

# Preflare Phenomena in Eruptive Flares

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## ABSTRACT

We report the results of a statistical study of the relationship between eruptive solar flares and an observed  $H\alpha$  preflare phenomenon we call moving blue shift events (MBSEs). The  $H\alpha$  data were gathered using the Mees Solar Observatory CCD imaging spectrograph (MCCD). The 16 events in our dataset were observed by both the MCCD and the Yohkoh Soft X-Ray Telescope (SXT), typically for at least three hours prior to the flare, and in some cases repeatedly for several days prior to the flare. The dataset contains both eruptive and non-eruptive flares, without bias. Focusing on three-hour periods before and after the flares, we found the average rate of MBSEs prior to the flares was  $\sim 5$  times greater prior to the 11 eruptive flares than prior to the 5 non-eruptive ones. Also, the average rate of MBSEs dropped by a factor of  $\sim 6$  after the eruptive flares. Earlier studies inferred that MBSEs reflect motions that originate in the readjustment of magnetic fields after magnetic reconnection. From the high correlation between eruptive flares and preflare MBSEs in the several hours prior to such events, we conclude that reconnection in the chromosphere or low corona plays an important role in establishing the conditions that lead to solar flare eruptions.

## 1. Introduction

Canfield and Reardon (1998) used  $H\alpha$  spectra and spectroheliogram movies to discover the moving blue-shift events that we call MBSEs in this paper. These events are characterized by strong  $H\alpha$  blue-shifts in relatively small regions moving at speeds of a few km/s, typically lasting a few minutes. They occurred with increasing frequency before the eruption of the well-observed Yohkoh flare of 15 November 1991. The blue-shift events were accompanied by transient dark  $H\alpha$  fibrils that connected an emerging flux system with a filament, which subsequently erupted. The spectra and spectroheliograms showed that after the initial appearance of the blue-shifts that give the events their name, regions of either upward or torsional motion were seen moving along the direction of the fibrils. Observations with the Yohkoh SXT (Tsuneta *et al.* 1991) typically showed small soft X-ray flare events that were spatially and temporally coincident with the MBSEs. These characteristics led Canfield and Reardon to interpret MBSEs in terms of equilibration of chromospheric and coronal magnetic field lines after episodes of magnetic reconnection between two flux systems, those of the filament and the emerging flux.

These observations of MBSEs prior to a single eruptive event suggest several obvious questions. Does the occurrence of MBSEs herald impending eruption or flaring, or is it a phenomenon that occurs all the time? Do MBSEs take place only before events that are eruptive, *i.e.* are accompanied by optical, X-ray, and radio evidence of large-scale eruption of coronal material, or are they also seen prior to events that are not? Are they uniquely associated with active regions that produce eruptive flares? Do they occur at the interface between flux systems, as in the 15 November 1991 event, or within a single flux system? In order to address these questions observations of more than a single event are required.

The force balance in the chromosphere and corona is dominated by magnetic forces, which can be described fully in terms of magnetic pressure and tension forces (*e.g.* Forbes and Priest 1995). Various authors have drawn analogies between the tension forces in magnetic field lines in a solar active region that is about to erupt and the “tethers” that hold a balloon from buoyantly rising (Moore and Roumeliotis 1992, Canfield and Reardon 1998, and Klimchuk 2001). Although the analogy is far from complete, the role of magnetic reconnection in altering the tension term in the force balance has variously been termed “tether cutting”, “tether release” or “tether straining”.

Forbes (2000) and Klimchuk (2001) have reviewed many models that seek to explain the initiation of CMEs and eruptive flares in related but different frameworks. Forbes uses an approach that distinguishes between resistive and ideal instabilities; Klimchuk distinguishes between “storage and release” models and those that are directly driven. Klimchuk’s use of analogues involving springs, ropes and weights makes a natural framework in which to discuss the role of magnetic reconnection and our observations of MBSEs.

In Section 2 we describe the methods and observations used in the paper, and include a table that summarizes much of the data observed for the 16 events. In Section 3 we discuss our observations, apply a statistical analysis, and display the results. Finally, in Section 4 we compare our results with current CME initiation models.

