Observations of the Failed Eruption of a Filament

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ABSTRACT

We have observed the fine temporal and spatial structure of a filament eruption on 2002 May 27 following an M2-class flare. Our observations at Big Bear Solar Observatory (BBSO) were made at the wavelength of H_α - 1.3 Å, with a cadence of 40 ms. The event was also observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) at X-ray energies from 3 to 50 keV and by the Transition Region And Coronal Explorer (TRACE) in Fe XII 195 Å. The event appears to be a "failed eruption", as the filament material, seen in absorption by TRACE, first accelerated, then decelerated as it approached its peak height of $\sim 8 \times 10^4$ km while the filament threads drained back to the Sun.

The fact that the eruption did not lead to a coronal mass ejection indicates that the coronal magnetic field near $\sim 8 \times 10^4$ km did not open during the flare. The height-time curve obtained from the TRACE 195 Å images during the deceleration phase shows that the deceleration of the filament exceeded the gravitational deceleration by more than a factor of 10, which suggests that the filament material was pulled back by magnetic tension.

Also of importance are three sequential, but co-spatial, features– brightenings in EUV, a looptop hard X-ray emission, and 'rupturing' of the H_α filament– which point to a release of energy (and probably magnetic reconnection) above the initial filament's location but well below its terminal height. Reconnection above a filament does not appear in most models, with the notable exception of quadrupolar and 'breakout' models. These observations provide evidence that at least two conditions are required for a successful eruption: a reconnection very low in the corona (possibly above the filament), and open or opening fields above that point.

Subject headings: Sun: magnetic field — Sun: corona — Sun: chromosphere — Sun: X-rays

1. INTRODUCTION

Filament eruptions on the Sun, which are associated with flares and coronal mass ejections (CMEs), have attracted increasing interest. It is known that filament eruptions trace out coronal magnetic reconfigurations or restructuring (Marque *et al.* 2001), and large scale morphological changes are observed in the topology of the loop systems (Uchida 1998). One key issue relevant to magnetic restructuring is whether it is necessary for the magnetic field around the filament to open up in order to allow the filament to erupt. In the classical 'CSHKP' model of a two-ribbon flare, the coronal magnetic field opens up over the erupting filament (Carmichael 1964, Sturrock 1966, Hirayama 1974, and Kopp & Pneumann 1976). In this scenario the coronal lines of force extend out into the corona, and there is no subsequent restriction on the upward motion of the filament.

Another class of model is that of the catastrophic evolution of a detached flux rope. The eruption may be caused by slow reduction of the overlying flux (Forbes & Priest 1995; Priest & Forbes 1990), by loss of equilibrium by reconnection beneath the filament (Chen & Shibata 2000), or viscous relaxation (Amari *et al.* 2000).

Models of flares in which two bipoles interact without opening the magnetic field to space have also been proposed (Low & Wolfson 1988). Hirose and Uchida (2002) have presented a quadrupole model for filament eruptions, that solves many of the difficulties in other models, particularly the problem of cutting through the filament's supporting field, but they point out that there is a closed magnetic field above the filament, and that might, if strong enough, prevent the ejection of the filament. Hirose and Uchida's model invokes reconnection below the ejected filament. A qualitatively similar model with two dipoles described by Karpen *et al.* (1996) has a nearly vertical current sheet with two Y-type cusps. In this magnetic configuration, if the upper cusp of the current sheet remains fixed, any ejection tracking the current sheet will fail to escape.

In 'breakout' models of CMEs, Antiochos and Devore (1999) suggest that shearing motions can open closed magnetic fields above an arcade, permitting an ejection to escape to infinity. If the higher magnetic fields remained closed, the eruption might not continue into the corona. A wide variety of topological configurations ('skeletons') of the magnetic field have been studied (see review by Priest and Forbes, 2002), and it is likely that some classes of magnetic topology may favor 'failed eruptions', although, to our knowledge, none have yet been published.

