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Peak flux of flares associated with coronal mass ejections

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Abstract Features of flares that occur in association with coronal mass ejections (CMEs) have often displayed variations compared to flares with no associated CMEs. A comparative estimation of peak flux values of flares associated with CMEs and those without CMEs is made. Peak flux values of flares associated with CMEs show distinctly higher values in comparison to flares with no associated CMEs. Higher peak flux of CME associated flares may be attributed to the heating of plasma to higher temperature when associated with CMEs. While providing a distinct difference between the flux values of flares clearly associated with CMEs compared to flares associated with no CMEs, this study also highlights an evident difficulty in making distinct flare-CME associations.

Key words: Sun: activity — Sun: flares —Sun: coronal mass ejections

1 INTRODUCTION

Although flares and coronal mass ejections (CMEs) often occur nearly simultaneously, it is still uncertain which event drives the other. There exists a large volume of research seeking to connect the two in terms of various characteristics associated with both sets of events (Tandberg-Hanssen & Emslie 1988; Green et al. 2001). Green et al. (2001) discuss the case of flares emitting less energy when associated with CMEs, suggesting that the latter carry away part of the energy which would otherwise have been available for the flare, implying that the net energy is somehow distributed between flares and CMEs. However, there are studies that highlight a variety of fundamental differences between the active regions where flares and CMEs occur compared to the active regions where flares alone occur. Nindos & Andrews (2004) conclude that the flare-CME active regions have a significantly higher estimated magnetic helicity than the active regions where flares alone occur. Liu et al. (2010 and references therein) suggest that due to the probable existence of an upper bound on the total magnetic helicity in the corona, CMEs could occur due to accumulated helicity. Liu et al. (2010) have also reported the property of growth of an arcade in association with the flux emergence and eruption of a CME. They also suggest that flare particle acceleration is strongly coupled to large-scale CME acceleration. Shanmugaraju et al. (2003) have reported that the CMEs associated with flares experience higher acceleration. Choudhary & Moore (2003) reported that CME producing filament eruptions are accompanied by two ribbon flares in Hα while the non-CME producing eruptions did not. Wang & Zhang (2007) have computed the distance between the flare site and the flux-weighted magnetic center of the source active region as a displacement parameter and concluded that the displacement parameter is much larger for a CME associated with an active region than for a confined flare. Cheng et al. (2011) reinforce this finding.

While the aforementioned characteristics of an active region indicate several differences between the two types of flares, there is also the indication that enhanced flux emission could be expected with CME associated flares. For example, Wang & Zhang (2007) have concluded that a higher magnetic flux in the high corona compared to that in the lower corona makes it difficult for an energy release in the low corona to ensure a CME is triggered. This implies that a higher amount of energy is required to drive CMEs, especially in cases where the magnetic flux is higher in the higher corona which means flares occurring in association with CMEs have to necessarily have higher flux. Harrison (1995) concluded that a CME generally originates from a much larger source structure than a flare. This could indicate a higher energy content in such flares. Lin (2004) reported that the higher the free energy, the higher the flare-CME correlation.

A relationship between the soft X-ray peak flux and the CME velocity is indicated by several authors (Hundhausen 1997; Chen & Zong 2009). Burkepile et al. (2004) found a correlation between the CME kinetic energy and the peak flux values of soft X-ray flares. Jain et al. (2010) note that heating of the coronal plasma is significant for the kinetics of a CME from the reconnection region where the flare also occurs, leading to strong inference that CME associated flares might carry more flux than flares with no associated CMEs. The magnetic field energy is converted into heating the plasma and accelerating the particles in the corona during reconnection. Hence, based on a strong relationship between the flare plasma temperature and the velocity of a CME, it has been suggested that the speed of CMEs depends upon the dominant process of conversion of the magnetic field energy to heating or accelerating coronal plasma in the reconnected loops (Jain et al. 2010).

Chen & Zong (2009) conclude that the correlation between the CME velocity and the X-ray peak flux is stronger than that between the CME velocity and the time-integrated X-ray flux of associated flares. They also emphasize that the acceleration of CMEs ceases near the peak time of soft X-ray flares. Being predominantly associated with high flare flux values, fast CMEs are regarded as good candidates for particle acceleration (Suryanarayana 2012 and references therein). Thus, the role of flare peak flux either as a quantity responsible for driving CMEs or as an indicator of the underlying cause that drives CMEs has gained heightened importance. In this connection, we may note that sufficient clarity does not exist as to whether flare peak flux associated with a CME is higher or not. Hence, there is sufficient reason to study the difference between the peak flux of flares associated with CMEs and flares with no associated CMEs.

