A SEARCH FOR CMEs ASSOCIATED WITH BIG FLARES

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Abstract. The relationship between flares and coronal mass ejections (CMEs) remains a topic of active research. This paper considers a complete set of 311 M- and X-class GOES soft X-ray flares observed during the years 1996–1999. The durations of these flares have been determined as part of this study. Possible CME candidates for the 229 flares with good LASCO data coverage were identified using existing on-line catalogs. Approximately 40% of the M-class flares do not have CMEs. The probability of finding a CME candidate does not depend on the solar location of the flare, which supports the conclusion that the lack of observed CMEs is not an observational selection effect. Thresholds of 6.0×10^{-5}Wm^{-2} in peak flux, 0.07 Jm^{-2} in total flux, and 4 hours in duration independently allow a 95% confidence in predicting that a CME will be observed. For flares with peak flux and duration below these thresholds, the fraction of flares with CME candidates is independent of the observed value of peak flux or duration. The close association between long-duration flares and CMEs reported in previous studies is not confirmed. There is the suggestion of a trend between total flux and the fraction of flares that have CME associations. The variation of the X-ray flux and flare activity over the rising phase of solar cycle 23 is considered in an appendix.

1. Introduction

Near-real-time data from the LASCO and EIT instruments on SOHO* are routinely displayed at the Naval Research Laboratory, Solar Physics Branch. We also display the Today's Space Weather web page from NOAA/SEC. The routine viewing of these data created the impression that big flares were usually (or always) accompanied by coronal mass ejections (CMEs). These CMEs appeared to be brighter and faster than the typical mass ejection. This study began as an attempt to verify these subjective impressions. This paper is limited to a presentation of the results of a search for CMEs that may be associated with all of the big flares from 1996–1999.

The possible association of X-ray flares and CMEs has been considered since the first space-based coronagraph data were analyzed. Gosling *et al.* (1974) considered observations by the HAO coronagraph on Skylab during 1973. They reported more than 30 instances of 'sudden mass-ejections' and indicated that three

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*LASCO is the Large-Angle Spectroscopic Coronagraph (Brueckner *et al.*, 1995). EIT is the Extreme-ultraviolet Imaging Telescope (Delaboudinière *et al.*, 1995). Both instruments are part of the Solar and Heliospheric Observatory (SOHO, Domingo, Fleck, and Poland, 1995). SOHO is a mission of international cooperation between NASA and ESA.

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of those events "… appear to have been flare-initiated." The characteristics of the associated flares were not presented

Sheeley *et al.* (1975) presented an analysis of 'long-duration' X-ray events observed by SOLRAD. There were sixteen X-ray events with duration greater than three hours that occurred during times with good data coverage by the Skylab HAO coronagraph. (Three of the X-ray events were identified with M- or X-class flares with all three having associated coronal activity.) They concluded that "The tabulation of these events suggests that all of the long-lived SOLRAD events involve transients in the outer corona."

This study was extended by Kahler (1977) to consider 31 long-decay events (LDEs) observed between June 1973 and January 1974, selected based on the decay rate of the X-ray flux. He defined the LDE X-ray events to be those in which the time to decay to a level of 0.1 of the peak flux was greater than two hours. 25 of the 31 LDEs had good data coverage by the HAO coronagraph. For 19 of these 25 LDEs, coronal transients were detected. (There were 7 M- or X-class flares in this list with coronal transients observed for all of the big flares.) The flares with solar longitude of greater than 50° were much more likely to have associated CMEs. Kahler concluded that LDEs "… appear closely related to the occurrence of white-light transients in the outer corona."

Pallavicini, Serio, and Vaiana (1977) reported observations of 43 limb events observed by the S-054 experiment on Skylab (including 4 M- and 1 X-class flare). They concluded that there were two distinct classes of flares. Their six class II flares (characterized by longer rise and decay times, greater height, larger volumes, and lower energy density) all had associated coronal transients. For the more numerous class I or compact flares, they reported only two coronal transients

A sample of 139 long-duration GOES X-ray events (approximately 49 M- and 23 X-class) observed during 1979–1981 was presented by Sheeley *et al.* (1983). They selected flares with significant emission lasting more than 30 minutes that were well isolated in time from other flares. They defined the duration to be "… the time for the logarithm of the flux to return to within approximately 10% of its pre-event level." They reported that the fraction of flares associated with CMEs increased monotonically from a probability of only 26% for durations less than two hours to 100% for durations greater than six hours.

MacQueen and Fisher (1983) considered twelve 'loop-like' coronal transients observed from 1980 to 1982 by the K-coronameter on Mauna Loa, Hawaii. They associated five of these events with solar flares and report that "… flare-associated events are observed to exhibit systematically higher speeds, with those speeds being more-or-less constant." The rest of the events are associated with mass motions near the limb that probably correspond to prominence eruptions. They conclude that "… there is a definite distinction between flare- and eruptive-associated events." The flare-associated events were fast with constant speed while the eruptive-associated events had lower speeds with significant acceleration.

Webb and Hundhausen (1987) compared CMEs observed by SMM in 1980 with other forms of solar activity. They defined the event duration as the time for the flux to decay to the background level. However, due to the high background level at solar maximum, they state that the event duration is not useful and use a $1/e$ decay time greater than 12 minutes to identify LDEs. They reported that approximately 60% of the flares associated with CMEs were LDEs. This study demonstrated that flares associated with CMEs are often not LDEs.

Kahler, Sheeley, and Liggett (1989) considered 77 impulsive X-ray flares of M- or X-class with coincident Solwind difference images. In this study the total time above the C2 level was used to define the event durations. They considered only X-ray events with reported longitude greater than 40° "… to maximize the probability of detecting a associated CME." They reported that 6 of the 9 X-class flares had associated CMEs and only 8 of 68 M-class flares had associated CMEs. Based on the analysis of additional solar data, they concluded that the flares with associated CMEs were "much more energetic" than similar flares without CMEs. They also reported that these results are inconsistent with the idea that compact flares will not be associated with CMEs.