## 2. Observations

The observations for this paper combine  $H\alpha$  filter imaging with spectroscopy in order to gain the advantages of both techniques. Our primary data source is the Mees Solar Observatory CCD (MCCD) imaging spectrograph Penn *et al.* (1991). The MCCD scans were made with its standard  $H\alpha$  flare setup: spectrograph camera spatial scan field of view  $\sim 3' \times 4'$ ,  $2.''4$  pixels,  $18.7 \text{ \AA}$  spectral range (covering 50 pixels), completing one scan and one  $H\alpha$  monitor image each 15 - 20 s, except for one event whose scan time was 38 s. Though the spatial resolution of MCCD spectroheliograms is low relative to the broad-band  $H\alpha$  filtergrams at times of good seeing, the  $H\alpha$  profiles bring important diagnostic advantages. The most important derived parameter for this study is Doppler velocity, determined from the shift of the  $H\alpha$  line center. To maximize our Doppler-velocity sensitivity, we apply to the spectra Fourier filtering, interpolation, and padding

with zeros at the Nyquist frequency. We then fit the core of the  $H\alpha$  line profile with a parabola. From the shifts of the minima of the fitted profiles of each pixel, we construct Doppler velocity maps; from the intensity of the minima of each profile, we construct line-center spectroheliograms.

We have selected 16 flares for study, independent of the nature (eruptive or non-eruptive) of the event. The only basis for this selection was that the events were observed by both the MSO M CCD and the Yohkoh SXT. The preflare MSO observations typically extended at least three hours before the events studied. In some cases, the regions in which the flares occurred were observed for several days. Table 1 shows the HXT hard X-ray start times (Sato *et al.* 2003) and other properties of the events studied.

In order to most efficiently analyze the M CCD data, we used IDL to create side-by-side movies showing line-center spectroheliograms and Doppler velocity. Figure 1 shows a sample frame from a movie created for a flare which occurred on January 30, 1992. The velocity maps were inspected visually to identify (arrow) moving blue shift events (MBSE) whose radial velocity exceeded 2 km/sec (on the order of 1000 times the RMS velocity). In order to classify a dark feature in the velocity images as a MBSE, the spot must exhibit a very strong blue shift with respect to the whole image, must move in the  $x,y$  coordinate plane, be at least five pixels in size, have a duration of at least two minutes, and occur within approximately 50 arc seconds from the area which the flare later happens. Typical proper motions observed for the propagating blue shifts were  $\sim 20$  km/sec. Features in sunspots and motions of surges or large, long filaments (such as the one in the lower left of the sample image) were not included.

The higher spatial resolution of the M CCD image monitor camera allows us to see transient  $H\alpha$  fibrils associated with the MBSEs (see Figure 1 of Canfield and Reardon (1998)), when atmospheric observing conditions are satisfactory. During such periods, 77% of MBSEs were associated with such fibrils, which clearly indicate the orientation of magnetic field lines in the chromosphere.

Several factors involving filaments are of importance to our study. First, is there a filament present in the flare region? As can be seen in the last column of Table 1, for 14 of the 16 events, there is; in 9 of the 11 eruptive events, that filament erupted. Second, what is the location of MBSEs relative to the erupting filament/flare location? Of the MBSEs observed within three hours prior to the flares (the first number given in the fifth column of Table 1), most did not coincide spatially with the filament/flare. The number given in parenthesis in the fifth, MBSE/3hr, column of Table 1 is the number of MBSEs observed to occur away from the filament/flare. Third, what is the direction of MBSE propagation with respect to the filament? Out of the 98 MBSEs observed within three hours prior to the flares, 67% moved toward the filament which eventually erupted, and 31% moved away.

