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RELATIONSHIP BETWEEN CME KINEMATICS AND FLARE STRENGTH

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ABSTRACT

We have examined the relationship between the speeds of coronal mass ejections (CMEs) and the GOES X-ray peak fluxes of associated flares. Noting that previous studies were possibly affected by projection effects and random association effects, we have considered two sets of carefully selected CME-flare events: four homologous events and four well-observed limb events. In the respective samples, good correlations are found between the CME speeds and the GOES X-ray peak fluxes of the associated flares. A similarly good correlation is found for all eight events of both samples when the CME speeds of the homologous events are corrected for projection effect. Our results suggest that a close relationship possibly exists between CME kinematics and flaring processes.

Key words : Sun: flare—Sun: coronal mass ejection

I. INTRODUCTION

There is increasing evidence for close relationship between kinematics of coronal mass ejections (CMEs) and flaring processes. Recently, Zhang et al. (2001) and Neupert et al.(2001) investigated the initial phase of well-observed limb CMEs using the data obtained by the EUV Imaging Telescope (EIT) and the LASCO C1 on board *SOHO* and the GOES flare data. In these studies, it has been demonstrated that the impulsive acceleration phases of the CMEs very well coincide with the rising phases of the associated soft X-ray flares. Most recently, Shanmugaraju et al. (2003) also showed that the maximum acceleration of three well observed CME features occurs during the eruptive phase of associated flares.

Hundhausen (1997) studied the relationship between the log peak fluxes of flares and the log kinetic energies of related CMEs using SMM data and obtained a correlation coefficient of 0.53. Then he argued that the correlation is poor in the sense that for the intensity of a given flare, the kinetic energy of the ejection can still spread over a range of at least three orders of magnitude. Moon et al. (2002) also examined the relationship between the log X-ray fluxes of limb flares and the projected speeds of associated CMEs using all the LASCO CME data obtained from 1996 to 2000 and found a similar level of correlation between the two quantities with a linear correlation coefficient of 0.47. We can think of two reasons for these rather poor correlations. First, some flare-CME pairs in the sample may be wrongly associated due to insufficient information of event timings and positions. Note that half of the observed CMEs originate from behind the limb. This random association effect, though not completely avoidable, may be more or less controlled by adjusting the association window sizes. Second, we have only sky-projected velocities of CMEs whose propagation directions are possibly quite diverse. Therefore, the correlation could be stronger if the random association effect and the random projection effect were fully taken into account as suggested by Moon et al. (2002). Besides the random association effects and the projection effects, another difficulty in drawing flare-CME relationship from statistical studies consists in that each event in a data sample involves a different magnetic environment in terms of flux distribution, field topology, helmet streamer structures, solar wind conditions, etc.. The diversity in magnetic environments can spread the data distribution in the CME speed versus flare flux plots and smear the correlation between them. An additional complication arises due to ejection into the medium disturbed by the preceding CMEs.

A promising way to overcome the above problems is to study a series of homologous flare-CME events. This approach has several strong advantages over general statistical studies. First, there is little random projection effect because homologous CMEs have similar ejection trajectories near the Sun. Second, they reside in similar magnetic environments so that similar physical mechanisms are working there. Third, their homologous characteristics seen in both flares and CMEs guarantee their physical association; thus one can be relieved from a concern about possible random association. Fourth, the recurrence of homologous events may indicate that the deformation of magnetic environments due to the preceding CMEs is not significant. Summing up, an investigation of homologous events is a good way to get around random effect problems in-

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volved in general statistical studies. However, the difficulty in studying homologous events is their scarcity. One would hardly find a few good data samples in one solar cycle. Another problem in homologous event studies is that the confidence level of these studies is inevitably low due to the small sample size. With all these difficulties, we believe that studies of homologous events are still worth pursuing because of the aforementioned merits. In addition, carefully selected limb events also have a strong advantage because they are almost free from the projection effect.

In this paper we examine the relationship between CME kinematics and flare strength using two sets of carefully selected samples: a set of homologous CMEs and another set of limb events. In Section II, we introduce our data analysis and explain how to select homologous events. We present the results and discussions of our study in Section III. A brief summary and conclusions are delivered in Section IV.