In this paper, we present observations of a well-sampled filament eruption in H_α - 1.3 Å. This event was also covered by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and the Transition Region And Coronal Explorer (TRACE) at 195 Å.

The eruption was accompanied by an M2-class flare.

2. INSTRUMENT AND DATA

RHESSI utilizes Fourier-transform imaging with 9 bi-grid rotating modulation collimators and cooled germanium detectors to make observations of X-rays and gamma-rays from ~ 3 keV to ~ 17 MeV (Lin *et al.* 2002). The RHESSI data were analyzed within the framework developed by the RHESSI team (Schwartz *et al.* 2002). Using this software, we have made 'Clean' maps in the $12 - 25$ keV energy band.

In cooperation with the RHESSI team, with the aim of observing the details of flare energy precipitation on small temporal and spatial scales we carried out high-cadence flare observations at Big Bear Solar Observatory (BBSO) using a Dalsa camera (256×256) in H_α -1.3 Å, with a cadence of 40 ms. The pixel resolution is $0.89''$, which gives a field of view of about $228'' \times 228''$. We choose the blue wing in order to avoid strong thermal effects near line center and downflow effects in the red wing. On 2002 May 27, we observed a filament eruption in active region NOAA 9957 (N10 W87). We believe this is the first successful high cadence observation of filament eruption in the H_α blue wing. To get accurate position information for H_α blue wing images, we aligned a typical H_α blue wing image with an MDI continuum image taken 25 minutes earlier, for which there is accurate pointing information. The accuracy of the alignment is better than $1''$.

The TRACE instrument is a 30-cm aperture Cassegrain telescope intended to observe solar plasmas with temperatures from 6000 to 1.6 MK, with $1''$ spatial resolution and temporal resolution of ~ 10 s (Handy *et al.* 1999). We downloaded the 195 Å images from 18:00 to 18:30 UT. The field of view is 384×384 with a pixel resolution of $1''$ and a cadence of from 9 to 70 s.

3. OBSERVATIONS

The activation of the filament was fully covered by the TRACE 195 Å observations (Figures 1A-1G). In Fe XII 195 Å, the filament appeared as a dark linear feature. Just as in arch-filament systems, the darkness is due to absorption by hydrogen and helium continua in the cool filament plasma (Mein *et al.* 2001). The H_α -1.3 Å data started at 18:02:26 (within 1 min of the initial activation), after which we had continuous coverage at 40 ms cadence. After 18:06:30, the filament moved beyond the field of view of the H_α blue wing observations. For the purposes of this paper, we selected corresponding H_α blue wing images (c, d1-d3, e, and f in Fig. 1), which are displayed on the upper panel of Figure 1. The H_α blue wing images clearly show radial (upward) motions of the filament. In Figure 1, all images are overlaid with 40-s RHESSI maps in the energy range of $12 - 25$ keV.

The beginning of activity was marked by a brightening at a footpoint shown in Fe XII 195 Å images at a time between 18:00:47 - 18:00:56 (Fig. 1A). The brightening was accompanied by co-spatial HXR emissions. But, the first corresponding brightening in H_α blue wing was at 18:03:20, about 148 s later. The much delayed response in H_α blue wing suggests heating by thermal conduction, rather than by electron beams.

During the time interval 18:00-18:04 there were three HXR sources: two 'footpoint' sources and one weaker 'looptop' source above the filament. The footpoint sources coincide to within $\sim 2''$ with EUV brightenings, although the southern one appeared $\sim$ 60 seconds before the northern one, probably due to asymmetries in the magnetic geometry. 'Looptop' sources were observed several times by the Yohkoh/HXT imager, and there is a consensus that they indicate that the flare energy release, probably magnetic reconnection, takes place above the flare arcade (Masuda 2002).

The looptop HXR source was relatively weak at the beginning of the event and (from rough 15-s maps) reached its maximum value between 18:01:45 and 18:02:15 (Fig. 1C/1c), after which it faded, disappearing after 18:02:30. At this time the RHESSI attenuators (A_1) switched into operation, giving a $\sim$ 2-min interval in which maps could not be made.

