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X-ray Emission Characteristics of Flares Associated with CMEs

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Abstract. We present the study of 20 solar flares observed by "Solar X-ray Spectrometer (SOXS)" mission during November 2003 to December 2006 and found associated with coronal mass ejections (CMEs) seen by LASCO/SOHO mission. In this investigation, X-ray emission characteristics of solar flares and their relationship with the dynamics of CMEs have been presented. We found that the fast moving CMEs, i.e., positive acceleration are better associated with short rise time (< 150 s) flares. However, the velocity of CMEs increases as a function of duration of the flares in both 4.1–10 and 10–20 keV bands. This indicates that the possibility of association of CMEs with larger speeds exists with long duration flare events. We observed that CMEs decelerate with increasing rise time, decay time and duration of the associated X-ray flares. A total 10 out of 20 CMEs under current investigation showed positive acceleration, and 5 of them whose speed did not exceed 589 km/s were associated with short rise time (< 150 s) and short duration (< 1300 s) flares. The other 5 CMEs were associated with long duration or large rise time flare events. The unusual feature of all these positive accelerating CMEs was their low linear speed ranging between 176 and 775 km/s. We do not find any significant correlation between X-ray peak intensity of the flares with linear speed as well as acceleration of the associated CMEs. Based on the onset time of flares and associated CMEs within the observing cadence of CMEs by LASCO, we found that in 16 cases CME preceded the flare by 23 to 1786 s, while in 4 cases flare occurred before the CME by 47 to 685 s. We argue that both events are closely associated with each other and are integral parts of one energy release system.

Key words. X-ray flares: rise time, duration, peak intensity—CME: linear velocity, acceleration.

1. Introduction

Coronal mass ejections (CMEs) have been largely known for their impact on the earth's environment. The complex relationship between solar flares and CMEs has been studied extensively to understand the cause and consequence between them but so far no satisfactory result has been obtained. Although it has been known that the two phenomena often occur in conjunction, the relationship is not one-to-one and the exact nature of the flare and CME triggers is not known. Whilst statistical studies indicate that higher intensity events are more likely to be accompanied by a CME (Harrison 1995), this is not always the case. For example, Green *et al.* (2002) present analysis of an X1.2 class flare for which there was no associated CME.

Kahler (1992) pointed out if the CME is associated with flare then the CME originates in the explosive phase of the flare and such flares are long-decay events (LDEs); but the relationship of CMEs with impulsive flares is still unknown. Gosling (1993) showed that solar flares play no fundamental role in causing geomagnetic disturbances. He cited studies which indicate that CMEs are the primary cause of these disturbances. The probability of CME–flare association increases with flare duration (Sheeley *et al.* 1983): 26% for duration < 1 h and 100% for duration > 6 h. It must be pointed out that some major flares associated with large-scale CMEs are not long-duration events (Nitta & Hudson 2001; Chertok *et al.* 2004). Currently, there are three ideas about the flare–CME relationship:

1. Flares produce CMEs (Dryer 1996).
2. Flares are a by-product of CMEs (Hundhausen 1999), and
3. Flares and CMEs are part of the same magnetic eruption process (Harrison 1995; Zhang *et al.* 2001).

Studies on temporal correspondence between CMEs and flares have concluded that CME onset typically precedes the associated X-ray flare onset by several minutes (e.g., Harrison 1991). This observational fact is considered to be a serious difficulty for flares to produce CMEs (Hundhausen 1999). The reconnection that leads the flare and also forms post-flare loops can be thought of as the force that propels overlying loops as CMEs (Anzer & Pnueman 1982). Kahler *et al.* (1989) argued against such a model because they could not find evidence for a flare impulsive phase affecting the height-time history of CMEs. Zhang *et al.* (2001) investigated four CMEs and compared their time evolution with GOES X-ray flares. They found that the CMEs started accelerating impulsively until the peak of the soft X-ray flare, consistent with an earlier result that flare-associated CMEs are in general faster than other CMEs (MacQueen & Fisher 1983).