It is not clear how the flare/CME associations were identified in some of these early studies. Gosling *et al.* (1974) and Sheeley *et al.* (1975) do not detail how the associations were made. Kahler (1977) does state that the coronal transient was listed only if the position angle was within $30 - 40°$. He appears to have used a time window of 20 minutes before to 6 hours after the events. Pallavicini, Serio and Vaiana (1977) identified coronal transients based on temporal and spatial coincidence, but listed no specific criteria. MacQueen and Fisher (1983) do discuss how these associations could be identified but do not state any clear criteria for making the association. Webb and Hundhausen (1987) used a variable time window and a coincidence of the flare and the projected CME location. Kahler, Sheeley, and Liggett (1989) identified CME associations "based on the event onset time and position", but do not list the criteria used.

Burkepile, Hundhausen, and Seiden (1994) presented a study on the association of the 63 CMEs observed by SMM with 1351 X-ray flares (11 M- and 1 X-class) reported by NOAA for the solar minimum year of 1986. They associated the CMEs with flares using a 2-hour time window. They reported that a flare was always associated with a CME if any of 3 conditions were met: the flare intensity was greater than M3, the intensity was greater than C2 and the e^{-1} decay time was greater than one hour, or the flare had an Hα association and a decay time of greater than 55 minutes. The association of CMEs and M-class flares in this study did show strong solar longitude dependence. All three big flares within 30° of the limb had an associated CME while 1 of 8 M-class and the single X-class flares at larger angles had associated CMEs.

Kahler (1992) presented an excellent review of solar flares and CMEs containing a good bibliography of the literature on this topic. He stated several conclusions that probably summarized the 'common wisdom' on this topic: the fastest

CMEs originate in the explosive phases of flares; when CMEs are associated with flares, the flares are LDEs; and the relationship of impulsive flares to CMEs is still unknown.

Gosling (1993) authored a famous and controversial paper titled “The Solar Flare Myth”. In this paper, Gosling argued that solar flares play no fundamental role in causing geomagnetic disturbances. He cites studies that indicate that CMEs are the primary cause of these disturbances and expressed the opinion that there is no fundamental association between flares and CMEs. The views expressed in this paper were, in my opinion, rather extreme and led to a significant scientific controversy. This work and the subsequent responses did have the positive effect of generating renewed interest and research into the relationship between flares and CMEs.

Harrison (1995) reviewed the previously published studies relating CMEs and X-ray flares. He presented a thorough re-analysis of CMEs and flare activity for the years 1986 and 1987. There were 151 CMEs taken from the summary by Burkepile and St. Cyr (1993) considered along with 674 X-ray flares (38 M- and 1 X-class) as listed in *Solar Geophysical Data* (*SGD*; US Dept. of Commerce, Boulder, CO). He calculated flare duration based on “... the point where the intensity falls to within 20% of the pre-event intensity, or the X-ray profile has become flat.” He found 61 CMEs to be associated with flares that occurred within two hours (before or after) the first observation of the CME (9 of the 38 M-class and the single X-class flare had associated CMEs). He estimated that this is a factor of 3.1 times the number of associations that would have been found for randomly occurring events. He reported that for flares with solar longitude greater than 50° the association with CMEs is ‘considerably enhanced’.

The conclusions of Harrison (1995) are the starting point of this study. The most significant items are:

- Flares associated with CMEs tend to have longer durations than average flares. However, flares of any duration can be associated with CMEs.
- Brighter flares are more likely to be associated with CMEs.
- The first observation of the CME and flare onset occur within a few tens of minutes.
- Flares do not drive CMEs, and vice versa.
- Spatial analysis suggests that flares can occur anywhere within the span of the CME.
- Both flares and CMEs are signatures of the same ‘magnetic disease’: they represent the response of different parts of the magnetic structure.

Hundhausen (1999) presented a thorough review of CMEs based primarily on SMM observations. He presented a discussion of the origins of CMEs with special emphasis on the association of CMEs and soft X-ray flares. He presented three ‘obvious’ conclusions:

- Intense soft X-ray flares are neither a necessary or sufficient condition for the occurrence of coronal mass ejections.

- Significant soft X-ray emission (and the implied heating of the corona), if it does accompany a mass ejection, follows the acceleration of the mass ejection features and peaks well after the ejection is underway.
- The intensity of the soft X-ray flare (and again the implied heating of the corona) that accompanies a mass ejection is not closely related to the characteristics (such as speed, mass, and energy) of the ejections.

These conclusion are not consistent with those of Harrison (1995).

In a subsequent study, Hundhausen (1997) extended the comparison of flares and CMEs to include images from *Yohkoh* SXT and the Mauna Loa coronagraph. He argues that these data reinforce his conclusions, as stated above, that while soft X-ray flares are often “associated” with mass ejections the flares are not the “driver” of the CME.

Webb (2000) discusses the solar origin of CMEs. He presents an extensive review of the earlier results along with more recent observations from missions such as *Yohkoh* and SOHO. Švestka (2001) discusses the relationship between flares and CMEs. This paper presents a good review of both recent observations and modeling studies of CMEs and flares. Švestka argues that whether or not flares will be observed in association with CMEs depends on the association of the erupting magnetic structure with an active region. He concludes: “The only difference between flare-associated and non-flare-associated CMEs is the strength of the magnetic field in the region of field-line opening."

A recent review by Cliver and Hudson (2002) considered the relationship of CMEs to other types of solar activity. The references cited in this paper provide an excellent summary of recent work. The opinions and views of several scientists actively working in this field were presented to show both our current understanding on CMEs and the open questions.

In this study, I have taken a different approach to the association of CMEs and flares by starting from a complete list of M- and X-class X-ray flares. The X-ray events are considered in Section 2. The identification of CMEs that may be associated with these flares is considered in Section 3. These results and the relationship to previously published studies are considered in Section 4. An appendix is included that discusses the variation of the X-ray flux and flare events over the rising phase of the current solar cycle.