During the lifetime of the looptop HXR source it was stationary to a few arcseconds, while the filament rose toward it. Then when the filament reached the location of the (faded) HXR source at 18:03:46, the H_α blue-wing filament appeared to rupture around the site of the HXR source (d1-d3 in Fig. 1). This rupture in H_α was followed by the appearance two bright EUV "sheaths" at 18:04:32 (Fig. 1E) which flew away laterally from the filament. (We know of no similar report of this kind of phenomenon in the literature.)

The most significant characteristic of this behavior is that the HXR, H_α blue wing, and Fe XII 195 Å emissions all showed compact activity in sequence at the same location. A simplified picture is shown in Figures 2a-2d, where the looptop HXR source, the site of the H_α blue wing rupture, and the centroid of the Fe XII 195 Å brightenings appear to be co-spatial, even though they occurred at different times. This site of energy release was stationary during the period from 18:02:14 to 18:04:40 while the filament was rising. The site may be a magnetic singular point, perhaps a Y-type point below a current sheet, or a reconnection site where the magnetic field opened, letting the filament move upward. In any case, the release of energy seen in X-rays and EUV indicates that reconnection must have occurred above the filament.

From movies in both H_α blue-wing images and TRACE 195 Å images, it is obvious that the two flare ribbons do not move apart, i.e., the ribbons also remain stationary. It is possible that the lack of relative motion is due to the closeness of the ribbons to the limb. But if the lack of motion is real, this is contrary to the classical flare picture, in which flare ribbons separate laterally and/or longitudinally (Kopp & Pneuman 1976).

Figure 3 shows a plot obtained from TRACE 195 Å images of the projected height of the filament (measured by starting from a line connecting the two footpoints), velocity and acceleration as a function of time. For the height-time curve, we use the fitting functions: $H(t) = H_{01}/(1 - e^{\eta t^{-1.8}})$ for 18:00 to 18:05 and $H(t) = H_{02}(1 - 0.2625e^{-\xi(t-t_0)})$ for 18:06 (t_0) to 18:11, where H_{01}, H_{02}, η, and ξ are fitting parameters. The results of the fitting are shown by solid lines in Figure 3. From the height-fitting functions, we derived velocity functions, which are plotted by dashed lines in Figure 3. It can be seen that the filament began to erupt at about 18:01:00, which was nearly simultaneous with the initial Fe XII 195 Å brightening time. The most interesting feature of the velocity-time curve is that it decreases very rapidly in the deceleration phase. An acceleration curve (dotted line) is drawn to show this. From the acceleration curve, the maximum deceleration is about 10 times greater than the solar gravitational constant ($g = 2.74 \times 10^4$ cm s^{-2}). In our view, the rapid deceleration can only mean that the filament was pulled back by an inward magnetic tension force.

During the deceleration phase, the RHESSI hard X-rays showed a 'loop' structure which was brightest around 18:06:32 (Fig. 1F/1f). This feature appears as two legs at energies below 20 keV, and as a continuous loop in the 20-50 keV range. After this source faded, a post-flare loop appeared in Fe XII 195 Å (Fig. 1G) slightly lower than the HXR loop (by $\sim 5''$) s consistent with normal post-flare behavior, where opened magnetic loops close down progressively to lower heights.

As for the initial motion of the filament, it rose at one end while the another end remained rooted in the chromosphere (Fig. 1A-1D). This is a common characteristic of erupting filaments. Eruptions similar in this respect have been observed and analyzed previously (Kurokawa *et al.* 1987).

4. DISCUSSION

For the first time at BBSO (and probably anywhere), we have recorded a set of hi-cadence H_α blue wing data for a filament eruption event. The filament 'rupturing' lasted about 40 seconds and would be missed by normal low-cadence mode observations. In combination with RHESSI and TRACE observations, it provides evidence for release of energy above the initial filament position. This suggests the importance of hi-cadence observations for solar campaigns. Many so-called filament ejections, 'sudden disappearance' or 'disparition brusque' events might be interpreted differently with high-cadence observations.

