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Correlation between CME and Flare Parameters (with and without Type II Bursts)

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Abstract CMEs and flares are the two energetic phenomena on the Sun responsible for generating shocks. Our main aim is to study the relation between the physical properties of CMEs and flares associated with and without type II radio bursts. We considered a set of 290 SOHO/LASCO CMEs associated with GOES X-ray flares observed during the period from January 1997 to December 2000. The relationship between the flares and CMEs is examined for the two sets *i*) with metric-type IIs and *ii*) without metric-type IIs. Physical properties such as rise time, duration, and strength of the flares and width, speed, and acceleration of CMEs are considered. We examined the energy relationship and temporal relationship between the CMEs and flares. First, all the events in each group were considered, and then the limb events in each group were considered separately. While there is a relationship between the temporal characteristics of flares and CME properties in the case of with-type IIs, it is absent in the case of all without-type IIs. Among all the relations studied, the correlation between flare duration and CME properties is found to be highly significant compared to the other relations. Also, the relationship between flare strength and CME speed found in the with-type II events is absent in the case of all without-type II events. However, when the limb without-type II events (with reduced time window between flare and CME) are studied separately, we found the energy relationship and the temporal relationship.

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1. Introduction

A solar flare is an explosive energy release in the low corona observed as a sudden intensity enhancement in any part of the electromagnetic spectrum (X-rays, optical, micro, and radio waves). Coronal mass ejections (CMEs) are the magnetized plasma ejected from the Sun that are regarded as the main cause of geomagnetic disturbances (see, *e.g.,* Gosling, 1993). Type II bursts are produced by the magnetohydrodynamic (MHD) shocks generated by flares and/or CMEs. Large geomagnetic storms, shock waves/type II bursts, and energetic particle events often occur in close association with large solar flares and CMEs; see, *e.g.,* Gopalswamy *et al.* (2008) and references therein. The subject of CME-flare relationships and their relation to type II bursts is also very important (Kahler, 1992; Harrison, 1995, 2006; Dryer, 1996; Aurass, 1997; Hundhausen, 1999; Gopalswamy, 2000). Recently, a high degree of synchronization between the acceleration of a CME and the impulsive phase of a flare (Zhang *et al.*, 2001; Neupert *et al.*, 2001; Shanmugaraju *et al.*, 2003a; Zhang and Dere, 2006; Maričić *et al.*, 2007) has been reported. These studies have revealed a close temporal relation between the physical processes of eruptive flares and CMEs. While Hundhausen (1999) examined the correlation between the flare strength and kinetic energy of CMEs, Moon *et al.* (2002) studied the relation between the CME speed and the integrated X-ray flux. Both of them obtained only nearly 50% correlation. In addition, Moon *et al.* (2002) suggested that a close relationship possibly exists between CME kinematics and the flaring process. A similar conclusion was drawn by Temmer *et al.* (2008, 2010), who found a very high degree of synchronization of the CME acceleration and the flare hard X-ray burst in three well-observed events. In this context, Jing *et al.* (2005) also obtained a strong correlation between the reconnection rate and the acceleration of erupting filaments.

The soft X-ray characteristics of solar flares, both with and without associated CMEs, were investigated by Kay *et al.* (2003) using a comparison of flare parameters of a total of 69 ejective and non-ejective flares. They found that, while there is some relationship between the length of the rise and decay phases of flares, there are no systematic differences between the ejective and non-ejective flares. In addition, Vršnak, Sudar, and Ruzdjak (2005) investigated flare-associated CMEs and non-flare CMEs and found that both data sets show quite similar characteristics, contradicting the concept of two distinct (flare/non-flare) types of CMEs.

Even with the enormous data of CMEs and flares, we do not fully understand the relationship between them (see, *e.g.,* Qiu *et al.*, 2004; Yashiro and Gopalswamy, 2009). Also, the origin and sources of coronal type IIs are under debate (Cliver, Webb, and Howard, 1999; Gopalswamy, 2000; Nindos *et al.*, 2008; Vršnak and Cliver, 2008; Shanmugaraju, Moon, and Vrsnak, 2009). It has been found from statistical studies on the properties of type II associated flares and CMEs that, though the flares associated with type IIs are intensive and CMEs associated with type IIs are wider and faster, there are several such flares and CMEs without type IIs. For these cases, the condition that the shocks do not become super-Alfvénic was suggested (Gopalswamy, 2000). But the relation between CMEs and flare parameters has not yet been explored in connection with/without the type II bursts. In this paper, we have investigated the CME-flare relations by examining the physical relationship between the properties of CMEs and flares that are associated with type IIs and without type IIs.