According to Harrison (1995), the flare and CME are signatures of the same magnetic complexity, which represent the responses in different parts of the magnetic structure, to a particular activity, though they do not drive one another but are closely related. Su *et al.* (2007) examined the correlations between the soft X-ray peak flare flux (PFF), the CME speed (V_{CME}) and six magnetic parameters of the flaring active region. These six parameters were: the average background magnetic field strength (B), the area of the region where B is counted (S), the magnetic flux of that region (ϕ), the initial shear angle (θ_1, measured at the flare onset), the final shear angle (θ_2, measured at the time when the shear change stops), and the change of shear angle ($\theta_{12} = \theta_1 - \theta_2$) of the footpoints. They found no correlation between θ_1 and the intensity of flare/CME events, while the other five parameters were either positively or negatively correlated with both $\log_{10}$ (PFF) and V_{CME}. Among these five parameters, ϕ and θ_{12} showed the most significant correlations with $\log_{10}$ (PFF) and V_{CME}. The fact that both $\log_{10}$ (PFF) and V_{CME} are highly correlated with θ_{12} rather than θ_1 indicates that the intensity of flare/CME may depend on the released magnetic free energy rather than the total free energy stored prior to the flare. Torok & Kleim (2007) concluded that increased magnetic complexity, reflected on steep magnetic gradients in the source AR's corona, tends to produce faster CMEs. Good correlations have been found between different parameters representing the magnetic shear (or twist) or the non-potentiality of the active region and the flare/CME productivity (Falconer *et al.* 2006; Jing *et al.* 2006, and references therein).

This study aims to investigate the temporal correspondence of the X-ray emission characteristics of the flares with the dynamics of the associated CMEs. The unambiguous identification of X-ray emission characteristics with dynamics of CMEs will improve the understanding of the physical processes that link the solar and interplanetary relationship.

2. Data analysis and results

We have chosen the X-ray flares observed by Solar X-ray Spectrometer (SOXS) experiment onboard GSAT-2 Indian spacecraft (Jain *et al.* 2005, 2006) during November 2003 to December 2006 and those found unambiguously associated with coronal mass ejection (CME) observed by LASCO/SOHO. Our daily X-ray observations and the preliminary light curves revealed by Si and CZT detectors in the energy range 4–25 and 4–55 keV respectively are presented at the SOXS website (http://www.prl.res.in/∼soxs-data/). The observations of CMEs and preliminary kinematics are presented in the LASCO/CME Catalog at the website (http://cdaw.gsfc.nasa.gov/CME_list/). This catalog contains all the CMEs detected by the LASCO coronagraphs C2 and C3, which cover a combined field of view of 2.1 to 32 Rs. The actual increase of CME's height (in units of Rs) with time as it expands away from the Sun is available in the text file on the website. Each CME is characterized by the linear speed obtained by fitting a straight line (a linear or first-order polynomial fit) to the height-time measurements. The second-order fit gives the average acceleration of the CME. The acceleration of a CME can be positive, negative or close to zero suggesting CMEs speed up, move with constant speed or slow down within the FOV of the LASCO instrument. A minimum of three height-time measurements are required for an estimate of the acceleration, but the accuracy increases with more measurements. We succeeded in choosing 20 solar flare events clearly associated with CMEs for the current investigation and their temporal characteristics are presented in Table 1. The flares have been observed by both Si and CZT detectors of SOXS experiment in 4–25 and 4–55 keV respectively. The temporal characteristics and the peak flux of the flare observed in 4.1–10 keV of the CZT detector are presented in Table 1. The magnitudes of the flares range between B2.0 and M6.4 of GOES intensity class. The CME central position angle (CPA), angular width, the plane of-sky velocity and acceleration magnitude are also shown in Table 1.

Since hard X-ray emission is one of the most significant properties of solar flares we exploit this emission in current investigation to better understand the relation between flares and CMEs in addition to soft X-ray emission in 4.1 to 10 keV band. Figure 1 shows the evolution of the solar flares observed by CZT detector of SOXS on 30 July 2003, 31 October 2004 and 25 August 2005 respectively in the energy bands 4.1–10, 10–20, 20–30 and 30–55 keV as a function of time.

Table 1. Summary of solar flares and associated CME observations.