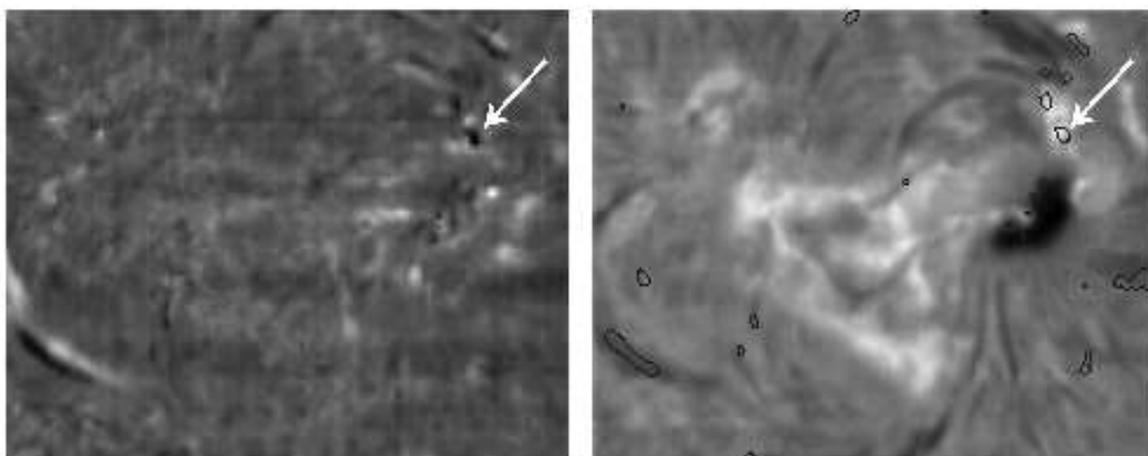


Fig. 1.— Sample frame used in the analysis process, from the January 30, 1992 flare event. Image sizes are  $\sim 4.4' \times 3.5'$ . Earth north is up. The right-hand panel shows the raw line-center spectroheliogram. The left-hand panel is the corresponding Doppler velocity map. White corresponds to red shift, black to blue. In the velocity image, the arrow points out an example of a blue shift event. Doppler velocity contours (level:1% off maximum blue shift) are overlaid on the line-center spectroheliogram.

Table 1. Events Observed.

Flare Date	UT	class	AR	MBSE/3hr*	eruptive <sup>†</sup>	filament
01/10/91	22:28	M1.8	$\beta\gamma\delta$	9(9)	v,y,t	yes
24/10/91	22:30	M9.8	$\beta\gamma\delta$	7(6)	v,y,t	yes
31/10/91	02:59	C7.5	...	0	no	yes
09/11/91	20:51	M1.4	$\beta\gamma$	6(6)	v,y,m	yes
15/11/91	22:34	X1.5	$\beta\delta/\beta\gamma$	13(8)	v,r,m,t	yes
10/12/91	00:40	M1.2	$\beta$	2	no	yes
26/12/91	21:35	M4.2	$\beta\delta/\beta\gamma$	0	no	yes
30/12/91	23:06	M4.6	$\beta/\beta\gamma$	8(3)	v,r,m,t	yes
07/01/92	20:21	C8.9	$\beta\delta/\beta\gamma$	15(10)	v,y,t	yes
30/01/92	02:25	M1.6	$\beta/\beta\gamma$	13(8)	v,y,m,t	yes
24/02/92	23:17	M5.0	$\beta\delta$	9(7)	v,y,t	yes
20/08/92	20:33	M3.0	$\beta\gamma\delta$	0	no	yes
10/09/92	22:51	M3.2	$\beta\gamma$	5(3)	v,r,m	no
02/02/93	03:43	C6.3	$\beta$	0	no	yes
30/06/94	21:18	M3.9	$\beta/\beta\gamma$	0	v,y,m,t	yes
13/12/94	20:58	C6.5	...	9(6)	v,r	no

\*see text, section 2

<sup>†</sup>v=H $\alpha$  proper motion, r=type II, y=Yohkoh, m=H $\alpha$  radial motion, t=H $\alpha$  ribbons