A set of 290 CMEs and their associated flares compiled by Moon *et al.* (2002) was divided into two sets by Shanmugaraju *et al.* (2003b) to study the difference between the statistical characteristics of CMEs and flares associated with coronal type IIs and those not associated with type IIs. They analyzed the physical properties of both flares and CMEs and

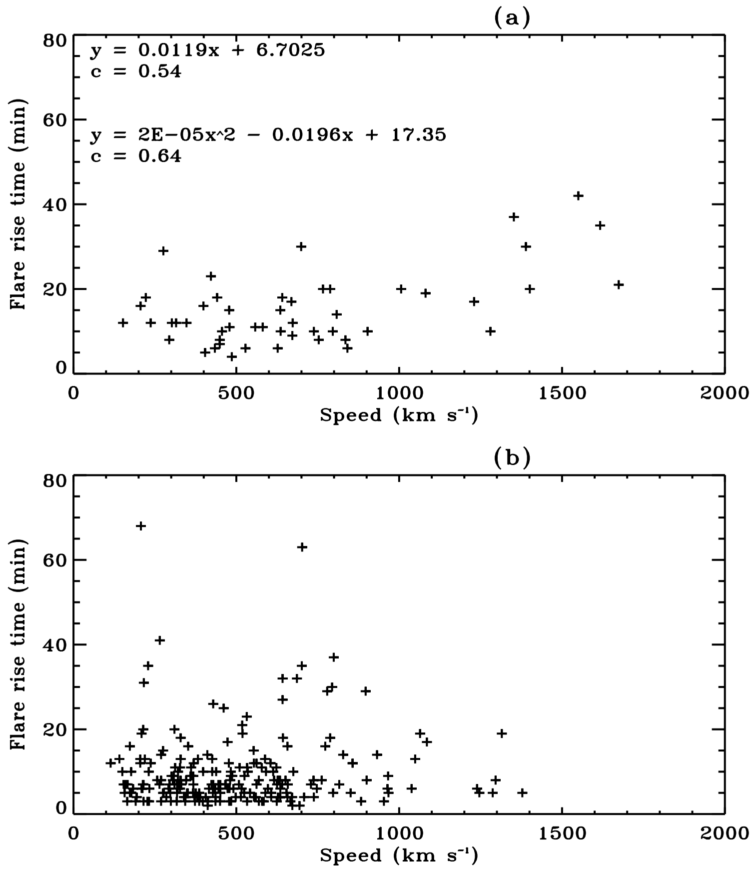

Figure 1 Relation between CME speed and flare rise time for (a) with-type II events and (b) without-type II events.

found that the properties are statistically different for the two sets of flares/CMEs with type IIs and without type IIs. In this paper, we have extended that study primarily to examine the CME-flare relationship.

In the next section, we describe the data analysis. The results are discussed in Section 3, and a brief conclusion is presented in Section 4.

2. Data Analysis

Among the 290 events, 59 events are with-type II and another 227 events are without-type II. These two groups of events are considered in the present study, and their cataloged properties of the associated flares and CMEs (http://cdaw.gsfc.nasa.gov/ and ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA) are utilized for analyzing the CME-flare relationship. We have considered the average linear speed obtained by a linear fit on height-time plots, final speed at $20R_{\odot}$ obtained by a second order fit, width and acceleration of Large Angle and Spectrometric Coronagraph (LASCO) CMEs, and *Geostationary Operational*