2. X-ray Events

NOAA operates the Geosynchronous Operational Environmental Satellites (GOES). This series of satellites has included a space weather monitor (Space Environment Monitor - SEM) since 1974. The SEM X-ray sensor measures the disk-integrated solar emission in two bands covering $1.0 - 8.0$Å and $0.5 - 4.0$Å. Thresholds of peak X-ray flux are used to define classes of X-ray events. M-class flares have peak flux of 10^{-5} to $10^{-4}\mathrm{Wm}^{-2}$. All events with peak flux greater than $10^{-4}\mathrm{Wm}^{-2}$

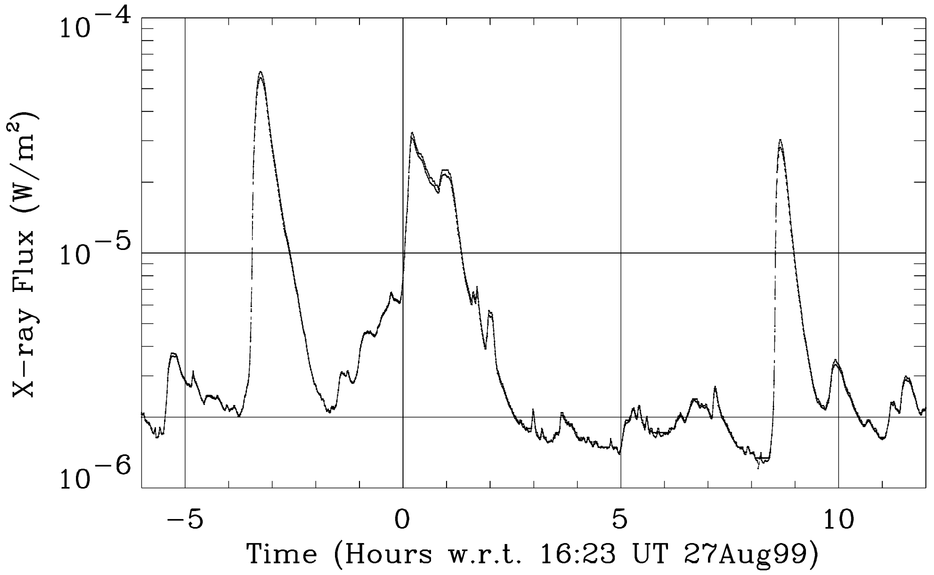

Figure 1. GOES-8 and -10 1.0 – 8.0Å data from August 27 and 28, 1999. Close examination of the figure is required to see that there are two curves plotted. The zero point on the horizontal axis is the start time of a specific M-class flare. For the eighteen-hour span of data plotted in Figure 1, there were 3 M-class and 18 C-class flares.

are X-class events. On-line access to both GOES data and documentation can be obtained from *http://www.sec.noaa.gov/Data/ goes.html*. The long-term archive of GOES data is maintained by NOAA-NGDC in Boulder, Colorado.

This study considers a complete list of 311 M- and X-class flares. The X-ray data are from the GOES-8, -9 and/or -10 satellites 1.0 – 8.0 Å channel. The short wavelength data have not been considered in this analysis. There are always two GOES satellites in operation with each satellite providing almost complete coverage. When the data from two satellites are combined, there are no significant gaps in these solar observations. A brief analysis of the variation of the solar X-ray flux and flare properties is presented in an appendix since this interesting topic is not directly relevant to this paper.

The selection of only the M- and X-class flares is a compromise between having enough events to form a significant sample and selecting those events well above the background level. Figure 1 shows an example of the GOES data from August 27 and 28, 1999. There were three M-class flares observed during the eighteen hours of data displayed in Figure 1.

The solar event data as reported by the NOAA Space Environment Center (SEC) for dates after July 30, 1996 can be obtained on-line from *http://www.sec.noaa.gov/ftpmenu/indices.html* in the form of edited events lists. During the eighteen-hour period shown in Figure 1, there were eighteen C-class flares reported in the edited events. This is typical of periods when there are a significant number of big flares. Many C-class flares are observed and the properties of those flares are not easily identified when they occur during the declining phase of larger flares. Including the C-class flares in this study would have made the number of flare events unmanageably large.

The flare list considered in this study was generated at my request by E. Erwin of NOAA-NGDC. The event list contained the following key parameters based on or calculated from the $1.0 - 8.0$ Å data:

- The start time of the flare. The start time is determined by finding the point at which the slope of the curve shows a sudden increase. The start time is usually well determined. (All times are expressed as hours and minutes UT.)
- The stop time of the X-ray event. This is the time at which the flux has decreased to $1/e$ of the peak value.
- The time of peak flux.
- The latitude and longitude of the flare. The latitude is in units of degrees north or south. The longitude is degrees east or west. Both angles are the distance from the center of the solar disk. The location is obtained from ground-based Hα observations.*
- The peak X-ray flux.
- The total X-ray flux. This parameter is calculated by integrating the flux from the start to stop times of the flare, not available prior to 1997.

Both the peak and total X-ray fluxes are disk integrated values, there is no background subtracted. This is probably not a significant problem for the M- and X-class flares considered in this study except for periods with very high background flux or for the simultaneous observation of multiple big flares. (H. Garcia, private communication. See Garcia (1998) for a thorough discussion of the processing of GOES X-ray data.)

Consider the three flare events shown in Figure 1. The differences between the flare start and end times (hereafter event time, or T_E) are 32, 44 and 26 minutes. The differences between the flare peak and end times (the time to decay to $1/e$) are 15, 31, and 14 minutes. This is the e-folding time, T_f, that has been used to identify events with long decay times by Burkepile, Hundhausen, and Seiden (1994) and Webb and Hundhausen (1987) among others. Another parameter that can be used to characterize the flare is the difference between the start and peak times (hereafter rise time, or T_R).