### 3. Analysis

We use various signatures to identify eruptive flares, and indicate their presence with the following notation in Table 1: (v) tens of M CCD pixels with saturated  $H\alpha$  blue shifts at the flare site during the onset phase. (r) type II radio emissions listed for the event in NOAA Solar-Geophysical Data Reports. (y) Yohkoh SXT images showing transient X-ray cusps or arcades, moving large-scale brightenings, or transient coronal holes. (t) two spreading  $H\alpha$  ribbons during the gradual phase of the flare. (m) moving dark  $H\alpha$  material (proper motion). A 'no' denotes that none of these indicators were recorded in the sources cited. Since these events were selected for good Yohkoh and M CCD coverage, the least complete coverage is that of radio bursts by Solar-Geophysical Data Reports. Using these indicators, we concluded that 11 of the 16 events were eruptive.

We were able to observe with the M CCD all but three of the 16 regions of interest for three hours prior to flare onset time, and the remaining ones for one or two hours. Figure 2 shows the hourly average rates of MBSEs during this period for the 11 eruptive flares, taking into account times where there were no observations. The individual rates of MBSEs for these events vary from zero to nine per hour, and this variation is reflected in the error bars shown.

Interestingly, Figure 2 shows that the rate of MBSEs drops dramatically after the eruptive flares. We observed 8 of the regions for at least 2 hours after flare onset, and 3 for at least 3 hours. The error bars for the hourly averages reflect the variability among these events. The overall average preflare rate of MBSEs in the period 3 hours prior to the flare is  $3.45 \pm 3.27$ , while the same rate for three hours after is  $0.57 \pm 0.92$ . In other words, the preflare rate is significant at the one sigma level, and the postflare rate is not significantly different from zero. The poor significance is due to the large variation in the rates of MBSEs per hour (from 0 to 9 per hour).

The phi coefficient Daniel (1990) is designed for evaluation of statistical significance in studies using dichotomous variables, which can take on only one of two mutually exclusive values. Our events are dichotomous, in the sense that they either show blue shift events or not, and they are eruptive or not (Table 2). This coefficient is related to chi-square values, which can be compared to tabulated chi-square values with one degree of freedom. By evaluating the phi coefficient ( $\phi = 0.545$ ) and then the corresponding chi-square statistic ( $\chi = 2.18$ ), we find that we can reject the null hypothesis with 97% confidence. In other words, the correlation between the presence of MBSEs prior to a flare and the flare being eruptive is significant.

Does this significant relationship obtain for periods more than just a few hours prior to the time of the flare event? To address this question, we selected three events for further analysis, as data were available (Table 3). We compare two eruptive events with a non-eruptive one, as indicated in column 3. The results are inconclusive. We see just as many MBSEs prior to the non-eruptive event as the eruptive ones. It may be important to note that in the region of the August 20, 20:33 event, just twelve hours later, there was a flare with eruptive signatures (type II radio bursts). This suggests that the MBSEs seen in the days prior to August 20 might have been