While the question of whether a flare drives the CME or vice-versa is likely to remain unsettled for a long time to come, the aforementioned studies clearly point to a scenario of flares being more energetic when associated with CMEs. Hence, a study to quantitatively assess the same is needed. We seek to fulfill this requirement in the present paper. The differences highlighted so far between flares associated with CMEs and those not associated with CMEs pose a fundamental problem when two flares, one associated with the CME and the other not associated with the CME, cannot be compared. However, since magnetic reconnection is believed to be the common trigger for both flares and CMEs, it is reasonable to compare flares with the same duration so as to know the difference in their peak flux emissions. This is also enabled by the fact that the CME occurrence rate increases rapidly with flare duration (Sheeley et al. 1983; Kahler et al. 1989). Hence, flare duration is a reasonable barometer to assess the difference, if any, between the flare peak flux values occurring in association with the CMEs as opposed to flares with no associated CMEs. The remaining part of this paper is organized as Data in Section 2, Results and Analysis in Section 3 and Discussion and Conclusions in Section 4.

2 THE DATA

The present analysis makes use of the flare duration and peak flux values of soft X-ray flares observed by the Geostationary Operational Environment Satellite (GOES) in the 0.1–0.8 nm wavelength bands (Veronig et al. 2002; Kay et al. 2003) and archived as Solar Geophysical Data (SGD)[1]. Flares are divided into A, B, C, M and X class as per their peak flux as shown in Table 1.

Table 1 The GOES class of solar flare and the peak flux range. n is the numeric code indicating the sub-class that varies between 1.0 and 10.0.

GOES Class	(W m^{-2})	(erg cm^{-2} s^{-1})
A	$< 10^{-8}$	$< 10^{-5}$
B	$n \times 10^{-7}$	$n \times 10^{-4}$
C	$n \times 10^{-6}$	$n \times 10^{-3}$
M	$n \times 10^{-5}$	$n \times 10^{-2}$
X	$>10^{-4}$	$> 10^{-1}$

The flares are listed with active region number, start, peak and end times, and peak flux. The soft X-ray flux is from the entire Sun. In a given moment one or more active regions may be flaring and more than one CME might be occurring simultaneously from different active regions. The CMEs are first observed when they are in the LASCO C2 field of view which is $\sim$1.5 solar radii from the center of the Sun. Hence, the exact time of CME occurrence is not available except by way of extrapolation. Therefore, associating flares with CMEs involves great uncertainty.

The Wind Waves website[2] has listed flare-CME associations which represent stringent association. Since the temporal association of CMEs with flares is uncertain, we separately obtain the results using flares from the SGD that can be associated with CMEs from the Wind Waves website. Hereafter we use the abbreviation WW to indicate flares associated with CMEs from the Wind