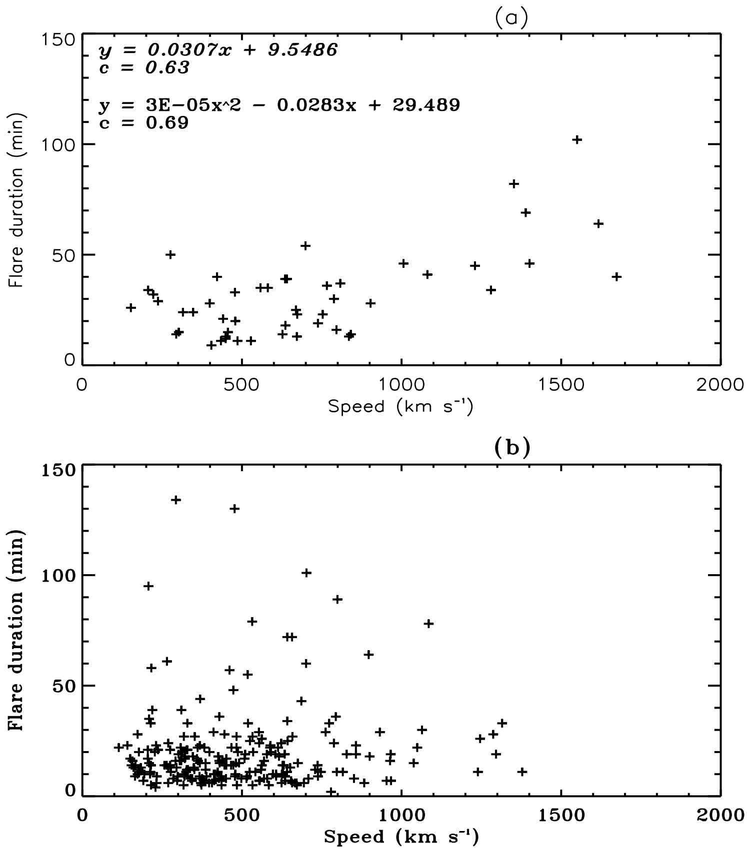

Figure 2 Relation between CME speed and flare duration for (a) with-type II events and (b) without-type II events.

Environmental Satellite (GOES) X-ray flare rise time, duration, decay time, peak flux, impulsiveness (peak flux/flare rise time), and fluence (flux integrated over the entire flare duration).

3. Results and Discussion

3.1. Relation between CMEs and Flares with/without Type II Events

First, the CME-flare relationship is analyzed using 59 with-type II events. We found that the temporal characteristics of X-ray flares (such as their flare rise time, duration, and decay time) are nicely related with the CME properties (such as their speed and width). For example, the CME speed and flare rise time are related, as shown in Figure 1a, with a linear correlation coefficient of 0.54. It is interesting that they are best fitted with a quadratic relation ($c = 0.64$). Similarly, the relation between flare duration and CME speed is shown in Figure 2a. In addition, we found that the CME speed at $20R_{\odot}$ (determined using the second order polynomial fit on the height-time data) is even better correlated (≈ 0.7) with

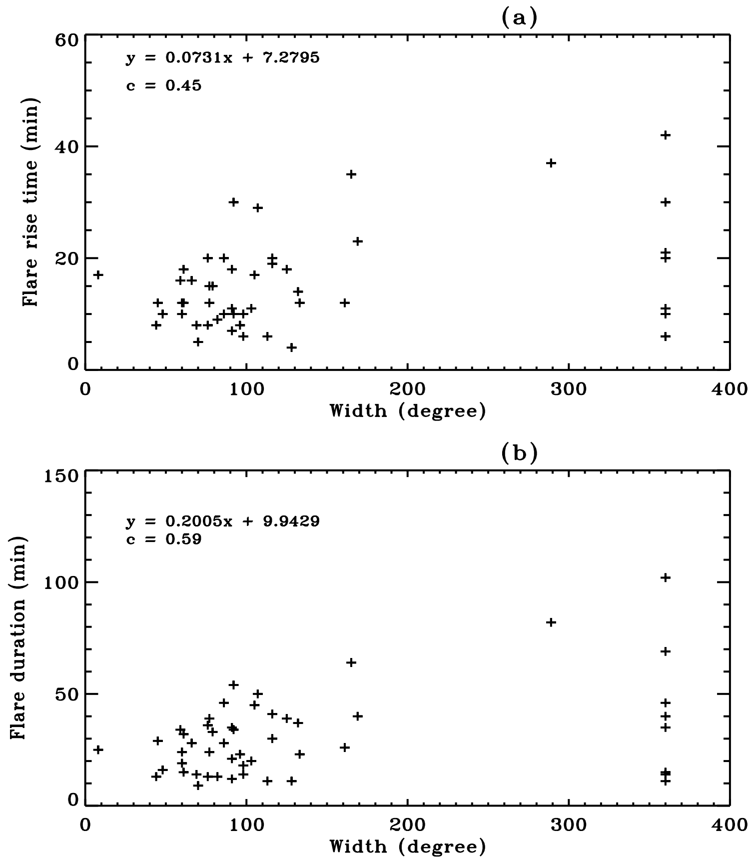

Figure 3 Relation between CME width and (a) flare rise time and (b) flare duration. The halo CMEs are shown at 360°.