In summary, our joint observations have shown that energy release and reconnection may occur above a filament during its acceleration phase. Further, it appears that in this 'failed' eruption, the high ($> 8 \times 10^4$ km) overlying coronal magnetic field remained closed.

This may well be a rare event. It does not look like the canonical CSHKP flare where the ribbons move apart and the reconnection point moves upward behind the filament. In the event presented here, the observed site of 'looptop' energy release appears to have been stationary to a few arcseconds during its ~ 2 minute duration and it was located above the initial filament position. The spatial coincidence of the EUV 'sheath' brightenings with the looptop source indicate that in all likelihood, the filament moved out along a current sheet estending above the looptop source. The filament eruption is also not the canonical type in which the eruption continues onward and upward into the corona.

Most models of filament eruption locate the reconnection site below the filament. Few, if any, models predict significant energy release above the filament, and few predict 'failure' of the ejection. Possible routes to an explanation of this event may, conceivably, be found in the exploration of the parameter space of topological magnetic 'skeletons' outlined by Priest and Forbes (2002). If a simple 'skeleton' is found with a finite-length, near-vertical current sheet, it might lead to an explanation for the observed energy release above the filament and the finite extent of the eruptive motion.

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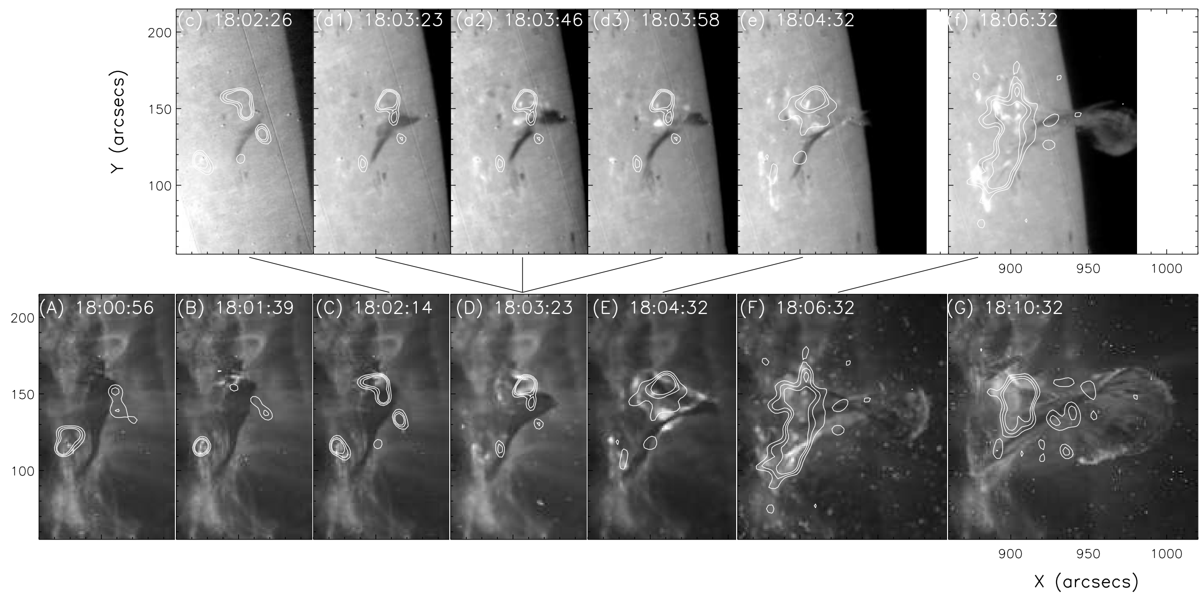

Fig. 1.— Lower panel: (A-G) TRACE Fe XII 195 Å images showing the eruption processes. Upper panel (c, d1-d3, and e-f): corresponding H_α blue wing images with TRACE Fe XII 195 Å. The contours are from 40-s RHESSI maps in the energy range of $12 - 25$ keV. The levels for the contours are 30%, 40%, and 50% of each maximum value. The RHESSI maps for d2 and d3 are same as that for d1, since 18:03:46 and 18:03:58 are too near the 2-minute RHESSI attenuator switching interval (during which mapping is impossible), to permit 40-s integration time.

