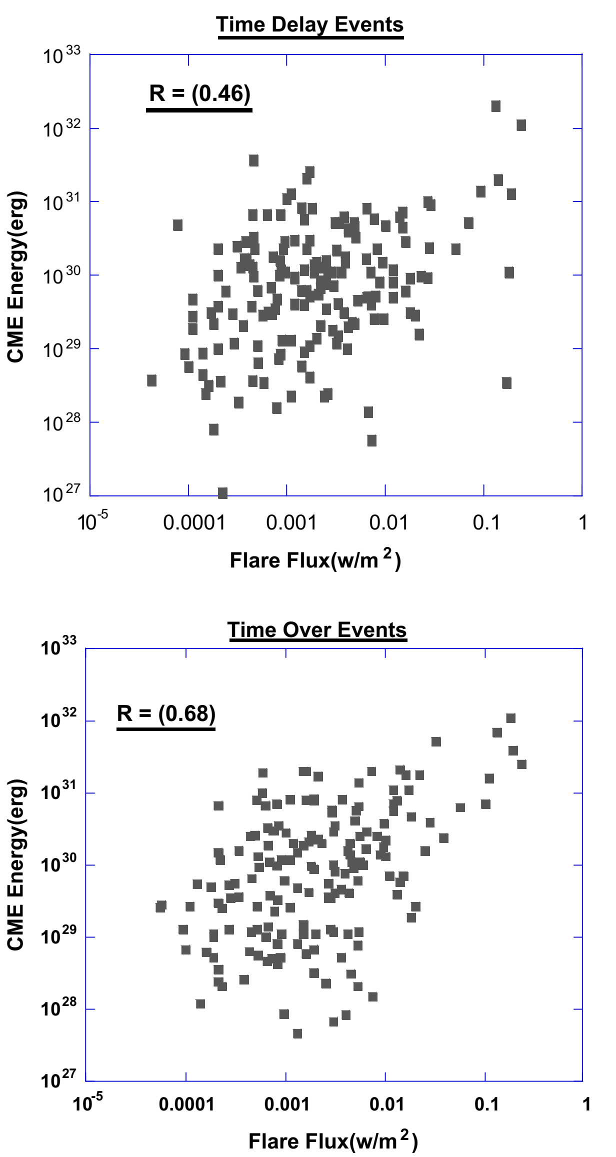

Fig. 6 Correlation between CME energy and X-ray flare flux for time over event (above) and time delay events (below).

From Fig. 6, we can show that the CME time over events (ejected from the sun after the occurrence of the associated flare) is more correlated to their associated flares (R_{Corr} = 0.68) than the delayed CME events which were ejected before the flare (R_{Corr} = 0.46).This result indicates that most of CMEs ejected from the sun are dynamical components of their associated previous flares.

The effect of the solar activity on the CME–Flare classification

Many authors have studied the CME–Flare correlation, Gopalswamy et al. (2005) used 44 CME–Flare associated events to study the relationship between the CME speed, Flare class and active region area from 1997 to 2002. They found that there is a good correlation between the X-ray flare flux and the active region area (R = 0.60) while they found that there is a weak correlation between CME speed and X-ray flare flux (R = 0.36) while there is a very weak correlation between CME speed and active region area (R = 0.11). Lin and Jun (2004) studied the relationship between solar flares and CMEs, they 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. They also found that the more energy that stored, and the better the correlation is (Hundhausen, 1999 and Moon et al., 2002) found that, there is a weak correlation (R = 0.53) between soft X-ray flare intensities and the associated CME energies. Five hundred and forty five Flare associated CMEs had statistically studied by Vrsňak et al. (2005), they found that the correlation between the soft X-ray flux and the energy of the associated CME events is also weak (R = 0.47).

From our point of view, the CME–Flare relationship is studied by focusing on the effect of the solar activity and on the correlation between the energy of the CME and the X-ray flux of the associated flare, for 46 CME–Flare events during the quite sun (1996–1997) and for 117 CME–Flare events during maximum solar activity of the 23rd solar cycle (2000–2001) and the results are as shown in Fig. 7, we found that the more active the sun the better the correlation is and vice versa.

Fig. 7(above) demonstrates that there is a weak correlation between the CME energy and the intensity of X-ray flux of the associated flare ($R_{\text{Corr.}}$ = 0.30) during quite sun. This result is in agreement with the result obtained by Vrsňak et al. (2005). By comparing the result obtained from Fig. 7(above and below), we found that the CME energies are more correlated to the X-ray flux of their associated flares during the active sun. This is because the large X-ray flares have more occurrence rate during active sun in addition to the CMEs associated with large X-ray flares are likely to be fast and wide (Gosling et al., 1976).

Classification of the CME–Flare associated events

In this section we classified the selected 778 CME–Flare associated events into four groups according to the flare class of their flare associated events as shown in Fig. 8.