Each of the flare events in Figure 1 clearly shows significant X-ray emission that lasts for a time significantly longer than tens of minutes. In order to quantify this, I have measured/estimated the duration (T_D) of each flare. Since the pre-event X-ray flux can vary widely, the durations were measured by finding the time at which the X-ray flux returned to three different levels: C1, C2, and pre-event. The C1 and C2 levels are 10^{-6} and $2*10^{-6}$Wm^{-2} respectively. The C1 level is the zero

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*There were no locations defined for 78 of the 311 events. These events either occurred behind the limb, were not observed from the ground, or the ground observations were ambiguous.

point of the vertical axis in Figure 1 with a horizontal line drawn at the C2 level. The pre-event level was calculated as 110% of the average flux for the six hours prior to the start time of the flare.

The automated processing generated three values for the duration. The plots of X-ray flux versus time were examined to visually determine which of the three levels best represented the end of the flare. There were a significant number of flares in which the X-ray flux remained above all three levels. For these flares, the duration was estimated by visual inspection, e.g., a reasonable guess was made. There were 73, 65, and 92 durations determined using the C1, C2, and previous levels. The durations of 78 flares were estimates by visual inspection. There were only 3 of 311 flares for which the duration could not be estimated. For these events, a second flare was observed that did not allow the decay of the preceding flare to be measured.

This method of determining the durations is well illustrated by the flares shown in Figure 1. The first flare did not decay to the C2 level but did reach the pre-event level. The decay of the second flare did reach the C2 level and that time was used to determine T_D. The third flare did not reach either C2 or the pre-event level due to a C-class flare that occurred during the decline. For this flare, the plot of flux versus time was examined and the duration estimated by visual inspection.

My estimates of T_D for the three flares in Figure 1 are 1.7, 2.6 and 1.2 hours. The first flare has a duration that is significantly longer than the third flare. The second flare, for which the decay takes a longer time, has a duration of greater than two hours. While the published data do not allow a direct comparison, the durations calculated in this study should be close to those of Harrison (1995) and Kahler, Sheeley, and Liggett (1989) and comparable to or slightly longer than the measurements of Sheeley *et al.* (1983).

3. Flare–CME Associations

The flare–CME associations have been made using only CMEs identified in existing catalogs, i.e., I did not identify the CMEs. These catalogs can be accessed through the LASCO web site, *http://lasco-www.nrl.navy.mil/cmelist.html*. The first catalog is the Version 2 CME list prepared by O. C. St. Cyr (St. Cyr *et al.*, 2000). These CMEs were identified in a comprehensive analysis of the LASCO C2 and C3 data from January 1996 through the SOHO mission interruption in June 1998. The following parameters are tabulated for each CME: time of first CME observation, central position and angular width, speed and acceleration (if significant acceleration is observed), along with three fields for comments.

St. Cyr *et al.* (2000) presented a thorough discussion of the accuracies of identifying CMEs in the LASCO data. They analyzed the ‘visibility function’ of CMEs to conclude that few, if any, CMEs were missed. They conclude that there is only a small probability that a CME occurred in the area imaged by LASCO but would not be observed.

The second catalog is the Preliminary CME List that continues to be updated and maintained by the LASCO operations staff: S. Plunkett, G. Lawrence, and K. Schenk. This list covers the period from late 1998 when operations began after the SOHO recovery up to the most recently observed CMEs. This list is usually generated within days of the observations and is less complete than the Version 2 catalog. The Preliminary List contains the time of first observation, an approximate location of the CME, and a comment field that often contains significant additional information.

I have done an independent study to find CMEs in approximately 90 days of LASCO data. The events I found agreed exactly with the events in the two CME lists referenced above. All of the events I found were in the catalogs and I detected all of the listed CMEs. This suggests that these two lists represent a reasonably complete CME list.

The third list is the SOHO LASCO CME Catalog developed by S. Yashiro and G. Michalek under the direction of N. Gopalswamy. This catalog was developed as a joint effort between the Catholic University and NASA-GSFC with assistance of the LASCO project at NRL. The catalog lists the time of first CME observation, the central position and angular width. The height–time measurements of the fastest position on the leading edge are fit using both linear (constant speed) and quadratic (constant acceleration) functions. The catalog is complete through 2002 and is being maintained and extended by S. Yashiro.

My initial candidate list was made by selecting all the CMEs in either the Version 2 List or the Preliminary List where the time of the first CME observation was within two hours of the start time of the flare. A few CMEs were added to this list in cases where the time of the first observation immediately follows a gap in the coronagraph data.

This analysis was completed before the SOHO LASCO CME Catalog became available. All of the associations were checked using this new CME list. The new list includes an analysis of LASCO data at the time of three flares where CMEs had not been identified in the Preliminary CME List. The associations I have made are based only on the Version 2 CME list for dates prior to the SOHO mission interruption. At later times, the Preliminary CME List was used. The only exceptions are the limited time periods when the SOHO LASCO CME Catalog is more complete than the Preliminary List.

A detailed examination of the LASCO data was undertaken to edit and reduce the number of CME candidates. This editing was required because there were a large number of chance coincidences. Figure 1 displays an eighteen-hour period with three big flares. There were four CMEs for this period (reported in both the Preliminary CME List and the SOHO LASCO CME Catalog). This is a CME rate of one every 4.5 hours. The probability of a chance coincidence with a four-hour time window is large.

Editing was done to eliminating multiple CME candidates for a single flare, e.g., the assumption was made that there should be only one CME associated with each flare. Positional information was used to identify the most likely CME candidate. The LASCO observations are relatively insensitive to the solar longitude of the CME, only the projected latitude is observed. For flares with a known location, the flare location was compared with the projected center and extent of the CME. For most of the flares with multiple candidates in the initial list, there was only one CME for which projected latitude of the CME included the flare location; this CME was selected as the most likely to be associated with the flare.