	Flare characteristics					CME characteristics				
	Time									
Date	Onset	Peak	End	GOES class	Peak flux*	Onset time	CPA (Deg.)	Angular width (Deg.)	Linear speed (km/s)	Acceleration (m/s^2)
30 July 03	4:07:58	4:09:39	4:29:18	M2.5	3842	4:06:40	55	9	589	58.7
13 November 03	5:00:23	5:01:48	5:15:49	M1.6	1182	5:00:00	105	62	598	−5.9
7 January 04	3:55:41	4:01:12	4:45:00	M4.5	3932	3:35:50	78	171	1581	−60.4
8 January 04	4:56:36	5:03:00	5:34:42	M1.3	371	4:45:20	83	144	1713	−14.6
19 March 04	4:13:19	4:15:36	4:24:39	C1.2	22.3	4:00:00	52	37	302	31.2
5 April 04	5:37:41	5:50:57	6:35:29	M1.7	1607	5:19:48	111	191	608	−9.7
11 April 04	3:57:13	4:08:44	4:56:25	C9.6	103	3:58:00	203	314	1645	−77.6
16 June 04	4:28:16	4:33:03	4:58:01	C2.8	50	4:10:00	72	127	603	−2
26 June 04	4:17:11	4:22:48	4:30:54	C1.3	29.2	4:20:50	250	69	775	7.5
21 July 04	4:55:20	4:57:47	5:02:37	C8.9	23.3	4:47:00	165	65	419	11.4
12 August 04	4:41:38	4:43:58	4:58:30	M1.2	56.2	4:11:52	198	115	176	−2
17 August 04	5:01:05	5:02:40	5:37:26	M1.1	271	5:12:30	116	131	637	14.4
19 August 04	4:12:10	4:15:54	4:24:23	B2	20.1	3:50:00	103	39	279	6.5
23 October 04	3:58:35	4:00:05	4:05:25	C1.8	70.4	4:00:00	99	61	468	14.4
31 October 04	5:21:35	5:31:02	5:54:04	M2.3	4209	5:05:00	251	62	265	7.6
12 July 05	4:15:23	4:28:19	4:38:19	B6.0	28	4:08:20	280	34	711	−3.9
27 July 05	4:38:35	4:53:34	5:30:22	M3.7	3096	4:38:00	Halo	360	1787	−75.4
3 August 05	4:57:18	5:04:12	5:24:50	M3.4	3811	4:40:00	104	65	479	−6.7
25 August 05	4:33:05	4:39:25	5:04:11	M6.4	7346	4:25:00	115	146	1327	−66.5
3 November 05	4:33:41	4:44:13	4:53:37	B9.1	15.7	4:13:48	155	77	304	21.6

*(Counts/s/cm^2/keV in 4.1–10 keV).

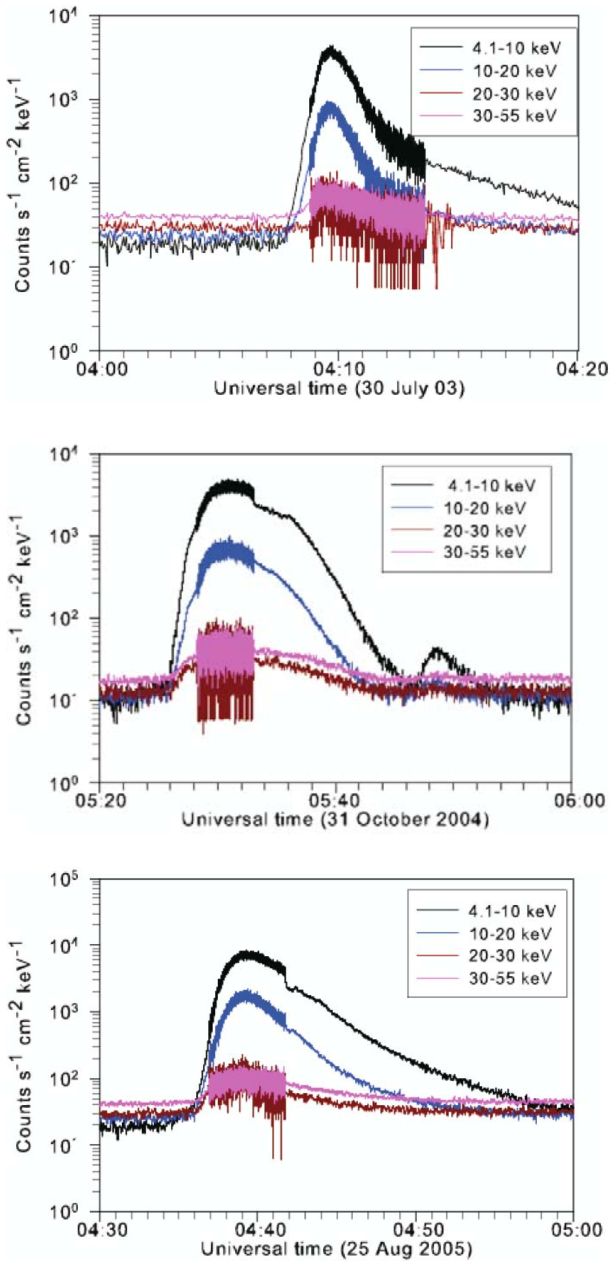

Figure 1. Light curves of 30 July 2003 (top), 31 October 2004 (middle) and 25 August 2005 (bottom) solar flares as observed by CZT detector of SOXS in 4.1–10, 10–20, 20–30 and 30–55 keV energy ranges.