[1] *ftp://ftp.ngdc.noaa.gov/STP/SOLAR DATA/SGD_PDFversion/*

[2] *http://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html*

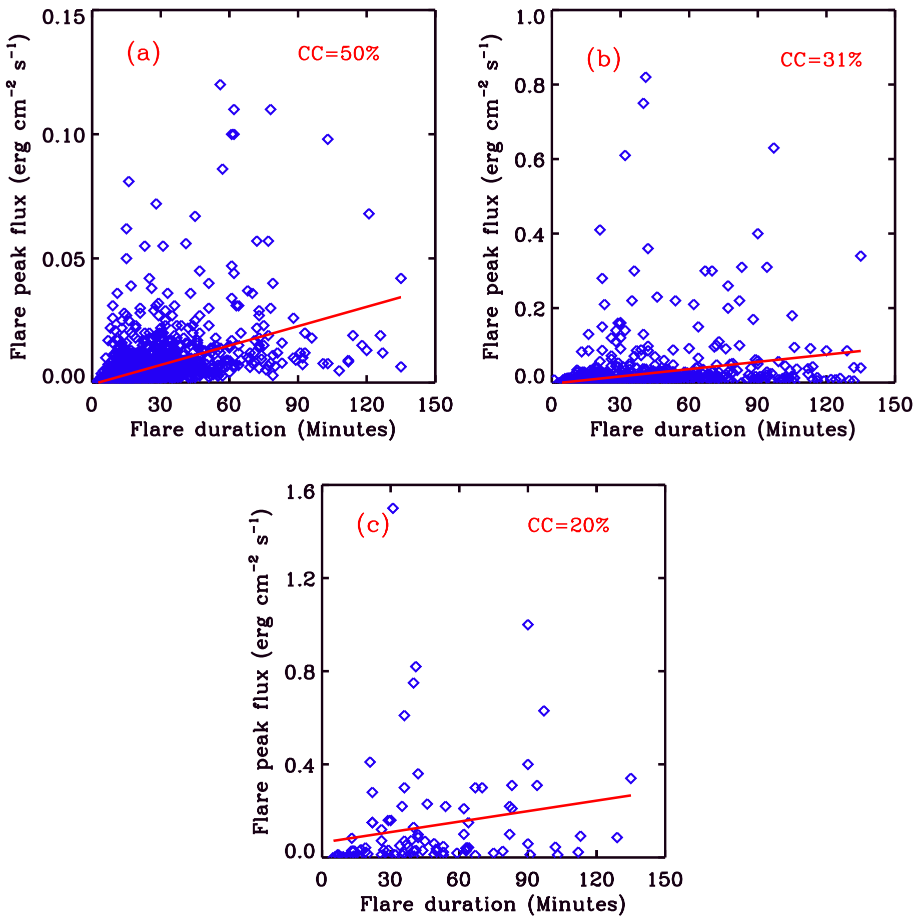

Fig. 1 Duration and peak flux of flares. Flares in (a), (b) and (c) are not associated with CMEs, associated with CMEs and associated with CMEs from the WW archive, respectively.

Waves list. A total of 99 events of flare-CME combinations for the years 2000 and 2001 is reported in the WW archive. These flares are a subset of the flares associated with CMEs, temporally.

We collect the CME data from the Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO)[3] archive such that flares are listed within a time window of 2 hours of the CMEs. Studying a data set of 92 CMEs, Harrison (1991) reported that 43 CMEs had an X-ray flare within a ± 2 hour time window around the time of CME observation. This criterion was reinforced in another paper by Harrison (1995). Hence, we collect flare data for the years 2000 and 2001 such that flares are listed within ± 2 hours of the time the CMEs are observed. Thus, out of a total of 5201 flares reported in the SGD for the years 2000 and 2001, $\sim$98% or 5097 flares occur within ± 2 hours of the time the CMEs were observed. In these statistics, 1853 flares are associated with CMEs and the remaining 3244 flares are not associated with CMEs.

[3] *http://cdaw.gsfc.nasa.gov/CME_list/*

3 ANALYSIS AND RESULTS

In Figures 1(a) and 1(b), we plot the flare duration and peak flux in order to compare the peak flux values of flares not associated with CMEs with the peak flux values of flares associated with CMEs. In Figure 1(c) we show the variation of peak flux values of flares and their durations for the flares associated with CMEs from the WW listing.

In Figure 2 we demonstrate this phenomenon clearly. In Figure 3 we plot the flare peak flux values and durations by binning the flare durations at an interval of 10 min. The corresponding peak flux values are also binned. For each bin, we compute the error bar using the formula $\sigma/\sqrt{n}$ where σ is the standard deviation and n is the number of points in each bin. The error bars in

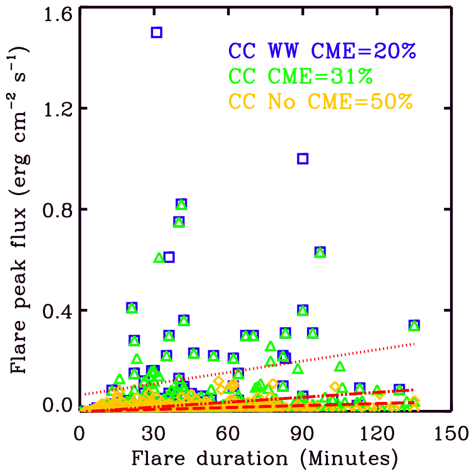

Fig. 2 Scatterplot of flare duration and peak flux values of flares. *Diamonds in yellow*, *triangles in green* and *squares in blue* indicate the flares with no associated CMEs, flares associated with CMEs and flares associated with CMEs from the WW list, respectively. The *dashed line*, *dash-dotted line* and *dotted line* represent the respective linear least squares fits. The respective correlation coefficients are also provided.