I did use my personal expectation, or bias, in determining the most likely CME candidate. The GOES list contains big flares. I expected big flares to be associated with big, bright, and fast CMEs. If there was a big, bright, or fast CME that coincided with the timing and location of the flare, that CME was selected as the most likely event to be associated with the flare. The flare events with only one CME association in the initial event list were also examined. These associations were retained except where the flare and CME observations seemed to be clearly inconsistent. This method of associating flares and CMEs is subjective and an equally skilled observer would probably determine a different set of candidate CMEs. For the three flares of Figure 1, only the third flare has an associated CME candidate.

Harrison (1995) tested the significance of his CME associations by calculating the number of chance associations that would be expected assuming a random distribution of CMEs. The CME rate for LASCO is much higher than for SMM. He used a catalog of 151 CMEs for the two year period of 1986 and 1987. Burkepile, Hundhausen, and Seidel (1994) considered 63 CMEs reported by SMM for the solar minimum conditions in the year 1986. As a comparison, the SOHO LASCO CME catalog contains 73 CMEs for the three months of October through December during the 1996 solar minimum. Thus, the CME rate for the LASCO coronagraphs is approximately 5 times that of SMM. Chance coincidence of flares and the LASCO CMEs is thus likely and the editing of the event list to eliminate many of the chance associations was required.

This analysis has yielded a set of CMEs that may be associated with big flares. The associations are based on coincidence of event timing and, where known, a consistency of the reported event locations. Multiple CME candidates were eliminated by analysis and some judgment. The results of this analysis are summarized in Table I and discussed in the next section.*

4. Results and Discussion

Table I summarizes the results of a search to find CMEs that may be associated with M- and X-class flares. The summary is presented with a breakdown by year. There

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*All of the flare information along with data on the identified CME candidates has been collected in Excel spreadsheets. These spreadsheets can be obtained by contacting the author.

TABLE I

Summary of CME Candidates

Year	Level	Number of flares	Number of obs.	CME	%	No CME	%
1996	X	1	1	1	100	0	0
	M	4	3	0	0	0	100
	Subtotal	5	4	1	25	3	75
1997	X	3	3	3	100	0	0
	M	21	19	10	53	9	47
	Subtotal	24	22	13	59	9	41
1998	X	14	6	6	100	0	0
	M	94	52	31	60	21	40
	Subtotal	108	58	37	64	21	36
1999	X	4	4	4	100	0	0
	M	170	141	78	55	63	45
	Subtotal	174	145	82	57	63	43
96-99	X	22	14	14	100	0	0
	M	289	215	119	55	76	45
	Total	311	229	133	58	96	42

was good data coverage by LASCO for only 229 of 311 big flares. The Number of Obs. column indicates the number of flares with good LASCO data coverage. The percentages shown in Table I are based on the well-observed flares only. The coverage is particularly poor for the second half of 1998 during the SOHO mission interruption. The coverage is also poor during early 1999. All of the 14 well-observed X-class flares have CME candidates. There are CME candidates for 119 of 215 M-class flares with good LASCO coverage, only 55% of the M-class flares have an associated CME candidate.

I found this result to be somewhat surprising. My expectation when beginning this study was that almost all of these big flares would have associated CME candidates. This expectation was clearly incorrect.

One possible explanation for this lack of CME candidates is that these flares do have associated CMEs but the coronal disturbance is too small and/or faint to be observed. However, Figure 2, Panel a, demonstrates that this is not a correct explanation.

Figure 2 shows normalized histograms for four flare characteristics. The flares' solar longitude, peak flux, total flux, and event duration are shown in Panels a–d, respectively. In each panel, the histogram has been normalized by dividing the number of flares with associated CMEs by the total number of flares in that bin.