In preview that the relative intensity on time scale may provide important information on the heating and cooling processes of the coronal flare plasma we measure rise time, decay time and total duration of each flare in soft and hard X-ray bands viz., 4.1–10 and 10–20 keV respectively. Start time of the flare is acquired as the time when

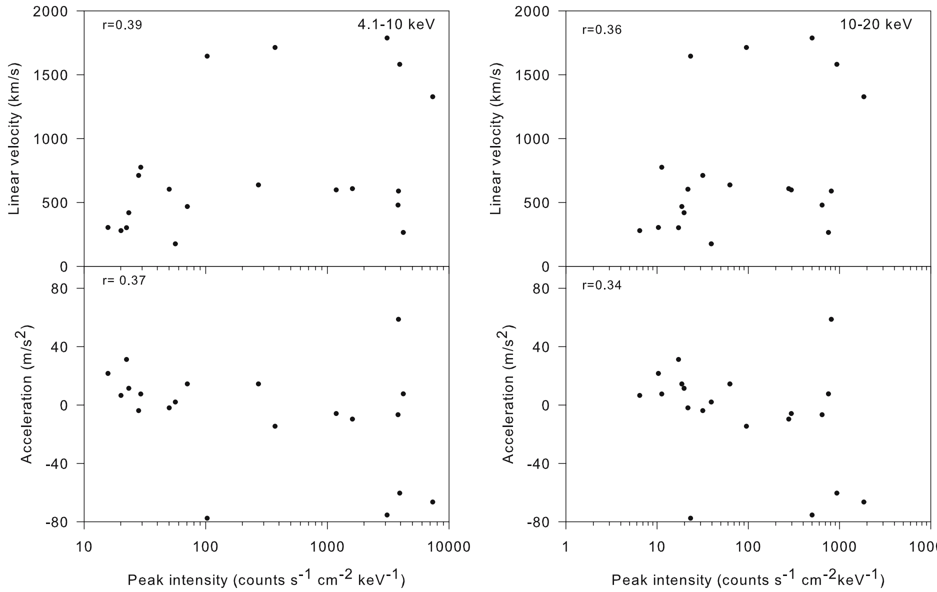

Figure 2. Velocity and acceleration of CMEs as a function of peak intensity of the flare in 4.1–10 (left) and 10–20 (right) keV energy bands.

the flux is 5σ above the background counts where σ is the root mean square of the time averaged background. End time is obtained as the time where the intensity of the flare returned to the pre-flare background or where it leveled off, whichever occurred earlier. Peak flux is the maximum flux obtained by taking the average of the measured counts in 100 ms in the flare mode and the corresponding time is the peak time of the flare. Rise time of the flare is defined as the time from the start of the flare to the peak of the emission as seen by CZT detector, while the decay time refers time from the peak of the flare to the end time. The flare duration is characterized as the time between start and end of the flare.

Shown in Fig. 2 is the variation of the linear speed and acceleration of the CMEs with peak intensity of the associated flares in 4.1–10 and 10–20 keV bands. The peak intensity of the flares varies between 15 and 8000, and 6 and 2000 counts/cm^2/s/keV in 4.1–10 and 10–20 keV respectively. The CME linear speed and acceleration vary between 150 and 2000 km/s and -80 and 60 m/s^2 respectively. The correlation coefficient between peak intensity of the flares and linear speed and acceleration of the associated CMEs is not strong rather it ranges between 0.34 and 0.39 in both 4.1–10 and 10–20 keV energy bands.