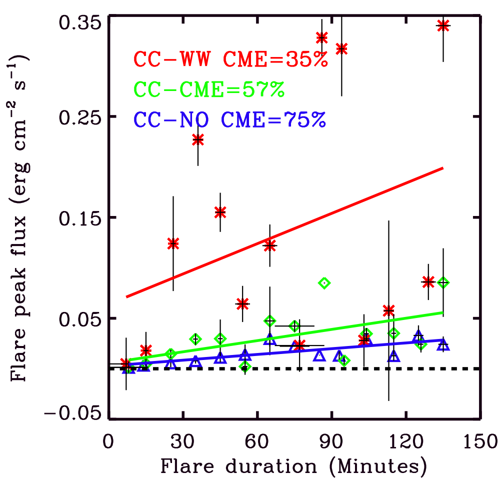

Fig. 3 Plot showing the binned values of flare durations and peak flux values of flares associated with no CMEs, flares associated with CMEs and flares associated with WW CMEs, which are indicated with *triangles*, *diamonds* and *crosses*, respectively. The continuous lines in *blue*, *green* and *red* represent the respective linear least squares fits. The dashed horizontal line represents $y = 0$.

Figure 3 reflect these error values. We report the results from the analysis.

The peak flux values of flares associated with CMEs and the flares associated with CMEs from the WW list are successively higher than the peak flux values of flares with which no CMEs are associated.

Table 2 The average peak flux and duration of flares associated with no CMEs, with CMEs and with WW CMEs. The ratios are between the peak flux values and durations of flares associated with CMEs to the peak flux value of flares with no associated CMEs.

	1 No CMEs	2 With CMEs	3 With WW CMEs
Peak flux (erg cm^{-2} s^{-1})	4.90×10^{-3}	1.59×10^{-2}	1.34×10^{-1}
Ratio		3.2	9.1
Duration (min)	17	26	54
Ratio		1.5	3.2

The average peak flux of flares associated with CMEs is ∼3 times higher than the peak flux of flares with no CMEs. The results obtained using WW listed flares are even more significant. The average peak flux of flares associated with CMEs from the WW listing is ∼9 times that of the peak flux of flares with no CMEs. Thus, the peak flux of flares associated with CMEs is distinctly higher than the peak flux of flares with no associated CMEs. We present these results in Table 2.

The correlation coefficients between the flare duration and peak flux for each class of flares is reflected in the respective figures as evident in Figure 1(a), Figure 1(b) and Figure 1(c) with correlation coefficients being 50%, 31% and 20%, respectively for these three correlations. The plot with binned data in Figure 3 shows the association with correlation coefficients of 75%, 57% and 35%. Thus, the flare peak flux is correlated reasonably well with the flare duration in the case of flares with no associated CMEs. In comparison, flare peak flux is weakly correlated with duration when associated with CMEs. Further, the flares in the WW list present a low correlation. This might imply that the occurrence of a CME is generally associated with a flare when the later shows a greater departure from the duration-peak flux correspondence. In other words, CMEs may occur when flares experience a sudden surge in their flux emissions. This is consistent with the view by Kay et al. (2003) that the occurrence of a CME intrinsically affects the timescale of energy release. Sun et al. (2015) have studied three active regions. Of these, AR 12192 is reported with a flare that has much longer duration (66 min) for the same peak flux than the remaining two active regions. The latter two active regions are associated with CMEs in which flares with comparable peak flux occurred but have much shorter durations (38 and 22 min).

While these results point to an unmistakable flux enhancement in the instances of flares with associated CMEs, we also note that the significant difference between the peak flux values of a purely temporal associ-

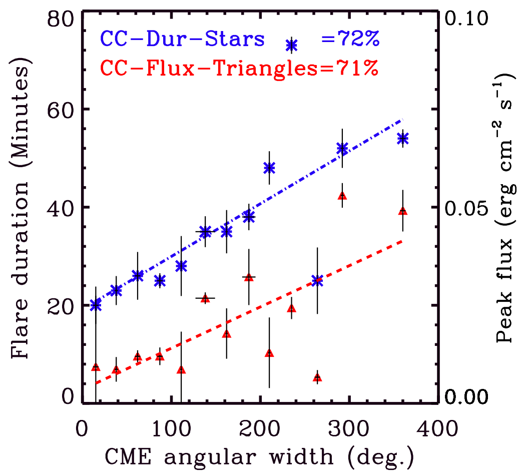

Fig. 4 The peak flux values and durations for CME associated flares are plotted as a function of CME angular width. *Triangles in red* and *crosses in blue* represent the flare peak flux values and the flare durations, respectively. The *dashed line in red* and *dash dotted line in blue* represent the linear least squares fits for peak flux and durations of flares, respectively. The correlation coefficients are 0.71 and 0.72 between the CME angular width and flare peak flux, and the CME angular width and the flare duration, respectively.

ation of flares with CMEs and the WW list of flares is an indication of the difficulty in accurately arriving at flare-CME associations by resorting to purely temporal flare-CME associations.