the flare's temporal characteristics. These results indicate that high speed CMEs are observed with long duration flares, in agreement with earlier results (Sheeley *et al.*, 1983; Kahler, 1992). Also, these results obtained from the with-type II events are similar to statistical values of Shanmugaraju *et al.* (2003a, 2003b), where they found that CMEs with type IIs are bigger and faster, and flares with type IIs have greater rise time and duration. The results are also similar to a recent study on the X-ray emission characteristics of flares associated with CMEs (Aggarwal *et al.*, 2008). They reported that the CME velocity increases with respect to flare duration in both 4.1 – 10 and 10 – 20 keV bands. The correlations found in Figures 1a and 2a are significant with p-values of 0.036 and 0.0015, respectively; p-values less than 0.05 are significant.

When the above CME-flare relations were investigated using 229 without-type II events, surprisingly, we found no relations in these events among the temporal characteristics of flares and CME speed (see Figures 1b and 2b).

Similarly, the relations between CME width and rise time and duration of flares have been examined for both the with-type II and without-type II events. While the with-type II events exhibit a correlation of 0.45 – 0.60 (Figure 3) irrespective of the large scatter of points, the without-type II events do not have any relation. The correlation of flare rise time

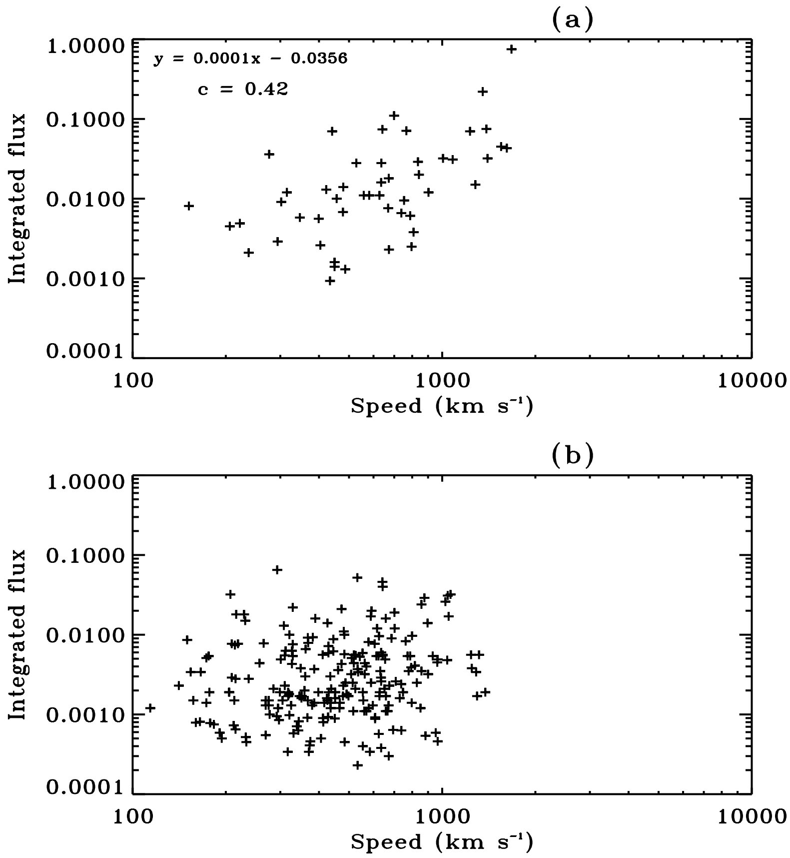

Figure 4 Relation between flare strength and CME speed for (a) with-type II events and (b) without-type II events.

with CME width is not significant ($p = 0.127$), but the correlation of flare duration is found to be significant ($p = 0.025$).

The flare strength and CME speed were investigated in the past by several authors (*e.g.*, Hundhausen, 1999; Moon *et al.*, 2003; Nitta, 2002; Burkepile *et al.*, 2004; Maričić *et al.*, 2007) for studying the CME-flare relationship. We have also obtained a similar relation between these two parameters, as shown in Figure 4a. This correlation is found to be highly significant with a very small p-value (1.868×10^{-5}), implying that there is a definite relation between the energetics of these two events; *i.e.*, the stronger the flares, the faster the CMEs. Recently, Yashiro and Gopalswamy (2009) examined the statistical relationship between the peak flux, fluence, and duration of flares and the speed and width of CMEs. They obtained a 48% correlation between the CME kinetic energy and flare peak flux, and 62% between the CME kinetic energy and flare fluence. However, as shown in Figure 4b, the relation between the CME speed and the flare fluence seems to be absent for without-type II events.