The association rate is calculated as the fraction of the associated CME–Flare events of each flare type with respect to the total solar flare events of each flare type. We found that for B,

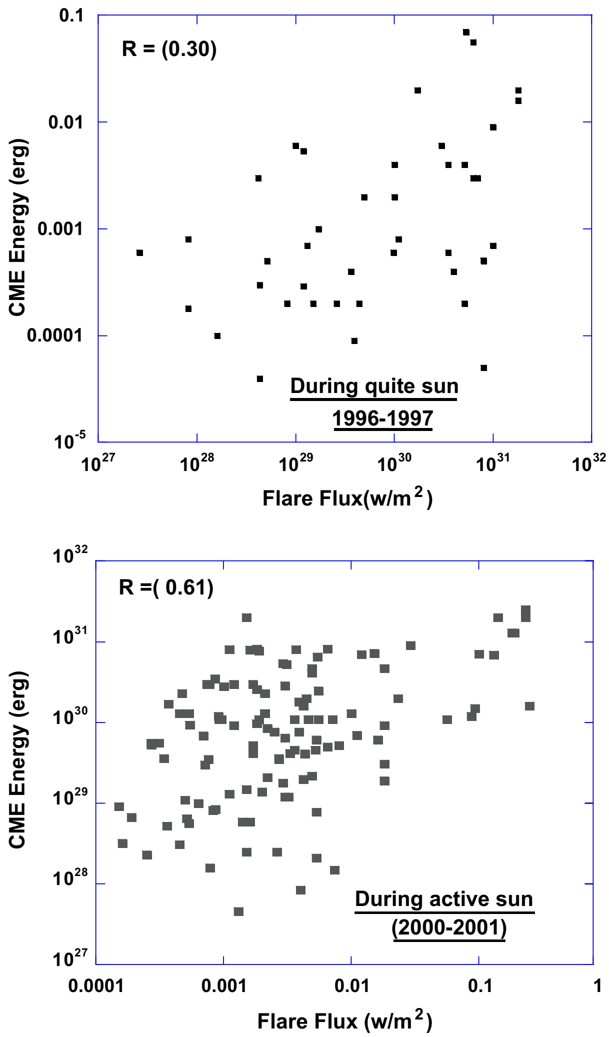

Fig. 7 CME–Flare relation during quite (above) and during active sun (below).

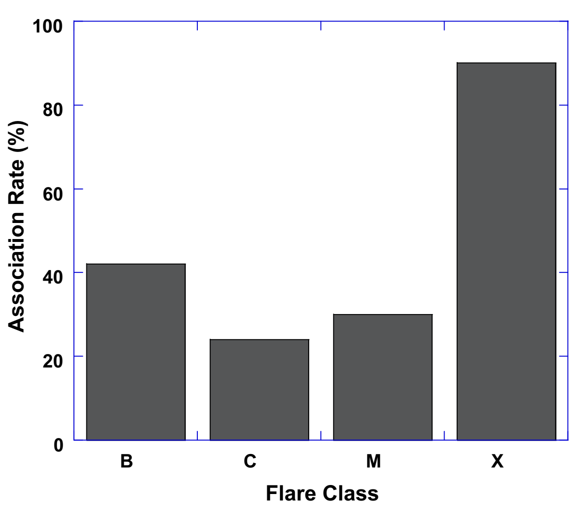

Fig. 8 CME–Flare classification of the total 778 events.

C, M and X type, the associate rate is 42%, 24%, 30% and 90%, respectively.

It is easily noticed from Fig. 8 that, the association rate of the CME–Flare associated events is dominant for X-Flare events.

Conclusions

We have studied the relation between coronal mass ejection (CME) and solar flares during the 23rd solar cycle. It is found that the best interval time between the detection time of the CME and the start time of its associated solar flare lies between ± 1 h. Also we tested our temporal and spatial conditions for the selected CME–Flare events, by studying the correlation coefficient between E_{CME} and X-ray flux with and without our conditions, and we found that the value of the linear correlation coefficient increases by using the two selected conditions. According to this study the following results have been obtained. Our main conclusions can be summarized as follows:

(1) The lift-off time of CME–Flare associated events having a time interval within the range $+15$ to $+30$ min after the occurrence time of associated flares.
(2) It is found that 67% of the 778 CME–Flare associated events (530 events) ejected from the solar surface after the occurrence of the associated flare and this result sustain the idea that flares produce CMEs as suggested by (Dryer et al., 1996), not the idea that flares are byproducts of CMEs as postulated by (Hundhausen, 1999).
(3) Also we noticed that the CME energies are more correlated to the X-ray flux of their associated flares during the period of high solar activity.
(4) In addition, we found that the CME association rate of the 778 selected CME–Flare events is dominant for X-Flare events.

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