Figure 3 represents the linear speed and acceleration of the CMEs as a function of rise time of the associated flares in 4.1–10 and 10–20 keV bands. The rise time of the flares varies between 100–900 and 50–800 seconds in 4.1–10 and 10–20 keV bands respectively. It may be noted from this figure, though not unambiguously but by and large, that speed of CMEs increases with rise time in both 4.1–10 and 10–20 keV bands, which, however, appears better in soft X-rays, viz., in 4.1–10 keV. On the other hand, we observe deceleration of CME speed with increasing rise time of the flare, which, however, appears better in 10–20 keV hard X-rays. Figure 3, therefore, indicates that fast moving CMEs showing positive acceleration are better associated with short rise

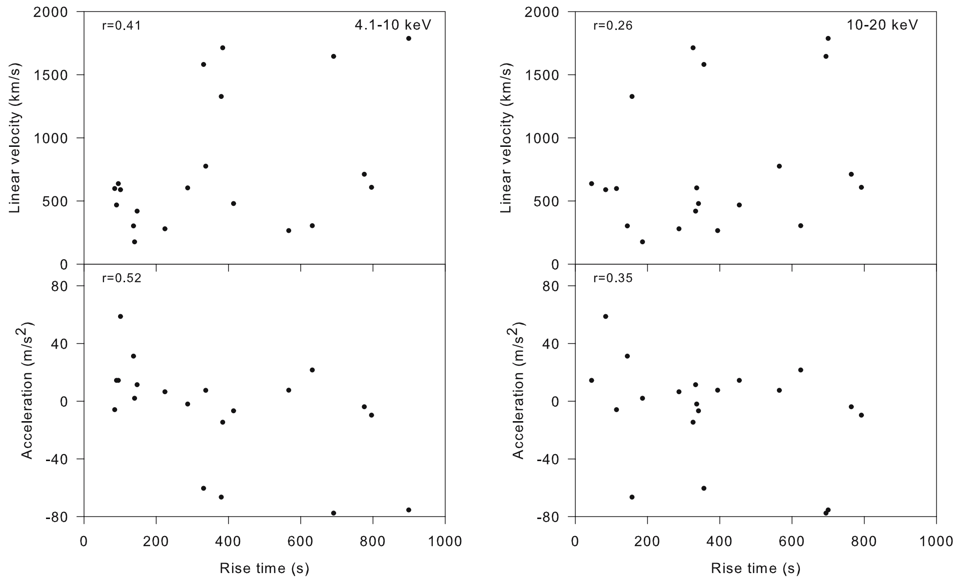

Figure 3. Variation of linear speed and acceleration of CMEs as a function of rise time of the associated flares observed with CZT detector in 4.1–10 keV (left) and in 10–20 keV (right) energy bands.

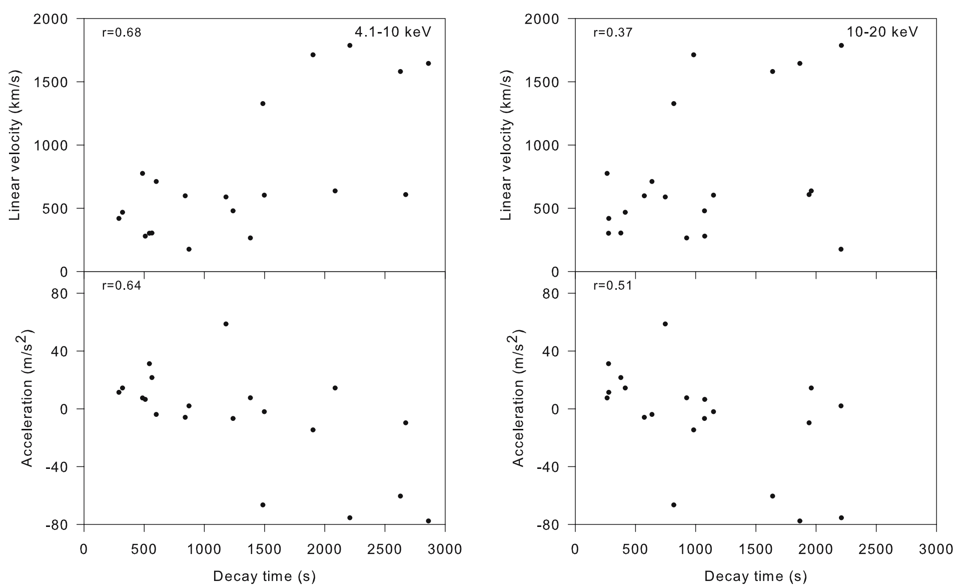

Figure 4. Variation of CME linear speed and acceleration as a function of decay time of the flare in 4.1–10 (left) and 10–20 (right) keV respectively.

time (< 150 s) i.e., impulsive flare events. However, this conclusion is subjected to limited number of events analyzed in this investigation.