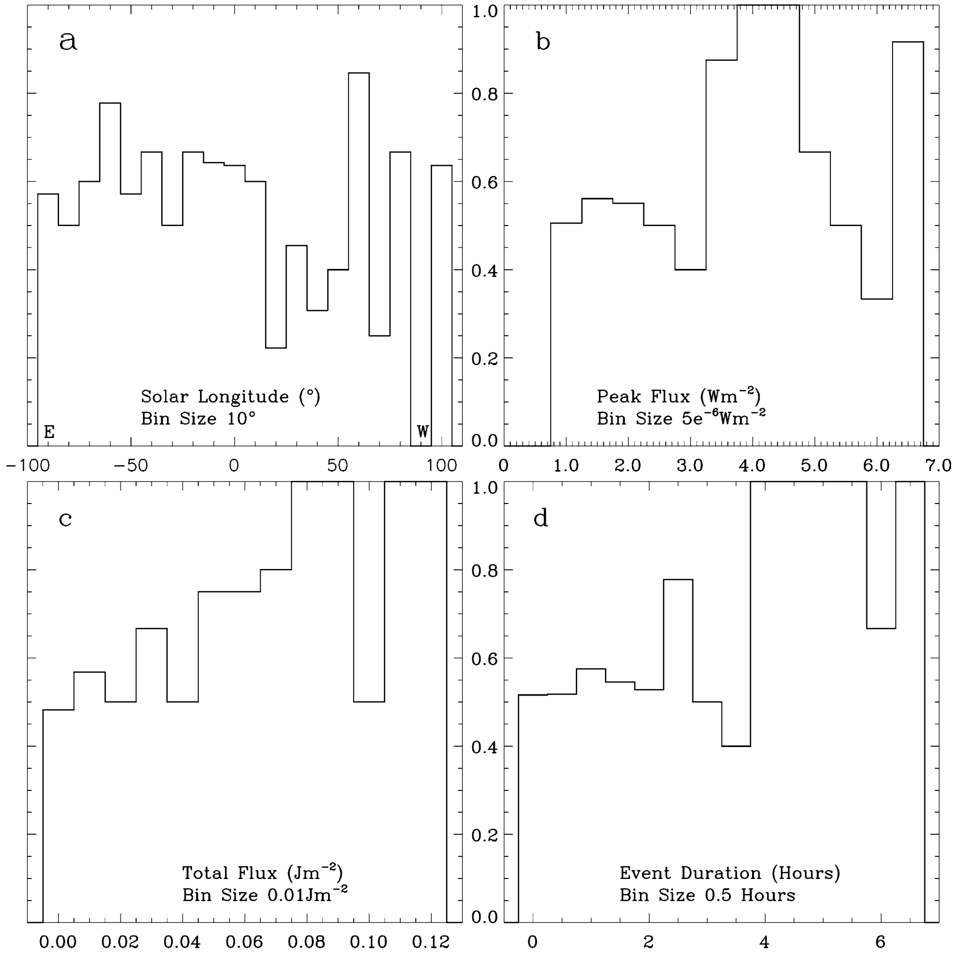

Figure 2. Normalized histograms showing the fraction of flares with associated CME candidates. *Panel a* shows the fraction of CME candidates as a function of solar longitude. The bin at 100° contains all of the flares for which the solar longitude is not known. *Panels b*, *c*, and *d* show the fraction of flares with associated CME candidates versus peak flux, total flux, and event duration, respectively.

All of the flares without a known solar longitude have been included in the bin at 100° in Panel *a*.

The data plotted in Panel *a* show no significant longitude variation in the fraction of flares with CME candidates. A CME is most visible when located above the solar limb (Andrews, 2002a). If the lack of CME associations is due to unobserved small/faint coronal disturbances, those flares with locations near the solar limb would have the largest fraction of CME candidates. No such variation is observed.

This lack of an observed longitude variation in CME associations is different from previous studies (Burkepile, Hundhausen, and Seidel, 1994; Kahler, Sheeley, and Liggett, 1989) where the fractions of flares with associated CMEs showed a large variation with the longitude of the flare. The likely explanation for this difference is that the LASCO coronagraphs are observing a significant number of CMEs not recorded by the earlier instruments. St. Cyr *et al.* (2000) concluded that the LASCO coronagraphs see nearly all ($\sim$95%) CMEs. This provides a natural explanation for the difference between this paper and previous studies. LASCO sees all of the CMEs, while the detection of CMEs in the previous studies depended on solar longitude.

There is a suggestion that flares located to the east of the solar meridian were more likely to have CME candidates. There were 85 (89) flares with longitude east (west) of the Sun center with 53 (45), or 62% (51%), having associated CME candidates. There is a larger variation as a function of solar latitude. There are 83 (91) flares with locations north (south) of the solar equator with 53 (45), or 64% (49%), having associated CME candidates. I do not think these differences are significant. For the 55 flares with unknown location, 35, or 64%, have associated CME candidates.

Panels *b–d* of Figure 2 show the fraction of flares with associated CME candidates as a function of peak flux, total flux, and my estimates of event duration. Since there are only a small number of flares with the largest flux/longest duration, all of those events are included in the highest valued bin. These three flare properties are the only measurements that show any usefulness in predicting whether a CME would be observed. Each of these parameters can be used to define a threshold, e.g., a level for which the observation of an associated CME candidate becomes almost certain. These levels are 6.0×10^{-5} Wm^{-2} for peak flux, 0.07 Jm^{-2} for total flux, and 4 hours for duration. These thresholds are the levels at which approximately 95% of the flares have associated CMEs.

36 of 229 flares are at or above one or more of these thresholds. 20 flares have peak flux levels above 6.0×10^{-5} Wm^{-2} with 19 events having associated CME candidates. 19 events have total flux above 0.07 Jm^{-2} with 18 CME associations. 24 events have durations of 4 hours or larger with 23 of these flares having CME candidates. There were no flares that exceeded two of the thresholds without having a CME candidate.

There are examples of X-class flares with no LASCO CME observed. Andrews (2001) considered an X1.9 flare observed 12 July 2000. This flare had a very short duration but a total flux of approximately 0.14 Jm^{-2}, twice the threshold. Based on an analysis of *in-situ* data, Andrews concludes that there may have been an unobserved CME associated with this flare.

Green *et al.* (2002) report the observation of an X1.2 flare on 30 September 2000 with no associated coronal disturbance. This was a relatively short duration event with a total flux of 0.06 Jm^{-2}, that is slightly below the threshold defined above. In addition, unpublished preliminary analysis of LASCO data indicates an X1.2 flare observed on 31 October 2002 of very short duration and total flux 0.02 Jm^{-2} that did not have an associated CME. While additional analysis can be expected to show more examples of flares above these thresholds that do not show CME associations, I am not aware of any flare events exceeding two of the three thresholds that do not have an associated CME.

The situation is much less clear for flare events below the thresholds. Panel *b* shows that about 50% of the observed flares have CME candidates independent of the peak flux. I am not aware of any other studies with a significant number of X-ray events that consider the association of the flares and CMEs as a function of peak X-ray intensity.

Panel c suggests that the fraction of flares with CME associations may increase with increasing total flux. Since this parameter has been calculated only for events observed after the end of 1996, it could not be included in the earlier referenced studies. While Kahler, Sheeley and Liggett (1989) concluded that more energetic flares were more likely to have CME association, I am not aware of other studies that specifically address this. Further research is required to determine whether the total X-ray flux correlates with observable CMEs.

Panel *d* shows that for durations shorter than the threshold of 4 hours the fraction of flares with associated CME candidates remains about 50% and does not decrease for shorter duration events. In this study, 16 of 31 flares with duration less than 0.5 hours have associated CME candidates.

This does not agree with several of the previously published studies. In particular, Sheeley *et al.* (1983) reported a duration threshold of 6 hours and that for the shorter duration events the fraction of flares with associated CMEs increases linearly with flare duration. While the difference between 4 and 6 hours for the duration threshold is probably not significant (N. Sheeley, private communication), the variation of CME fraction versus duration is significant. This difference may be due to the greater sensitivity of LASCO, e.g., LASCO detects CMEs that were not visible in the previous study. Alternatively, this difference may be due to selection effects. This study considered all of the M- and X-class flares while Sheeley *et al.* (1983) selected flares of C-class or larger based on long decay times. It should be noted that this study considered approximately three times as many big flares as the study of Sheeley *et al.* (1983).