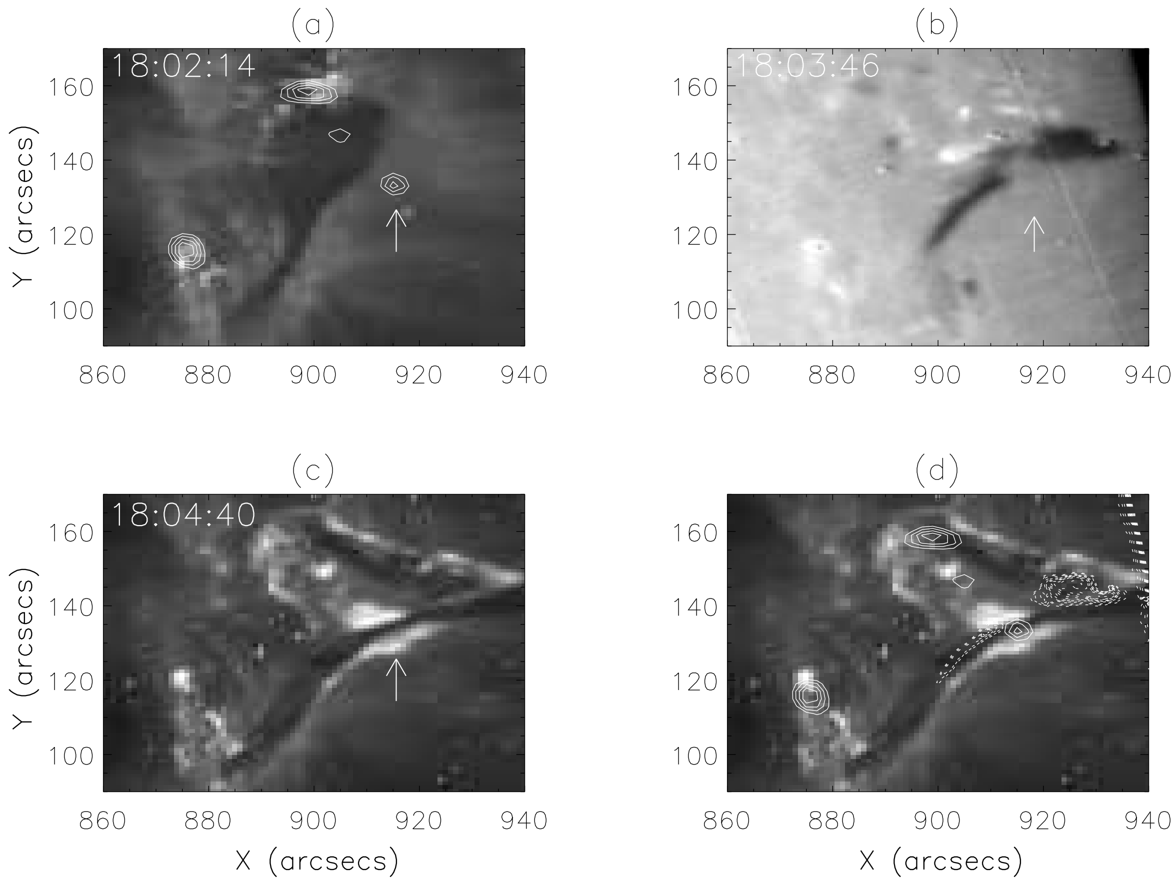

Fig. 2.— (a-c) Cospatial looptop hard X-ray source, 'rupturing' shown in H_α blue wing, and Fe XII 195 Å brightening sheaths at different times show energy release and suggest an above-filament reconnection. The levels for the HXR contours are 60%, 70%, 80%, and 90% of the maximum value. (d) Dashed contours: H_α blue wing filament at 18:03:46; solid contours: HXR emissions at 18:02:14; background: Fe XII 195 Å filament at 18:04:40.