Figures 4 and 5 represent the variation of linear velocity and acceleration of the CME with the decay time and duration of the associated flares respectively. We found the

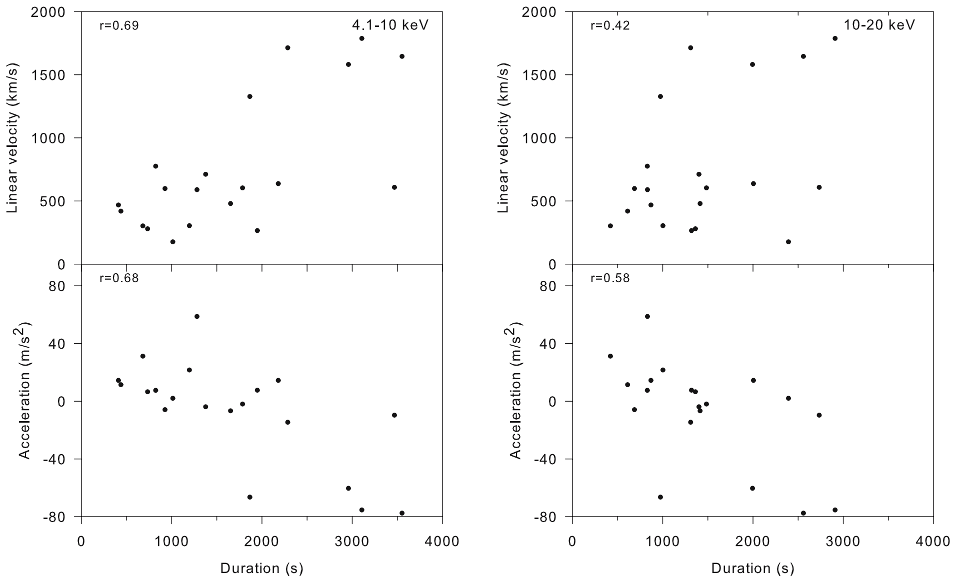

Figure 5. Variation of CME linear speed and acceleration as a function of duration of the flare in 4.1–10 (left) and 10–20 (right) keV respectively.

decay time of flare varies between 250 to 2800 and 250 to 2300 seconds in 4.1–10 and 10–20 keV energy range respectively. The higher linear velocity of CME seems to be associated with longer decay time of the flare as observed in 4.1–10 keV and 10–20 keV energy bands, however more obvious in 4.1–10 keV. This enables us to conclude that the larger speed CMEs (above 1500 km/s) are associated with flares of longer decay time (> 1500 s). However, on the contrary, CMEs decelerate faster with increasing decay time of the flares. Figure 4 also suggests that the flares associated with the CMEs of high positive acceleration decay faster than those associated with CMEs of small positive acceleration. The duration of flares (*cf*. Fig. 5) varies between 400–3550 and 400–2900 seconds in 4.1–10 and 10–20 keV respectively. We found better association of linear velocity and acceleration of CMEs with the duration of the associated flares. It may be noted from Fig. 5 that the velocity of the CMEs increases as a function of duration in both 4.1–10 and 10–20 keV bands. Again, this association appears better in 4.1–10 keV. The acceleration of CME reduces with increase of duration of flares in both the energy bands. This indicates that the possibility of CMEs with larger speeds exists with long duration flare events though they decelerate faster. However, the CMEs associated with short rise time or short duration flares show positive acceleration though they do not attain very high speeds (< 1000 km/s).

3. Discussion and conclusion

We studied temporal relationship between the dynamics of the CME and the peak intensity, rise time, decay time and duration of the associated solar flares. Our current investigation of 20 solar flare events observed by SOXS mission and found associated with CMEs suggests that higher peak intensity of the flare in 4.1–10 and 10–20 keV band is not indicative of higher speed of the associated CMEs, which is in contrast