3.2. CME-Flare Relationship of Limb Events

In order to check the above relation more quantitatively in with-type II events, we separated a set of 13 limb events (they have flare longitude ≥ 60 degrees) from the 59 events and

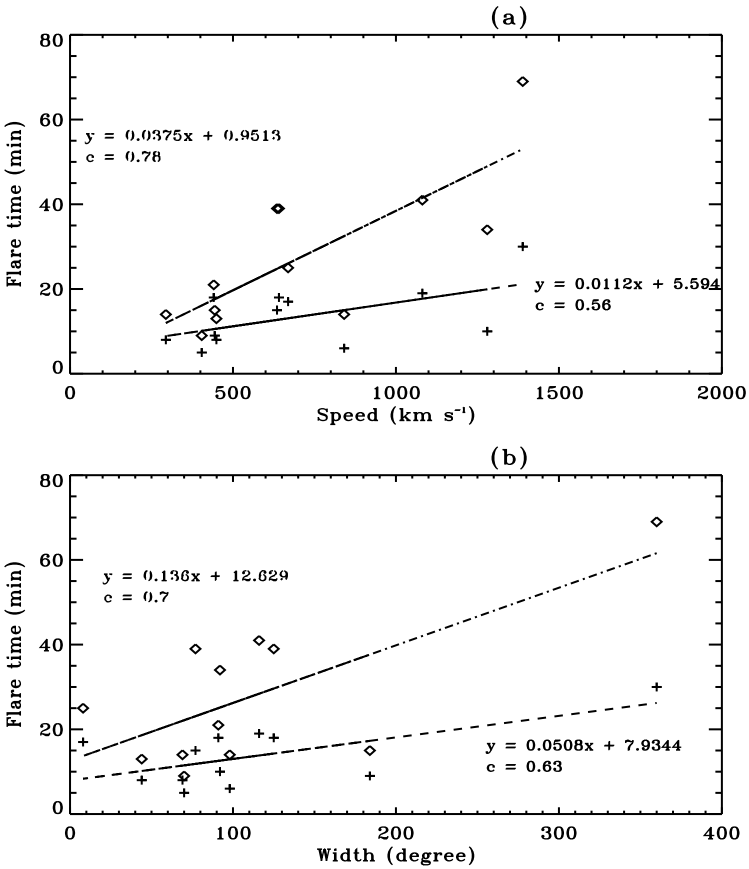

Figure 5 With-type II events: Relation between flare rise time (plus symbols) and flare duration (diamond symbols) with (a) CME speed and (b) CME width for the limb events alone.

examined the relations again. An improved relation was then obtained, as shown in Figure 5, between the flare rise time and duration with CME speed and width. In both cases, the flare duration showed a correlation of up to 0.78. While these correlations are not significant for flare rise time, they are significant for flare duration.

In order to ascertain the absence of a CME-flare relationship for without-type II events, we separated a set of 35 limb events (occurring beyond 60 degrees longitude) and examined various relations. However, only a poor correlation of less than 20% is obtained for the flare rise time and duration with CME speed (see Figure 6). We also noted that the correlation between the flare fluence and the CME speed is weaker than that of the with-type II events (Figure 7). The correlation in Figure 7a is found to be slightly significant ($p = 0.0614$), but it is not significant in Figure 7b.

For the without-type II events, if we reduce the time window to ± one hour, then the correlations of flare rise time-CME width, flare duration-CME width increase to 30 – 40%. But there is no correlation for CME speed. On the other hand, if we reduce the time window to ± 30 min, then there is no correlation found for flare rise time and duration either with CME width or speed. But for limb cases alone, there seems to be a relation between flare rise time and CME speed. From this particular analysis, note that, while these relations are