II. DATA SELECTION

Recently, Nitta & Hudson (2001) reported six recurrent flare-CME events that occurred in NOAA Active Region 9236 and examined their characteristics in Yohkoh, GOES, and SOHO images. Out of these six events, Zhang & Wang (2002) studied five X-class flare-CME events in detail and argued that they are homologous since they have similar characteristics in the aspect of the associated surface activity, the solar disk signature, and the coronagraph appearance. For the present work, we again consider the six recurrent CME-flare events (five X-class flares and one M-class flare) studied by Nitta & Hudson (2001). Although the last two events were also considered to be homologous by Zhang & Wang (2002), we doubt their homology for the following reason. A comparison between Yohkoh HXT images and MDI images has shown that HXT flare kernels of the first four events are different from those of the last two events as seen in Figure 3 of Nitta & Hudson (2001), implying that different flaring processes were involved.

In order to check their characteristic differences more thoroughly, we have inspected BBSO Hα full-disk images of 1-minute cadence observed on November 24-25, 2000. The full-disk images were taken with an 8 inch Singer telescope together with a 2032 × 2032 Apogee KX4 14-bit digital CCD camera. The pixel size in the images is about $1''$, which yields a spatial resolution of $2''$. Figure 1 shows two series of BBSO Hα centerline images for the X1.8 flare (upper panel, the third event of Nitta & Hudson 2001) on November 24 and for the X1.9 flare (lower panel, the fifth event of Nitta & Hudson 2001) on November 25. A detailed description of the X1.8 event has already been provided by Wang et al. (2002) who noted three flaring ribbons (two stationary ones and one moving one). From the Hα images, one can note that different types of filament eruptions and flaring processes are involved in the two events. In the case of X1.8 flare, a filament (denoted by F1 in Fig. 1) was expanding westward (right direction in the figure) accompanied by moving flare ribbons. Near the final stage (21:53 UT), two stationary flare ribbons appeared near the leading sunspot. In the X1.9 flare case too, a filament (denoted by F2 in Fig. 1), which may be a remnant of the lower part of the filament F1, seems to have erupted. But it does not show any visible expansion or any remotely moving flaring ribbons as in the case of the X1.8 flare. A close look at the two flare ribbons in the last Hα image taken at 18:57 UT shows that the F2 filament eruption is directed more vertically than the F1 filament eruption. This actually prevents us from seeing the eruption of the dark filament in Hα centerline images due to the Doppler effect. Different directions of the filament eruption eventually result in different projection effects when their speeds are measured on the sky plane. This can explain why the LASCO CME speeds of the last two events are relatively slower than those of the first four events. Summing up, the last two events studied by Nitta & Hudson (2001) have different eruption dynamics and flaring processes from those of the first four events.

According to the previous studies by Nitta & Hudson (2001), Zhang & Wang (2002), and Wang et al. (2002), the four CME-flare events have similar characteristics in the following aspects: (1) Yohkoh SXT and HXT images, (2) LASCO difference images, (3) TRACE and EIT images, (4) EIT running difference images, and (5) photospheric magnetic field distributions. Thus we have selected the first four homologous CME-flare events out of the six events as the objects of our study because only they are regarded to be really homologous. The details of the four events are summarized in Table 1. All these flares appear to be associated with halo CMEs as inferred from their close temporal and spatial proximity to the CMEs seen in *SOHO*/LASCO images (Nitta & Hudson 2001, Zhang & Wang 2002). We also list the first appearance time of each CME in the LASCO/C2 field of view in Table 1.

Another set of data sample is taken from the four well observed limb events studied by Zhang et al. (2001) who examined their initial kinematics using LASCO/C1 and EIT images. Their longitudes are approximately E92°, E78°, W69°, and W60°, respectively. While three events have front side origins, one event is located just on the limb. Since the CME-flare associations for these events were well identified and since they originated near the limb, they should also be regarded as a well-controlled sample. Observational details of these events are summarized in Table 1 of their paper.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the speeds of the CMEs in LASCO C2/C3 field of view and the log peak fluxes of the associated flares. The CME speed is taken as the mean of