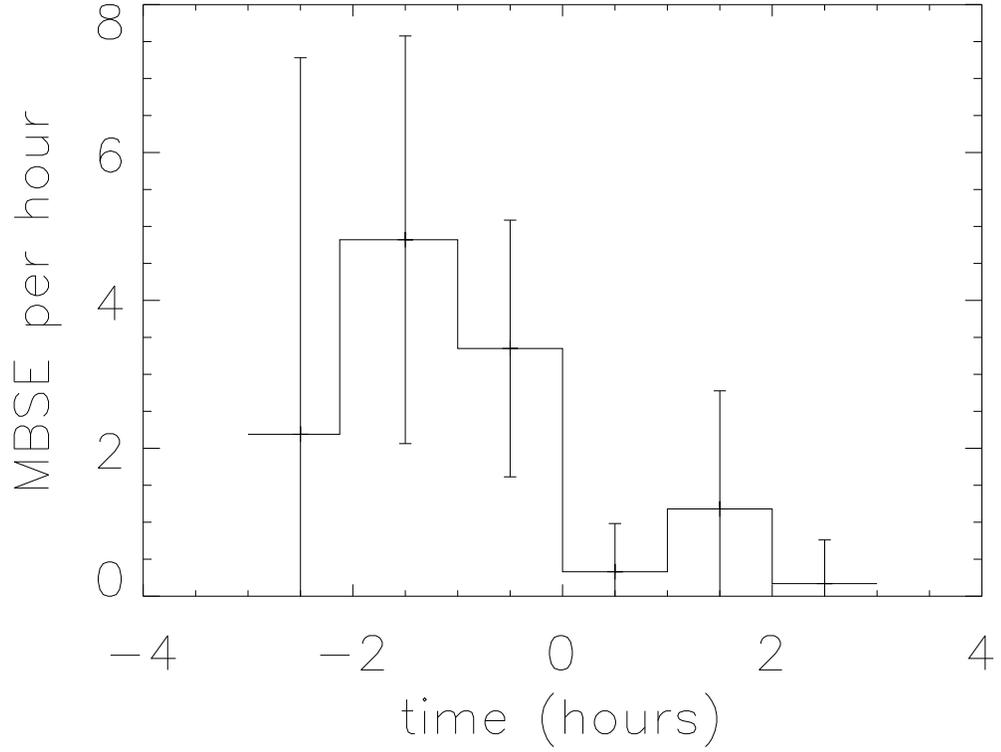


Fig. 2.— The average rate of MBSEs per hour for the 11 eruptive events as a function of time relative to the HXT start time. The error bars show one standard deviation.

Table 2: Eruptive flare and MBSE relationship.

Blue Shift Events?	Eruptive?	
	Yes	No
Yes	10	1
No	1	4

related to the eruptive August 21 event. However, it is evident from this example that we cannot claim to be able to classify every region as purely eruptive or non-eruptive, or uniquely relate the MBSE we observe for such extended periods to one flare event or another.

#### 4. Interpretation

The mechanical models and emphasis on “tethers” used by Klimchuk (2001) form a convenient basis for the questions posed in the introduction. Looking at 16 events during a time period of hours prior to flares, we find a statistically significant relationship between eruptive flares and the presence of MBSEs, which we believe are evidence for reconnections in the chromosphere. In the “tether” analogy, these reconnections are altering the tension term in the force balance of the magnetic field, perhaps heralding an impending eruption.

Our study of the direction of propagation of MBSEs prior to the flares shows that more than twice as many propagate toward the eruptive filament than away from it. We know that newly emerging flux tends to carry twist into the corona from subphotospheric convection (*e.g.* Leka 1995, Longcope, Fisher, Pevtsov 1998), where it may, through reconnection events, be transferred to pre-existing flux systems. Hence, our interpretation of this finding is that twist is being put into the filament flux system, raising its free magnetic energy. However, we can say nothing about the role of this twist in the eruption itself.

Comparing the rate of MBSEs for a period of three hours prior to and after the eruptive flares, we find the rate prior is significantly higher than the rate after (Figure 2). This observation strongly indicates that MBSEs (reconnections) play an important role in establishing conditions that lead to eruption. The tether straining models reviewed by Klimchuk (2001) require reconnections prior to eruptive events, and therefore are supported by our observations. Reconnections are not required by the mass loading model, but perhaps they cause a force imbalance that leads to mass unloading and subsequent eruption. On the other hand, two CME models do not fit simply with our observations. In some flux rope models, reconnections occur only at or after the time of eruption, so our observations require some additional explanation. In the flux injection model, pre-eruptive

Table 3. MBSE rates for days prior to flare events.

Date	UT	Eruptive?	Date-1	Date-2	Date-3	Date-4	Date-5
November 15, 1991	22:34	Yes	.4	...	1.45	.95	.41
January 7, 1992	20:21	Yes	3.05	1.80	4.84	...	...
August 20, 1992	20:33	No	1.0	.83	.27	0	...

reconnections also do not play any role, again requiring some additional mechanism.