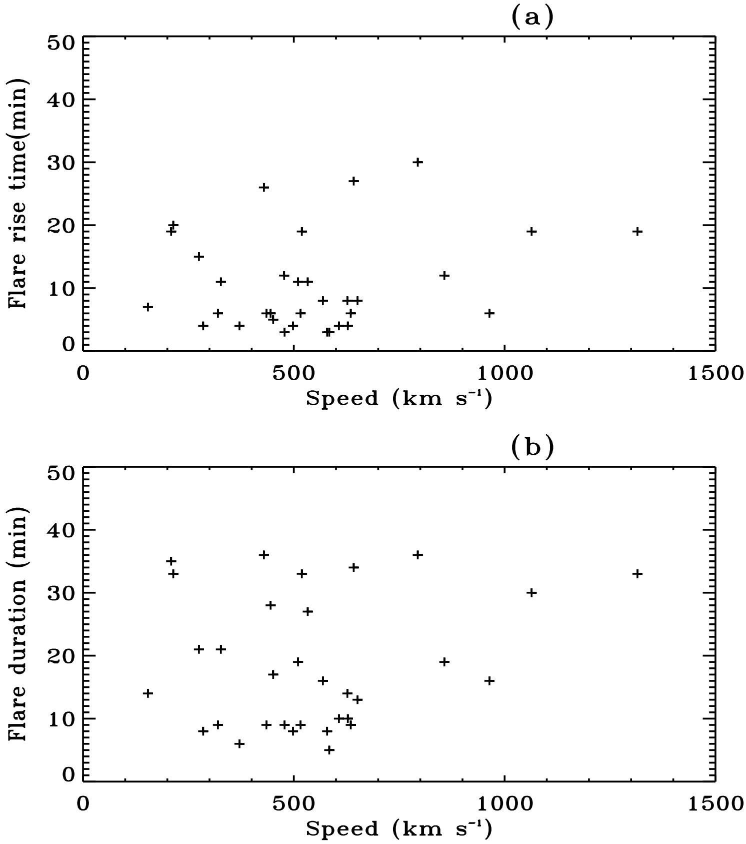

Figure 6 Relation for without-type II events between CME speed with (a) flare rise time and (b) flare duration.

absent in general for all without-type II events, there is some relation for limb events alone. This result implies that the absence of relation when all without-type II events are considered may be a consequence of projection effects.

3.3. CME and Flare Onsets for both with/without Type II Events

The delay time is determined to be between the first appearance time of the CME in LASCO and the flare onset. The distribution of this delay ranges between 0 – 50 min with a peak around 20 min (Figure 8a) for the with-type II events. It is compared with the similar distribution plot of CME-flare delay for the 229 without-type II events (Figure 8b). The CME-flare delay of without-type II events shows a wide range from −20 to 70 min. This result is similar to that of Zhang *et al.* (2002); namely the fast CMEs (with-type II) are closely temporally related with flare onsets, while the slow CMEs (without-type II) are only loosely related with flare onsets.

For the limb events alone in both cases, the average (standard deviation) values of the time delay are found to be 34.4 (16) min and 22.7 (45) min, respectively, for the with-type II events and without-type II events. Also the average (standard deviation) values of speed are 830 (542) $\mathrm{km\,s^{-1}}$ and 547 (244) $\mathrm{km\,s^{-1}}$, respectively; the with-type II CMEs are faster than