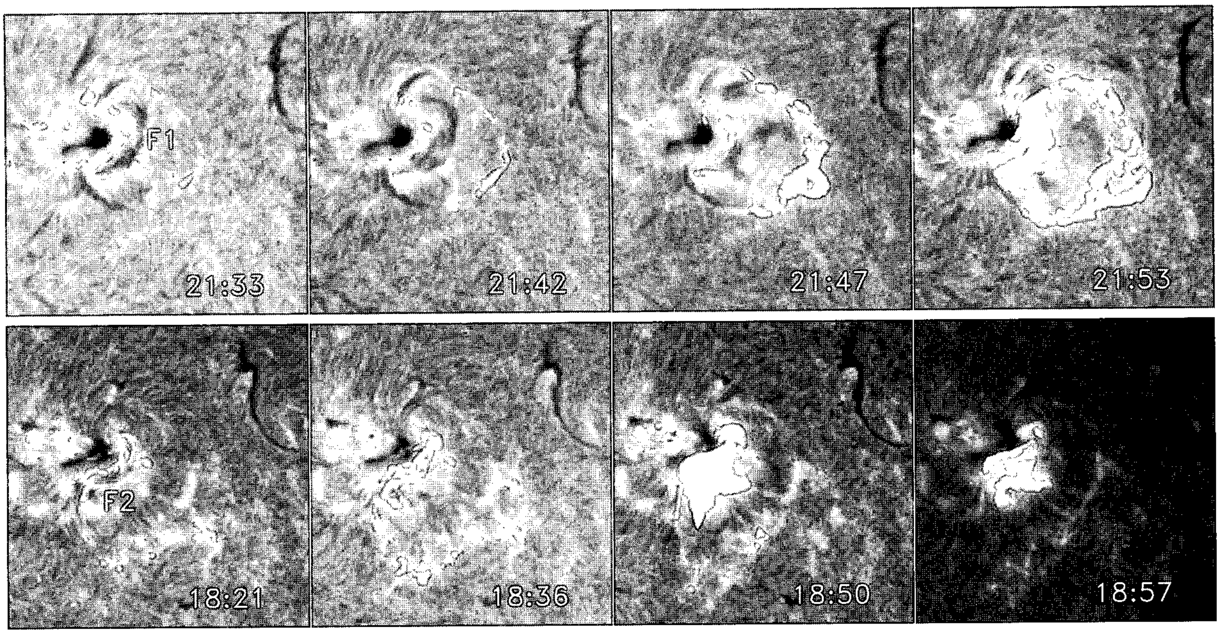

Fig. 1.— BBSO Hα images for the X1.8 flare on November 24 (upper panel) and for the X1.9 flare on November 25 (lower panel). The field of view is about $320'' \times 320''$.

Table 1. Details of the four homologous CME-flare events in NOAA AR 9236.

Date	Start	Peak	End	Coord.	X-ray	CME(C2)[a]	V_{CME} [b]
Nov. 24	04:55	05:02	05:08	W05	X2.0	05:30	1022
Nov. 24	14:51	15:13	15:21	W11	X2.3	15:30	1233
Nov. 24	21:43	21:59	22:12	W15	X1.8	22:06	998
Nov. 25	09:06	09:20	09:40	W21	M3.5	09:30	675

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[a] Indicates the first appearance time in the LASCO/C2 field of view.

[b] Indicates the representative speed in the LASCO C2 and C3 field of view, which is an average of the values taken from the the online *SOHO*/LASCO CME catalogue (http://cdaw.gsfc.nasa.gov/CME_list/) and Table 1 of Zhang & Wang (2002).

the values from two sources: the LASCO CME online catalogue (http://cdaw.gsfc.nasa.gov/CME_list/) and Table 1 of Zhang & Wang (2002). In the figure, one can see a good correlation between the speeds and the peak fluxes with a correlation coefficient of 0.93.

Although our analysis yields a far better correlation between the CME speeds and the flare fluxes than in previous studies, one may be skeptical about taking it as a general tendency because of the very small sample size. For this reason, we analyzed an additional well controlled CME-flare data sample: four limb events studied by Zhang et al. (2001), who analyzed SOHO/LASCO C1-C3 data. Figure 3 shows a relationship between the CME speeds listed in Table 1 of their paper and the log peak fluxes, which yield a correlation coefficient as high as 0.98. It is also noted that there is a good correlation of 0.90 for log peak fluxes vs CME accelerations. The adopted speeds are not the speed based on LASCO C2 and C3 as in the homologous event sample, but from low-corona observations (mainly LASCO C1 and C2). In fact, their data are regarded to be more appropriate for comparison with the flare measurement because their observations were made near the flare peak times.

Since the numbers of events under consideration are small, it is meaningful to estimate the statistical significance of the derived correlation values. According to Press et al. (1986), the statistic t value with the small data point number N for the Student's t-distribution is given by $t = r\sqrt{(N-2)/(1-r^2)}$, where r is the correlation. Using these t values, we have derived p values of the student's t-statistic test, which implies the likelihood that the resulting fitted slope could arise from randomly distributed data. The resulting p values for for the homologous events and the limb events are 0.034 and 0.009, respectively, which are smaller than a commonly adopted critical value (e.g., 0.05).