The three events we analyzed for extended time periods show that MBSEs are observed not just hours, but as much as days, prior to a flare. However, when observing on this time scale, it becomes hard to associate MBSEs with a particular flare in our data. Had there been a significant event in the extended time period, we would have included it in our detailed study. In each of the three cases for which an active region was observed for multiple days, we saw MBSEs. Each of those active regions produced at least one eruptive flare within a day of MBSEs. Over the same span of days, non-eruptive flares were also seen. Therefore, we could not label a region as producing only eruptive or non-eruptive events.

It is interesting to note that the levels of MBSE occurrence in the post-flare time period of Figure 2 (and quantitatively given in Section 3) are similar to the levels given in Table 3 (with the possible exception of the January 7th event). One might take this to be a measure of a background level. The possible inference is that there is an increase in the MBSE occurrence rate in the hours just prior to eruption, after which the MBSE rate falls back to the background level. In the 15 November 1991 event, studied by Canfield and Reardon (1998) for  $\sim 5$  hours before the eruption, the MBSE occurrence rate indeed did increase greatly in the 2-3 hours just before the event, compared to its earlier value.

To what extent do our observations support the role of reconnection in altering the tension term, as envisioned in the tether release models? Canfield and Reardon(1998) show that MBSEs are plausibly the dynamic manifestation of equilibration of the chromospheric magnetic field after reconnection events. Hence, we believe that our study supports those eruptive flare initiation models for which either (1) chromospheric reconnection is required or (2) chromospheric reconnection is a natural accompaniment to the process that is envisioned by the authors of the model. If taken literally, neither the “breakout” model (Antiochos 1998, Antiochos *et al.* 1999) nor Forbes and Priest’s tether straining model completely coincide with the fact that 70% of the MBSEs occur away from the filament/flare. The breakout model envisions reconnection in the corona, above the flare location, not in the chromosphere. If this were the case, MBSEs would move away from the filament, not toward it, as we find for 67% of the events (Section 2). The tether straining model requires reconnections directly below the filament. While these could occur in the chromosphere, they would be observed at the filament location, rather than away from it, as we find.

The presence of filaments in 14 of the 16 flare events does not favor one model over another. Both Forbes and Priest’s tether straining model and the breakout model have topologies in which a filament could form. The mass loading model can obtain adequate compression from a small volume of extremely dense filament material, or from abnormally high density coronal material filling a large volume.

What do our observations have to say about the role of magnetic complexity, *e.g.* the presence of multipolar vs. bipolar topology? Of the 10 eruptive events studied here with known Mt. Wilson magnetic classification, all had at least  $\beta$ - $\gamma$  complexity. The two flares with simple  $\beta$  classifications

were both non-eruptive events. Only the breakout model requires a multi-polar active region; the flux rope, tether straining, flux injection, and mass loading models do not.

To conclude, we find that our observations support only those CME initiation models that directly or indirectly require reconnection prior to the event. The flux injection models of Chen (1989), for example, do not obviously account for preflare reconnections for *hours* before the eruption. On the other hand, it is possible that mass unloading, as envisioned in the models of Low (1999) and others is enabled by such reconnections. In Klimchuk's (2001) tether release and straining categories, reconnection in a current sheet beneath the filament, envisioned by Forbes and Isenberg (1991), Forbes and Priest (1995), Mikić and Linker (1999) and Amari *et al.* (2000) is not consistent with our observation that MBSEs occur away from the filament. In the tether straining category, the breakout model (Antiochos 1998, Antiochos *et al.* 1999, Klimchuk 1996) is most consistent with our observations in that both a multipolar geometry and pre-eruption reconnection are essential parts of the model. However, the reconnection in that model takes place in the corona above the plausible filament location, not in the chromosphere away from the filament. The observed direction of motion of MBSEs, primarily toward the erupting filament, apparently rules out an interpretation in which MBSEs are the chromospheric response to such a coronal reconnection event. From the topological point of view, the detailed location of the reconnection that accomplishes the opening of overlying field lines is not fundamental. Any location that enables the overlying field lines to be removed as effective tethers will do. We believe the chromospheric reconnection events that we observe as MBSEs away from the filament location, perhaps on the interface between flux surfaces as in the 15 November 1991 event, may accomplish just that, although this remains to be shown in detail.

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