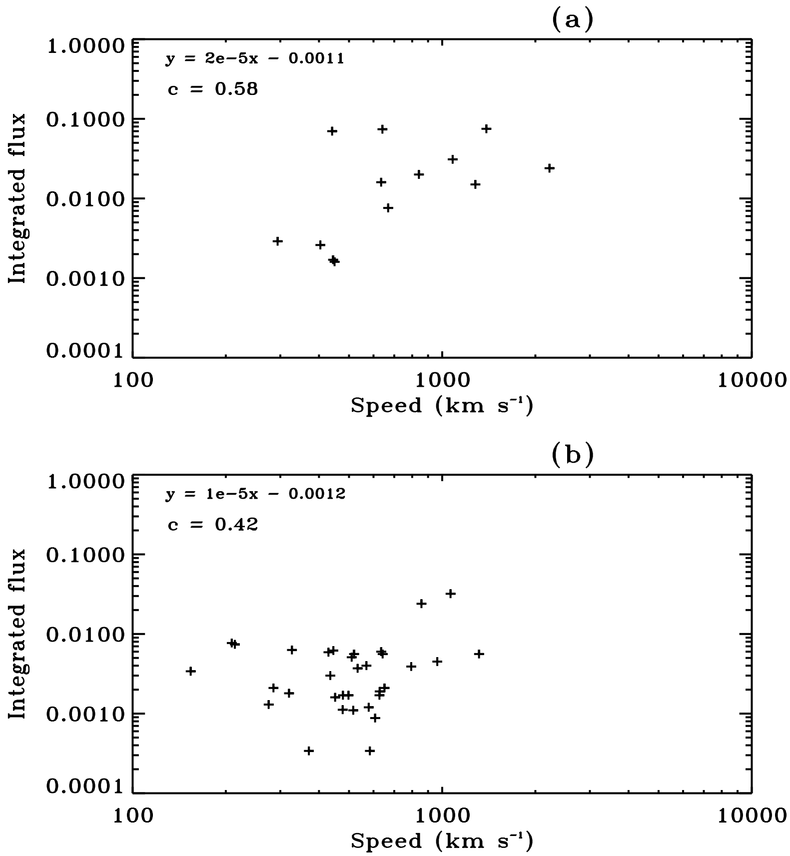

Figure 7 Relation between flare strength and CME speed for limb events alone: (a) with-type II events and (b) without-type II events.

the without-type II CMEs. As suggested by Zhang and Golub (2003), the morphologies of flares and hence the magnetic topologies may be different for fast and slow CMEs.

Utilizing these average speeds and the average time delays, we determined an approximate distance traveled (using a constant speed approach) by the CME as $2.15R_{\odot}$ and $1.07R_{\odot}$, respectively, for with-type II and without-type II events. By assuming $3R_{\odot}$ as the first detection height in LASCO C2 images for all the CMEs and assuming that the flares are located near the solar surface, the above distances reveal that the with-type II CMEs must have onset heights much closer to the flares than the without-type II CMEs. Even after taking into account the standard errors in speed and delay time, we found that the distance traveled by the CMEs is $2.15 \pm 0.75R_{\odot}$ and $1.07 \pm 1R_{\odot}$, respectively, for the with-type II and without-type II CMEs. Note that the CMEs either generate the type II shocks themselves or may create a favorable atmosphere of low Alfvén speed for the flare-blast waves to generate shocks in the corona (Wagner and MacQueen, 1983; Cliver, Webb, and Howard, 1999). It is quite possible that at such low coronal heights the CMEs accelerate (see, *e.g.*, Zhang *et al.*, 2001; Shanmugaraju *et al.*, 2003a).

In addition, the CME onset times were determined using the following two back-extrapolations to the solar surface: *i*) a linear fit to all the height-time data, and *ii*) a quadratic

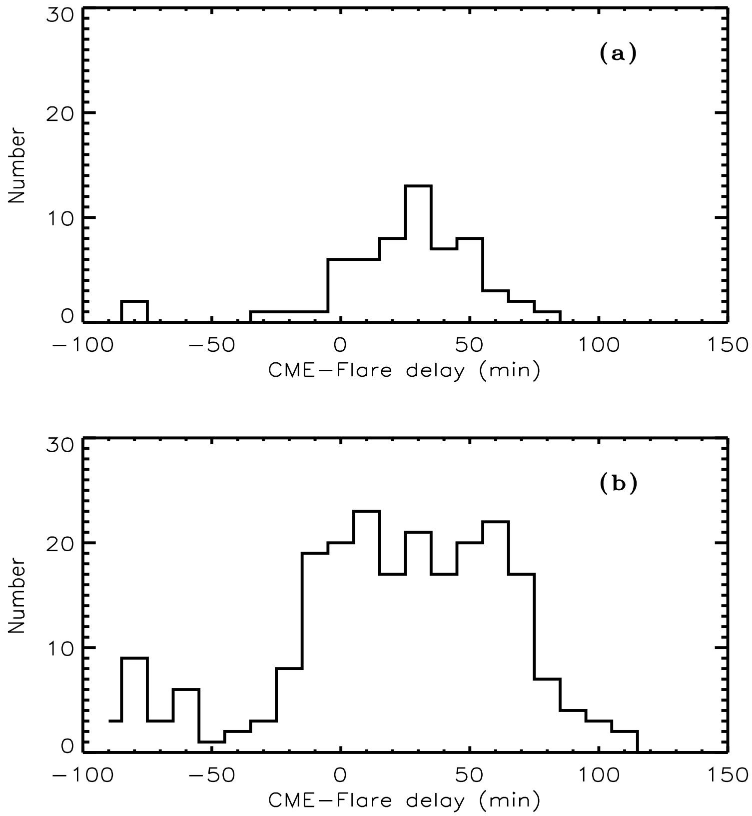

Figure 8 Distribution of CME-flare delay for (a) with-type II events and (b) without-type II events. The CME-flare delay is the interval between the time of CME's first detection and the flare start.