Moore et al. (2007) presented a relationship for the strength of the magnetic field in the area covered by the flare arcade following a CME-producing ejective solar eruption as a ratio of the final angular width of the CME and the final angular width of the flare arcade. This implies that the angular width of a CME is a function of the magnetic field of the active region. Hence, to extend this analogy to verify whether any association exists between the CME angular width and the peak flux of the associated flare, we plot the angular width and flare peak flux in Figure 4. A correlation coefficient of 0.71 suggests a good association between these two parameters. Also in the same plot, we find a good association between the CME angular width and the flare duration with a correlation coefficient of 0.72. The CME angular widths are binned at an interval of 25 degrees and the corresponding flare duration and peak flux values of associated flares are also binned. For each bin, we compute the error bar using the formula $\sigma/\sqrt{n}$, where σ is the standard deviation and n is the number of points in each bin. These error bars are shown in the figure.

By estimating the required field strength for CME occurrence from the flux content of the CME and the observed area covered by the flare, Moore et al. (2007) have noted that the estimated required field strength in the flare, being much stronger than the observed field, is an indication that the CME did not occur in the active region where the flare occurred. Hence, an association between the magnitude of the peak flux of flares and the magnetic field of the active regions via the CME angular width suggests a clearly enhanced peak flux emission in the flares associated with CMEs compared to the flares with no associated CMEs.

4 DISCUSSION AND CONCLUSIONS

It has been argued that flares and CMEs are an integral part of a single energy release system (Harrison 1995; Shibata 1996; Zhang et al. 2001). The non-thermal particles accelerated during a flare in the corona induce chromospheric heating that results in chromospheric evaporation. The later fills magnetic loops with hot, dense plasma (Brosius & Holman 2012). CMEs are expected to be ejected as a result of catastrophic detachment of coronal loops. However, we know that not all flares have an associated CME. Hence, flare characteristics ought to be distinct in the case of flares with associated CMEs compared to flares with no associated CMEs. However, it is known that at least some big flares do not have associated CMEs (Green et al. 2002; Jing et al. 2015). Nindos & Andrews (2004) have found that the coronal helicity of active regions is smaller when not associated with CMEs and concluded that this explains the difference between characteristics of an active region that produces a flare with or without a CME.

Hence, in this paper we analyze the peak flux emission of soft X-ray flares archived in the SGD to compare the peak flux emission in flares associated with CMEs with peak emission from flares not associated with CMEs. We collect the CMEs from the SOHO LASCO archive. We also make use of the flare-CME associations listed in the WW archive where flare-CME associations are estimated more stringently. Since increasing soft X-ray flare intensity with duration appears to be the consequence of a rise in temperature, perhaps caused by the outgoing CME (Aggarwal et al. 2008), we use flare duration as the basic unit and compare flares of two classes - with and without CMEs.

The present analysis points out that the peak flux of flares associated with CMEs is distinctly higher than peak flux values of flares with no associated CMEs. This phenomenon is evident across the entire range of flare duration. The difference is more pronounced in the case of improved flare-CME associations as evident from the WW listed flares. Also, a clear dependence of peak flux and duration of flares is identified with increasing CME angular width, which further emphasizes that the flare peak flux emission is enhanced in the case of flares with associated CMEs. This supports the suggestion that the increased heating of coronal plasma results in association with the occurrence of a CME and flare compared to a flare alone. Phenomenologically, this is consistent with the conclusion by Nindos & Andrews (2004) that the preflare coronal helicity of active regions witnessing flares alone is lower than the ones from which both flares and CMEs emerge. Concurrently, we note that the decay index of the transverse magnetic field in the low corona ($\sim$10 Mm) is higher when associated with a CME (Cheng et al. 2011). Also, the ratio of the magnetic non-potentiality and the background field (Sun et al. 2015; Aschwanden 2013) needs to be taken into account as a probable causative factor related to increased heating of the plasma associated with CME occurrence.

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