RHESSI AND TRACE OBSERVATIONS OF MULTIPLE FLARE ACTIVITY IN AR 10656 AND ASSOCIATED FILAMENT ERUPTION

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ABSTRACT

We present Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and Transition Region and Coronal Explorer (TRACE) observations of multiple flare activity that occurred in the NOAA active region 10656 over a period of 2 hr on 2004 August 18. Out of four successive flares, three were class C events, and the final event was a major X1.8 solar eruptive flare. The activities during the pre-eruption phase, i.e., before the X1.8 flare, are characterized by three localized episodes of energy release occurring in the vicinity of a filament that produces intense heating along with non-thermal emission. A few minutes before the eruption, the filament undergoes an activation phase during which it slowly rises with a speed of \( \sim 12 \text{ km s}^{-1} \). The filament eruption is accompanied by an X1.8 flare, during which multiple hard X-ray (HXR) bursts are observed up to 100–300 keV energies. We observe a bright and elongated coronal structure simultaneously in E(UV) and 50–100 keV HXR images underneath the expanding filament during the period of HXR bursts, which provides strong evidence for ongoing magnetic reconnection. This phase is accompanied by very high plasma temperatures of \( \sim 31 \text{ MK} \), followed by the detachment of the prominence from the solar source region. From the location, timing, strength, and spectrum of HXR emission, we conclude that the prominence eruption is driven by the distinct events of magnetic reconnection occurring in the current sheet below the erupting prominence. These multi-wavelength observations also suggest that the localized magnetic reconnections associated with different evolutionary stages of the filament in the pre-eruption phase play an important role in destabilizing the active-region filament through the tether-cutting process, leading to large-scale eruption and X-class flare.

Key words: Sun: corona – Sun: flares – Sun: X-rays, gamma rays

Online-only material: color figures

1. INTRODUCTION

Solar eruptive phenomena correspond to various transient activities observed in the solar atmosphere in the form of flares, prominence eruptions, and coronal mass ejections (CMEs). It is widely accepted that the fundamental processes responsible for these phenomena are closely related and of magnetic origin (Priest & Forbes 2002; Lin et al. 2003). There is also a near-universal consensus that magnetic reconnection is an essential aspect of the eruption and energy release processes. Investigation of the origin and propagation of solar eruptions is essential to further our understanding of the Sun–Earth connection.

Prominences, or, equivalently, filaments, are relatively cool, dense objects of chromospheric material suspended in the hotter corona by magnetic fields. When these structures erupt, both filament material and magnetic fields expel together. Decades of observations reveal that filament eruptions are often associated with and physically related to CMEs and flares. Therefore, the study of prominence activity not only forms a very interesting topic of research in itself, but also offers an opportunity to understand the physics of flares and CMEs. Filaments are commonly classified into two categories: active region and quiescent (Tandberg-Hanssen 1974, 1995; Tang 1987). Active-region filaments are low-lying and rapidly evolving structures, forming in the newly emerged magnetic fields of an active region. They do not protrude much over the solar limb. On the other hand, quiescent prominences are generally associated with the decaying phase of an active region and are long lived. They tend to be located high in the corona. Sometimes the activation and eruption phases of filaments are associated with flaring activity. In such cases, the location, timing, and strength of the X-ray emission provide important clues about crucial physical processes, such as the site of magnetic reconnection, particle acceleration, heating, etc. (Ding et al. 2003; Ji et al. 2003; Moon et al. 2004; Alexander et al. 2006; Liu & Alexander 2009; Liu et al. 2009; Vemareddy et al. 2012).

Examination of subtle activity near the filament and morphological changes within the filament during the pre-eruption phase has been considered very important to the investigation of the physical conditions of the solar atmosphere that lead to rapid energy release and large-scale eruption (e.g., Fárník et al. 2003; Chifor et al. 2007; Joshi et al. 2011). However, due to the limited sensitivity of the detector, a detailed X-ray imaging analysis is often not possible to obtain during this phase of mild energy release. We still do not have a clear idea about the association between short-lived magnetic reconnection events that occur in the pre-eruption phase and the main flare that involves large-scale magnetic reorganization. In this regard, it is very important to explore the pre-flare phase in order to determine the location/height of the reconnection sites as well as the non-thermal characteristics of energy release. The two representative solar eruption models—tether-cutting and breakout—exploit the role of the initial magnetic reconnection in two different ways in order to set up conditions favorable for the core fields to erupt. The tether-cutting model is fundamentally based on a single, highly sheared magnetic bipole, with the earliest reconnection occurring deep in the sheared core region (Moore et al. 2001). On the other hand, in the breakout model the fundamental topology of the erupting system is multi-polar.
Figure 1. SXR flux from the Sun observed by the GOES satellite in the 0.5–4 and 1–8 Å wavelength bands with a time cadence of 3 s between 16:00 and 19:00 UT.