fit to all the height-time data. Thus, the delay between CME onset and flare onset was obtained qualitatively; their distributions for both sets of events are shown in Figure 9. As shown in this figure, most of the with-type II events are closely temporally related, whereas many of the without-type II events are not. Now, the average delay between the onsets of CMEs and flares (of with-type II events) is 19.4 and 13.6 min for linear and quadratic fits, respectively. However, the values are 29.8 and 35.9 min for without-type II events. This shows that in the former case, as mentioned above, the flares and CMEs are closely temporally related. However, the delay is larger in the latter case. In many cases (nearly 90%), we found that the CME onset occurred before the flare onset.

The present paper may have some implication on the origin of type II bursts. A recent investigation of 13 events presented by Qiu and Yurchyshyn (2005) showed that the CME speed is proportional to the magnetic flux reconnected in the flare process below the CME, with a linear correlation coefficient of 89% and confidence level greater than 99.5%. Similarly, Jing *et al.* (2005) obtained a strong correlation between the reconnection rate and the acceleration of erupting filaments. These two papers as well as the results presented by Temmer *et al.* (2008, 2010) clearly indicate that the magnetic reconnection below the CME plays an important role in the acceleration of CMEs (for an interpretation see Vršnak, 2008). Our results in the present study show a strong temporal and energetic relationship

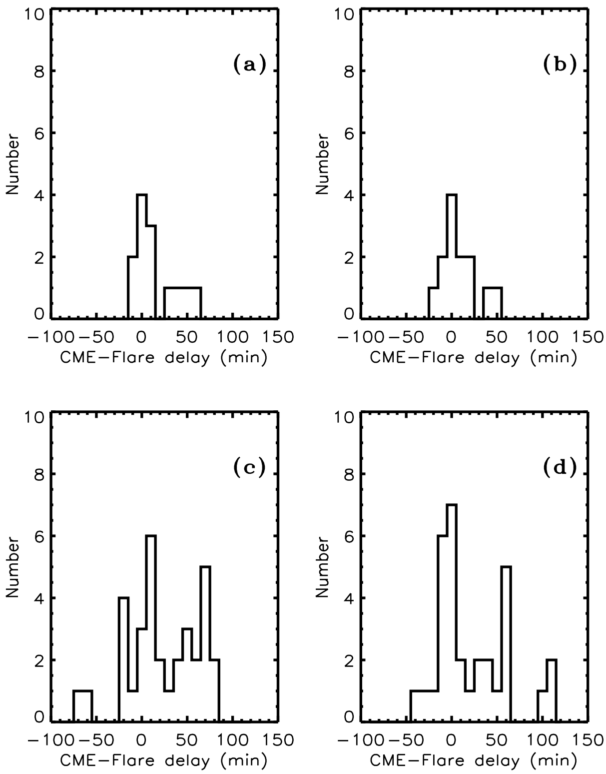

Figure 9 Distribution of CME-flare delay found from the onset time of flares and CMEs for (a) and (b) with-type II events, (c) and (d) without-type II events. The CME onset times were found using linear fit, (a) and (c); and quadratic fit, (b) and (d).

between CMEs and flares with type IIs. It shows a very intimate relationship among type II, reconnection process, and mass ejection.

However, as suggested by Lin, Mancuso, and Vourlidas (2006), occurrence of type II bursts depends on the Alfvén speed, which is determined by the magnetic field and plasma density. In addition, they found that occurrence of type II depends on the rate of magnetic reconnection. If it is slow, then the type II bursts may not occur even if the associated CMEs are fast ($> 800\ \mathrm{km\,s^{-1}}$).

4. Conclusion

A set of 290 events of CMEs and flares is considered in the present study. Of these, 59 events are with-type II and another 227 events are without-type II. The correlation between the CME-flare parameters (such as temporal relationship and energy relationship) is examined for both these groups. This analysis confirms that there is a definite relationship between flare integrated flux and CME speed for both with and without type IIs.

However, the strong relationship between the temporal characteristics of flares with CME speed and width exists only in the case of with-type II events. While it is absent in the case of all without-type II events, it is found in the case of limb events alone. Among all the relations studied, the correlation between flare duration and CME properties is found to be highly significant compared to the other relations.

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