The association of CMEs with short-duration flares is supported by previous studies. Webb and Hundhausen (1987) demonstrated that approximately 40% of flares associated with CMEs were not LDEs. Kahler, Sheeley and Liggett (1989) found that 22% of impulsive flares were associated with CMEs. Harrison (1995) determined that CMEs can be associated with flares of all durations.

I have also examined the fraction of flares with associated CME candidates as a function of T_R and T_E. The fraction of flares with CME candidates does not appear to vary with either the rise time or event time. While the LDE flares with very long durations are clearly more likely to have associated CME candidates, the flares with the shortest durations seem to have the same fraction of CME candidates as the flares with moderate durations of 1–3 hours.

In this study, I have not considered how the flare parameters correlate with the observed CME propertiess, e.g., total flux of the flare with kinetic energy of the CME. This will be considered in a future study that will focus on the CMEs identified in this study.

A preliminary analysis of 51 CMEs (32 of which were identified in this study) associated with big flares has been presented by Andrews (2002b). These CMEs had a launch time that was consistent with the start time of the flare with an uncertainty of approximately 10 minutes. These ejections were faster than the typical LASCO CME and had a small acceleration, constant speed, or significant deceleration. The fastest CMEs tended to show large decelerations.

5. Conclusion

There were 311 M- and X-class X-ray flares observed by GOES during the period 1996–1999. I have presented the results of a search for CMEs that may be associated with the 229 flares having good LASCO data coverage.

A key conclusion of this study is that approximately 40% of the M-class flares do not have associated CMEs. This was not my expectation and is not predicted by flare models (S. Antiochos, private communication). This study largely confirms the conclusions of Harrison (1995) that were the starting point of this study.

In this study, I have found independent thresholds of peak flux, total flux, and event duration where the probability that a CME candidate will be observed reaches approximately 95%. Below the threshold levels, there seems to be no significant variation in the fraction of flares with CME candidates as a function of peak flux or event duration. The fraction of flares with associated CMEs may increase as a function of total flux.

None of the flare characteristics considered in this study seem to be a good predictor of whether a given flare will have an associated CME. Further research is clearly required to understand why some of these big flares do have associated CMEs while other flares with identical properties as measured by GOES do not.

6. Appendix

While not the main topic of this paper, it is appropriate to briefly examine how the X-ray flux and flare activity change during the early part of solar cycle 23. Figure 3 compares 28-day smoothed sunspot number with GOES X-ray flux smoothed to a similar time average. The X-ray data have been rescaled by 5.0×10^5 to make the magnitude comparable to the sunspot number data.

The sunspot number and X-ray flux are both low until the middle of 1997 with roughly similar time variations. The small peaks in the X-ray flux coincide with the peaks in the sunspot number.

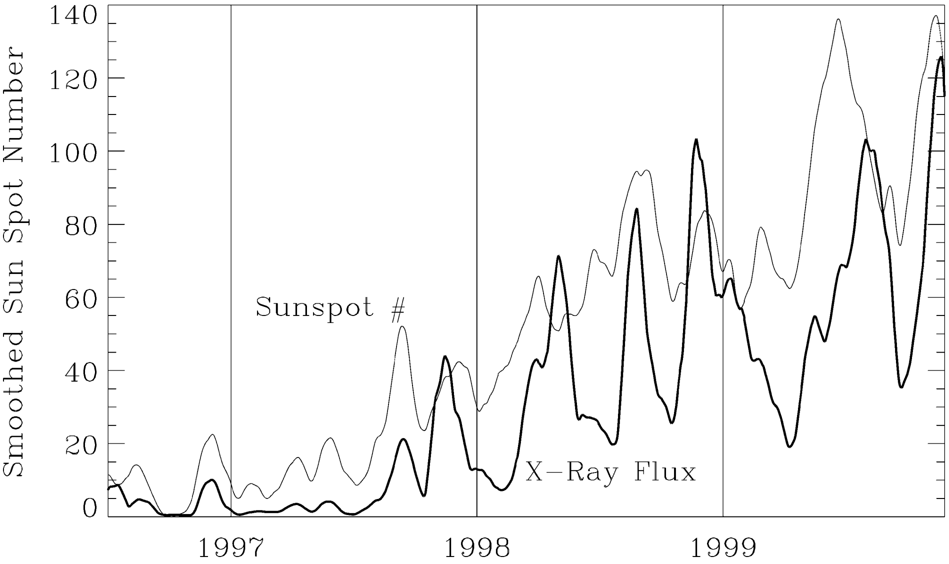

Figure 3. Comparison of sunspot number and X-ray flux for mid 1996 through the end of 1999. The thin line is smoothed sunspot number. The thick line is the 28-day average of 1.0 – 8.0 Å X-ray flux.

During the second half of 1997, the sunspot number shows a steady increase, with significant short-term variations, that continues through most of 1998. The short-term variations are typically about 20-50% of the slowly varying component. The X-ray flux also increases. However, the time variation in the X-ray data is significantly different from that of the sunspots. The magnitude of the short-term variation in the X-ray flux is 2–3 times as large as the longer-term increase. Furthermore, the time variations are different.

The X-ray flux peaks in late 1998 and then decreases steadily over the next several months. During this period, the sunspot number is roughly constant. Both the sunspot number and the X-ray flux show an increase beginning in April–May of 1999. The sunspot number increases to a level approximately twice that observed in 1998. Through much of 1999, the X-ray flux is lower than was observed in late 1998.

Both sunspots and X-ray emission are associated with active regions albeit at very different heights. These two measures of solar activity could, perhaps naively, be expected to show the same time variation. There is a significant period during the rising phase of solar cycle 23 when this is not observed.