In this paper, we present a comprehensive multi-wavelength analysis of multiple flare activity that occurred in NOAA AR 10656 on 2004 August 18. In total, we present observations of four successive flares. Out of these, three events are of class C, which occurred before the main eruption in the vicinity of a filament, while the final X-class flare is associated with the filament eruption. The objective of this study is to understand the role of magnetic reconnection during various stages of the eruption. We also focus on the important morphological changes in the filament prior to the eruption. From this study, we expect to refine our knowledge of the triggering mechanism of solar eruptions. This investigation utilizes an excellent set of high-resolution measurements from two unprecedented missions: Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) and Transition Region and Coronal Explorer (TRACE). In Section 2, we present multi-wavelength data analysis including X-ray spectroscopy. We discuss and interpret our observations in Section 3. In Section 4, we summarize the conclusions of the present study.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Pre-eruption Events and Eruptive X-class Flare

In Figure 1, we show the soft X-ray (SXR) flux from the Sun observed by the Geostationary Operational Environmental Satellite (GOES) satellite in the 0.5–4 and 1–8 Å wavelength bands between 16:00 and 19:00 UT on 2004 August 18. From this light curve, one can clearly distinguish two phases of the flux evolution. The first phase extends from 16:00 to 17:30 UT and is characterized by a gradual rise and fall of the GOES flux. We note that three impulsive sub-peaks are superimposed on the gradually varying SXR flux during this phase at 16:14:30, 16:25:00, and 16:45:39 UT, indicated in Figure 1 by vertical dashed lines. A careful examination of the GOES flux with EUV images taken from TRACE (details in Section 2.4) reveals that these sub-peaks represent localized events of energy release in the vicinity of a filament. Further, we note that these three sub-peaks are more pronounced in the high energy channel of GOES (i.e., 0.5–4 Å band) with the second one as the most impulsive. Hereafter, these sub-peaks are called pre-events I, II, and III as they correspond to the energy release prior to the eruption. The second phase corresponds to a major eruptive flare of class X1.8 between 17:30 and 19:00 UT during which the filament erupts as part of a CME. The multi-wavelength data set, analyzed in the following sections, suggests a link between the sequence of activities during the pre-eruption phase and subsequent large-scale eruption observed in the form of an X-class flare–CME event. The initiation and evolution of the associated CME are presented in Cho et al. (2009).

2.2. Structure of the Active Region

On 2004 August 18, NOAA AR 10656 was very close to the west limb of the Sun, with a mean position at S14W90. The white light images taken from the Solar and Heliospheric Observatory/Michelson Doppler Imager (SOHO/MDI) indicate that, at the time of the events, the leading part of the active region was behind the solar limb. Therefore, to get a better understanding of the magnetic configuration of the activity site, we present a white light image and a magnetogram taken by SOHO/MDI two days before the reported event in Figures 2(a) and (b). We note that the active region had a complex $\beta\gamma\delta$ magnetic configuration with sunspot clusters of negative and positive polarities as the leading and trailing sunspot groups,
Figure 2. SOHO/MDI observations of NOAA AR 10656. Since the active region was very close to the solar limb at the time of activity, we show a white light image and magnetogram taken two days prior to the event in panels (a) and (b), respectively. Close inspection of the region of interest (enclosed by a box) indicates a complicated magnetic polarity distribution on the surface. An estimate of the magnetic polarity inversion line is shown by the dotted line. The active region on the day of the events under study is shown in panel (c) and the activity site is marked by an arrow.

(A color version of this figure is available in the online journal.)