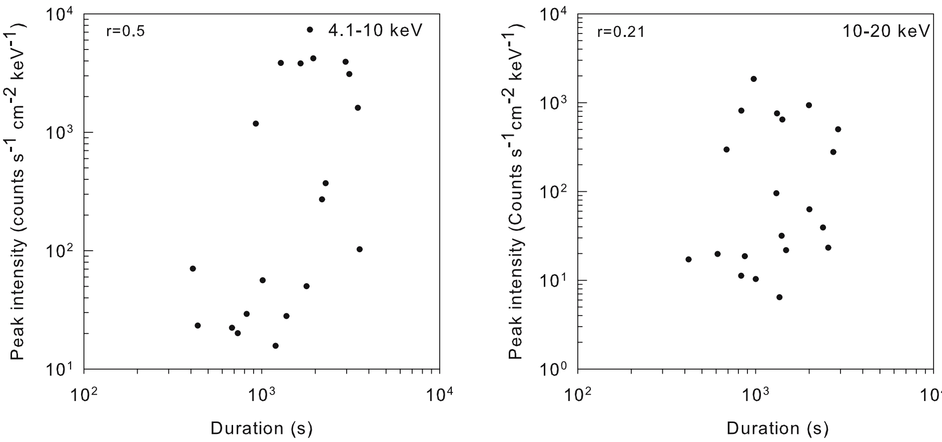

Figure 6. Variation of the peak intensity of the flares found associated with CMEs as a function of duration in 4.1–10 (left) and 10–20 (right) keV respectively.

to Munro *et al.* (1979) and Webb & Hundhausen (1987) who observed a common occurrence of the eruption and the high intensity and/or long duration flare. Kay *et al.* (2003) compared the flare parameters to find the relationship between solar flares with and without associated CMEs. They found a clear correlation between peak intensity and flare duration for the events without CMEs, while no correlation in the case of the flares found associated with CMEs, suggesting that the occurrence of a CME intrinsically affects the timescale for energy release and cooling within the flare. However, on the contrary to Kay *et al.* (2003) we found almost linear relationship between peak intensity and duration of the flare in soft X-rays, i.e., in 4.1–10 keV but not in 10–20 keV as shown in Fig. 6. This result suggests that occurrence of a CME and associated flare are two components of one energy release system that is seen at the reconnection site in the corona (Shibata 1996). Increasing soft X-ray flare intensity with duration appears to be the consequence of rise in temperature, perhaps, caused by the outgoing CME. On the other hand, no appreciable relationship between peak intensity and duration of the flare in 10–20 keV band suggests that occurrence of CME intrinsically affects the time scale for energy release in high energy bands of the flare X-ray emission, which has been described below.

We found that the faster CMEs are better associated with flares of short rise time (< 150 s) in both 4.1–10 and 10–20 keV energy bands. However, the CME associated flares showed significantly longer decay times in contrast to the rise-times, which is in agreement to Harrison (1995). The linear velocity of CMEs increases as a function of duration of flare in both 4.1–10 and 10–20 keV bands. Harrison (1995) showed that the CMEs could be associated with flares of any duration but better associated with long duration flare events, which supports our current findings. However, on the other hand, we observed deceleration in CME speed with increasing rise and decay times and duration of the flare, predominantly in hard X-ray 10–20 keV band, while CMEs associated with short rise time and/or short duration flares showed positive acceleration though they did not attain speeds higher than 589 km/s. Our current investigation shows that the linear velocity of the CME increases in general with rise time, decay time and duration of the flare, which suggests that both flare and CME are closely associated with each other and might be an integral part of the same energy release system. Further, based on the onset time of the flares and associated CMEs within observing cadence of CMEs by LASCO/SOHO, we found that in 16 cases CME (*cf.* Table 1) preceded the flare by 23 to 1786 s, while in 4 cases the flare occurred before the CME by 47 to 685 s. Our findings support the earlier results by Harrison (1991) and more recently by Kim *et al.* (2005), and enable us to conjecture the hypothesis that flare and CME both are driven by the same magnetic activity. According to Harrison (1995) such magnetic activity may arise from shear or reconnection within the magnetic structure, and the flare and CME simply reflect the responses in different magnetic environments within the structure. More recently Zhang *et al.* (2006) proposed flux rope eruption caused by magnetic reconnection with implication in coexistent flare–CME events. They showed that an isolated flux rope coexists with two current sheets: a vertical one below and a transverse one above the flux rope. The flux rope erupts when reconnection takes place in the current sheets, and the flux rope dynamics depends on the reconnection sequence in the two current sheets. Zhang *et al.* (2006) argue that both breakout-like and tether-cutting reconnections could be important for CME eruptions and associated surface activities, which is in consistence to our findings.

We conclude that the linear velocity of CME does not depend significantly upon the peak intensity of the flare, while in general it increases with rise time, decay time and duration of the flare. Based on our findings we propose that flare and CME are the two components of one energy release system.

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