One may have a question if such a good correlation still holds when two samples are combined into one sample. Since the homologous events originated near the solar disk center, they probably involve projection effect. As a simple remedy of correcting the projection effect, we adopt a formula by Leblanc et al. (2001), which assumes radial propagation of CMEs. In this formula, the radial speed ($V_{\rm rad}$) is given by

$$V_{\rm rad} = V_{\rm sky}\frac{(1+\sin\alpha)}{(\sin\phi + \sin\alpha)}, \qquad (1)$$

in which α is half the angular width of the CME and ϕ is the angle between the radial passing through the solar origin and the Earth direction given by $\cos\phi = \cos\lambda\cos\psi$, where λ and ψ are heliolatitude and heliolongitude, respectively. Unfortunately, it is very difficult to measure the angular width of halo CMEs that we are dealing with. As suggested by Leblanc et al. (2001), we have used the average half width (36°) for α. Using the above formula and the coordinate information of the homologous flare-CME events, we have

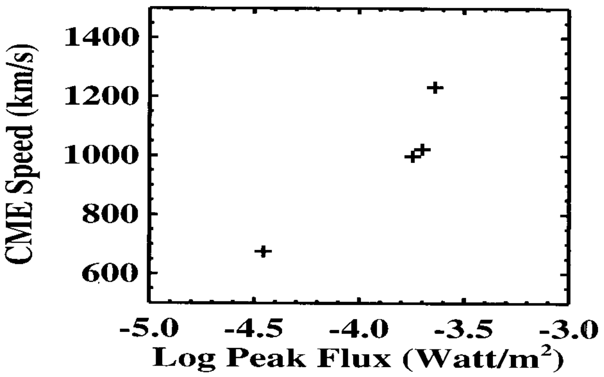

Fig. 2.— Representative CME speed in the LASCO field of view versus the GOES X-ray peak flux of the associated flare.

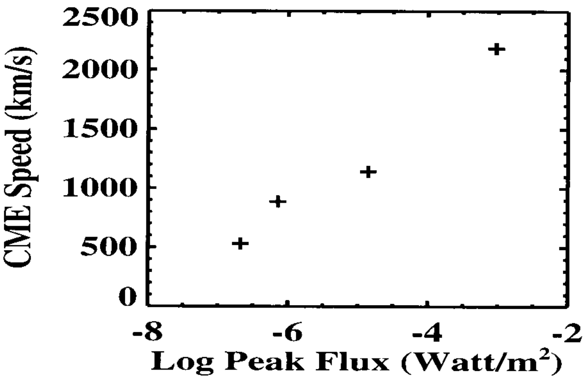

Fig. 3.— Maximum CME speed versus the log GOES X-ray peak flux of the associated flare for the well observed four limb events studied by Zhang et al. (2001).

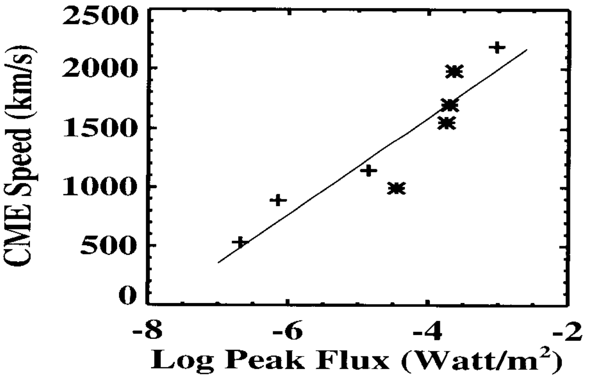

Fig. 4.— Corrected CME speed versus the log GOES X-ray peak flux of the associated flare for the all eight events. Cross symbols indicate the limb events and star symbols are the homologous events. The solid line is their linear regression given by $V_{CME} = 3237$ Log F + 412.