Figure 4 shows the magnitude and locations (where known) of the 311 M- and X-class flares observed in 1996–1999. Figure 4a shows the peak flux for all 311 events versus time of observation. Panel *b* and *c* of Figure 4 show the solar latitude and Carrington longitude for the 233 flares with known locations.

There were only seven M- and X-class flares observed prior to August 1997. Only one of these flares was X-class and 5 of the 7 flares were smaller than M2.

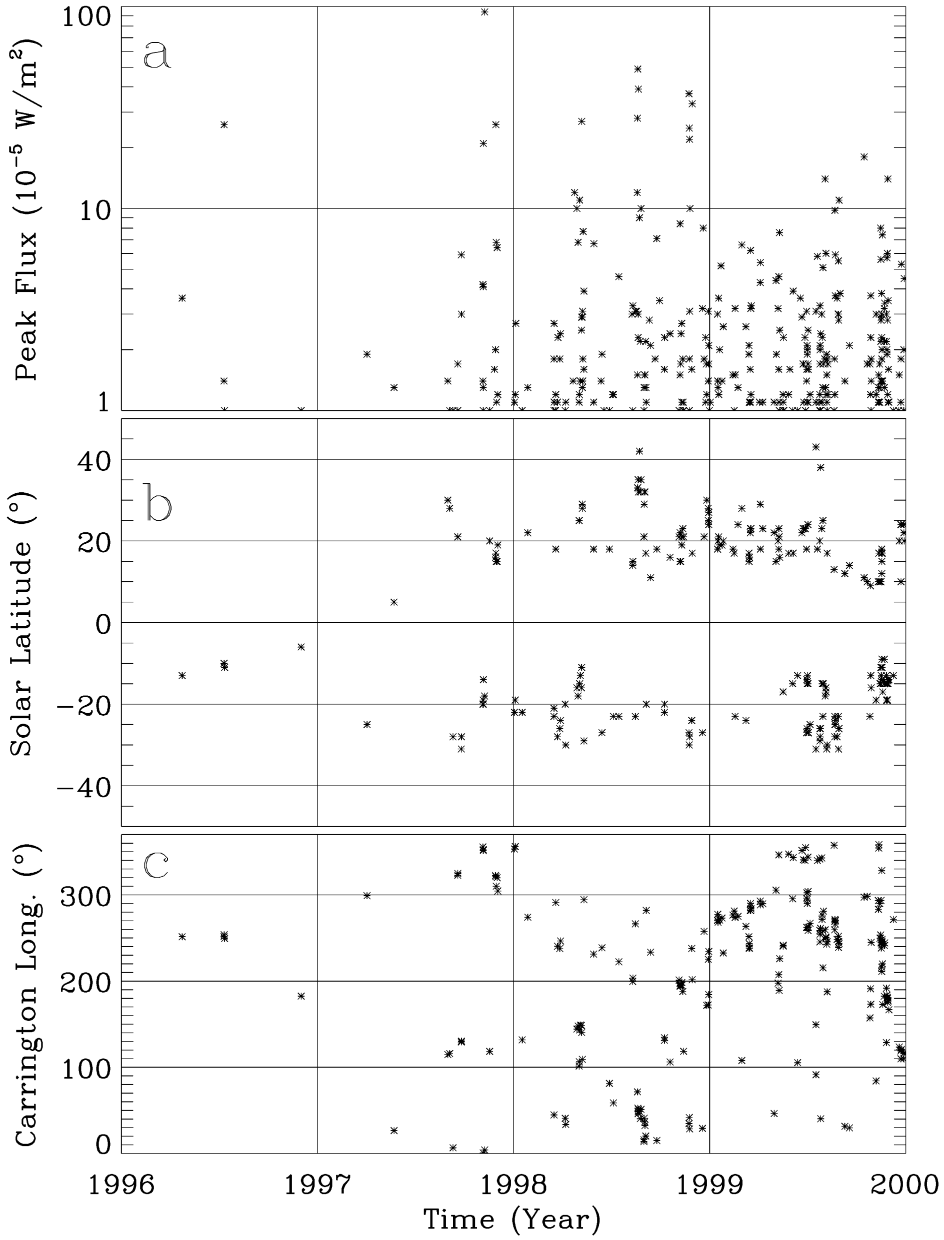

Figure 4. Characteristics of big X-ray flares, 1996-1999. Panel *a* shows the peak flux of each flare. Panels *b* and *c* show the latitude and Carrington longitude of those flares with known locations.

Six of the seven flares are probably associated with old-cycle activity and occurred at relatively low latitude over a narrow range of Carrington longitude.

The flare activity changed dramatically in late 1997. The most dramatic changes were observed during November when there were 13 flares observed. Three of these flares were X-class and included the largest peak flux of any flare observed during this four-year period. Only 6 of 13 flares were smaller than M2. The flare rate increases during 1998 in an irregular manner very similar to the total X-ray flux plotted in Figure 3. The very large flares continue to be relatively more common during 1998 when 14 of 108 big flares were X-class. The number of flares continues to increase during 1999. However, the number of very large flares actually decreases, with only 4 X-class flares observed during 1999.

The new-cycle flares were observed at higher latitudes. These flares occurred in two bands located at approximately 10−45° northern latitude and 10−30° southern latitude. During late 1997 through the first third of 1999, there are significantly more flares observed at northern latitudes than southern: 76 in the north versus 47 in the south. The flares in the north are found at higher latitude than in the south. This trend reverses after about March 1999. For the rest of 1999, there are more flares in the south than the north: 46 at northern latitudes versus 64 at southern latitudes.

The Carrington longitude of these flares also changes with time. For late 1997 through 1998, the flares have a relatively random distribution of Carrington longitudes. The situation is dramatically different in 1999, when 82 of 135 flares have Carrington longitudes within a 90° band from 210 to 300°.

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