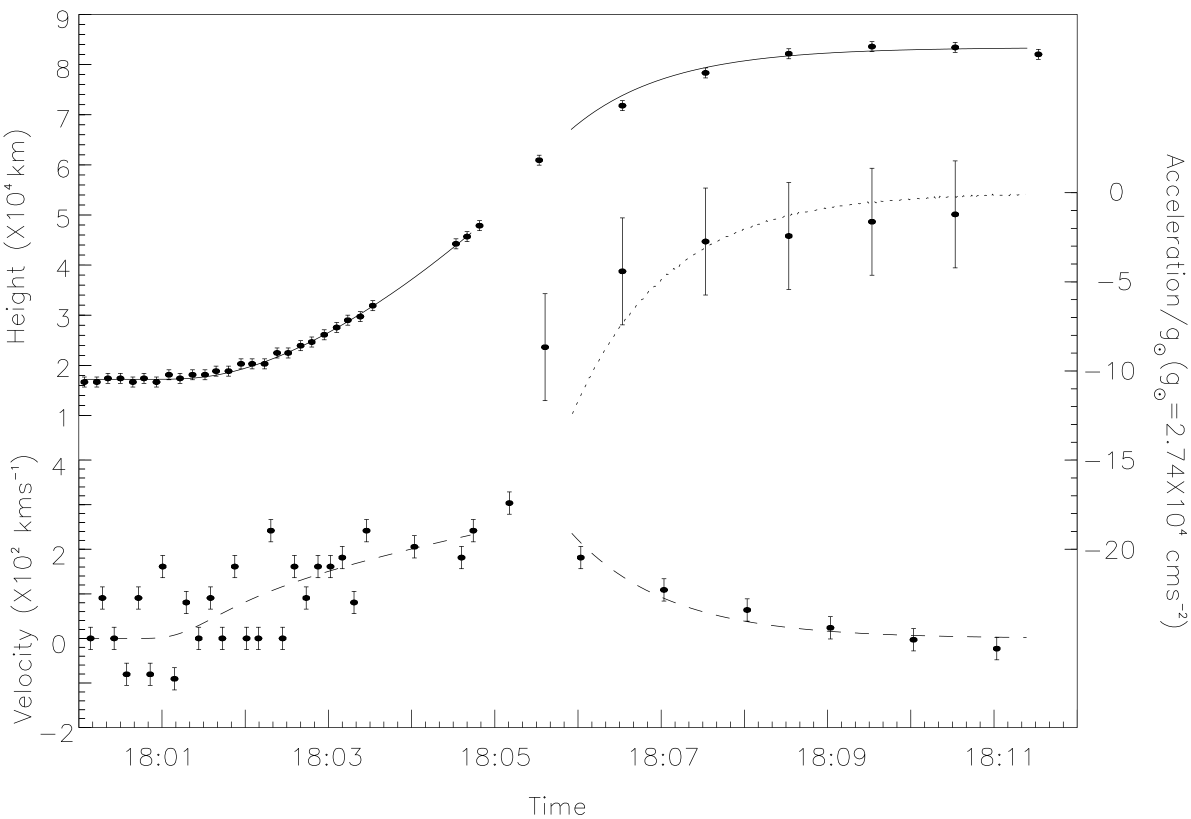

Fig. 3.— (1) Solid lines show the fitted height-time curve (see text). The points with small error bars are for the measured values of projected height. (2) Dashed lines show the velocity-time curve derived from fitted height-time curve. The points with medium-sized error bars are the measured values. (3) In similar fashion, the dotted line is the acceleration curve, also derived from function fitted to the height-time curve and the points with large error bars are the measured values.