estimated their radial speeds. The estimated correction factor ranges from 1.47 to 1.66. Figure 4 shows a relationship between the CME speeds and the log peak fluxes for all the eight events. Their correlation coefficient is 0.93 and the p value from the Student's t-test is 0.0005, which implies strong statistical significance. Their linear regression is given by $V_{\mathrm{CME}} = 3237\,\mathrm{Log\ F}+412$. Considering the uncertainty in correction factors, this correlation is very remarkable. We can speculate the implications of this result as follows. First, flare strength seems to have an universal relationship with CME speed regardless of data samples. Second, since Leblanc et al.'s correction formula works well, we may guess that most CMEs (not all) are ejected rather radially. Third, the projection effect is the most serious one among several ambiguities suggested in Introduction, at least in our data samples. Regarding the above arguments, however, further investigations should be made using more extensive data samples. If last two events of Nitta & Hudson (2001) are included in the above statistics, the correlation coefficient is 0.77 and the p value from Student's t-test is 0.004. From the present study, we can at least say that there may be a good possibility of a closer relationship between flare activities and CME kinematics than was thought previously and that this could be revealed by careful selection of samples. It should also be noted that Burkepile et al. (2003, in preparation) also found a better correlation (r=0.78) from more carefully selected data samples than that of Hundhausen (1997).

If there exists a good correlation between CME kinematics and flare strength, what is the physical meaning of it? To this question, we may have the following three answers. First, a flare might be a direct driver of a CME. In this regard, Dryer (1982) proposed that a coronal pressure enhancement caused by flares may drive mass ejections. According to our investigations (Moon et al. 2003, Moon et al. in preparation), a filament associated with a X1.8 flare (third event of Table 1) started to erupt with a speed of 10 km s^{-1} at 21:32 UT, which is about 10 minutes before the starting time (21:43 UT) of the GOES X-ray flare and about 20 minutes before the Hard X-ray starting time (21:53 UT). However, its maximum acceleration took place at the eruptive phase of the flare, which is consistent with Zhang et al. (2001). This fact may be itself a confirmation of the timing relationship of the Yohkoh dimming results (Hudson & Webb 1997). Therefore, although a flare may not trigger a CME, the CME propagation may be expedited by the flare energy release. The second possibility is that a mass ejection may be a direct driver of a flare. In this regard, we pay attention to the "plasmoid-induced reconnection model" of flares proposed by Shibata et al. (1995). In this model, a rising plasmoid stretches the field line below to create a thin current sheet, where fast magnetic reconnection is induced. Here, a rising plasmoid is an initial cause of the flare reconnection although a feedback effect is duly expected between the plasmoid rising speed and the flare reconnection rate after the initiation of flare reconnection. This model, however, does not tell us how the plasmoid is set into rising motion. The initiation of eruption may be an ideal MHD process (Kopp & Pneuman 1976, Chen 1996, Gibson & Low 1998, Sturrock et al. 2001) or a process involving magnetic reconnection of a non-flare type (Priest & Forbes 1990, Antiochos 1998, Choe & Cheng 2000). Third, we may think that there is no cause-effect relationship between two phenomena, but that they both are results of the same magnetic destabilization (Harrison 1995). In this case, the good correlation would be a natural consequence.

IV. SUMMARY AND CONCLUSION

In this paper, we have presented the relationship between CME kinematics and flaring process using two sets of carefully selected samples. We have selected four homologous CME-flare events that occurred in NOAA active region 9236 on November 24 and 25, 2000, and then compared the projected speeds of CMEs and the peak X-ray fluxes of the associated flares. The homology of the CME-flare events precludes various random effects which in previous statistics have probably obscured our findings in this paper. Our study has revealed that there is a good correlation between the ejection speed of the CMEs in LASCO C2/C3 field of view and the peak flux of the related flares. We have also considered an additional well-controlled data sample, the four limb events studied by Zhang et al. (2001). It also yields as good a correlation as that of the above homologous events. By correcting the CME speeds of the homologous events for projection effect, we have also found a similarly good correlation for the all eight events with strong statistical significance. Our results from those carefully selected samples suggest that there exists a closer relationship between flaring activities and CME kinematics than was previously thought.

Our study has dealt with CME speeds and log X-ray peak fluxes. We have not considered the kinetic energy of CMEs as in Hundhausen (1997) because the estimation of kinetic energy requires estimation of the CME mass and unavoidably incurs much larger errors than the estimation of the CME speeds only. Thus, it is not clear yet whether there exists as good a correlation between total flare energy and CME kinetic energy (Hundhausen 1997) as between CME speeds and log X-ray peak fluxes. The fact that the former two quantities have the same dimension does not guarantee a good correlation because the correlation between physical quantities depends on the physical mechanism of flares and CMEs. Thus, it should be also investigated by future studies which measurable quantities of CMEs and flares show the best correlation, and what physical mechanism can lead to that correlation.

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