Figure 3. RHESSI time profiles of the pre-eruption events with a time cadence of 4 s. The cross-hatched region indicates the time intervals during which RHESSI observations are contaminated by a particle event. In order to present different RHESSI light curves with clarity, the RHESSI count rates are scaled by factors of 1/80, 1/5, and 1 for the energy bands 6–12, 12–25, and 25–50 keV, respectively. The gray shaded areas denote the time intervals, in which the X-ray spectra were computed as shown in Figure 11.

respectively. The region of interest lies in the trailing part of the active region (marked by a box in Figures 2(a) and (b)). We find that the active region is spatially complex. However, it is also apparent that the activity site does not exhibit a lot of mixing of polarities, so a simple polarity inversion line (PIL) can be defined (indicated in Figure 2(b) by the red dotted line). The events occurred near the PIL, and the activity site is marked by an arrow in Figure 2(c). The TRACE EUV images clearly show that a filament structure exists along the PIL (see Section 2.4). From these longitudinal magnetograms, we conclude that the flaring region is mainly associated with a bipolar distribution of magnetic fields at the photosphere.

2.3. RHESSI X-Ray Light Curves

RHESSI (Lin et al. 2002) observations of the pre-eruption phase are available from 16:00 to 16:40 UT (Figure 3). The light curves in different energy bands (viz. 6–12, 12–25, and 25–50 keV) are constructed by taking average count rates from front detectors 1, 3–6, 8, and 9 in each energy band. We note that the RHESSI count rates between 16:10 and 16:20 UT are contaminated by a particle event (i.e., the RHESSI detectors were hit by high-energy particles trapped in Earth’s radiation belts). This interval covers only the first sub-peak of the GOES profile, during which the level of SXR flux was relatively low.
The second sub-peak, which is the most impulsive one, was nicely covered by RHESSI up to the 25–50 keV energy band. The third flare was partially observed by RHESSI between 16:35 and 16:40 UT as the spacecraft entered in the South Atlantic Anomaly. In Figure 4, we present RHESSI and GOES X-ray light curves during the eruptive X1.8 flare. The examination of GOES profiles clearly indicates that the flare emission is associated with two distinct phases (marked in Figure 4 as Phases I and II). The first phase is characterized by a rapid rise and a gradual decline of SXR flux between 17:30:00 and 17:33:30 UT. The flux further enhances after 17:33:30 UT and maximizes at ~17:40 UT which marks the overall maximum of the event. It is noteworthy that the first phase is associated with intense and prolonged high energy emission up to 100–300 keV. On the other hand, hard X-ray (HXR) emission during the second phase occurred in the form of three distinct HXR bursts, which are clearly identified in all the HXR channels above 25 keV.

2.4. (E)UV and X-Ray Imaging

The TRACE telescope has a field of view of 8.5 × 8.5 and a spatial resolution of 1 Jake (0.5 pixel⁻¹). During the period of the reported events, TRACE was monitoring the active region mostly with its EUV channel at 195 Å. However, during the filament eruption, TRACE also provided a few UV images at 1600 Å wavelength. The TRACE 195 Å filter is mainly sensitive to plasmas at a temperature around 1.5 MK (Fe xii), but during flares it may also contain significant contributions of plasmas at temperatures around 15–20 MK (due to an Fe xxiv line; Handy et al. 1999). The TRACE 1600 Å channel is sensitive to plasma at temperatures between (4–10)×10³ K and represents a combination of UV continuum, C i, and Fe II lines (Handy et al. 1999). The brightest and most rapidly varying features in the TRACE 1600 Å channel are likely to emit in the C iv lines as well (Handy et al. 1998).

To reconstruct RHESSI images, we have primarily used the CLEAN algorithm (Hurford et al. 2002). During the X1.8 flare, we also present X-ray images reconstructed by the computationally expensive PIXON algorithm (Metcalfe et al. 1996) to show precisely the location of X-ray emission during some of the crucial stages of the eruption. The PIXON algorithm provides more accurate image photometry than the CLEAN algorithm and is considered the best method to image extended sources in the presence of compact sources (Aschwanden et al. 2004). The images are reconstructed by selecting front detector segments 3–8 (excluding 7) with 20 s integration time.

Our analysis includes the identification of the spatial distribution of the X-ray emission derived from RHESSI measurements with respect to the filament evolution observed in E(UV) wavelengths from TRACE. However, pointing information from TRACE is often not good enough to obtain a precise co-alignment between TRACE and RHESSI images. For a full disk imager (such as SOHO/EIT), the solar limb provides a reference that helps in accurate determination of the absolute pointing of the telescope. Moreover, thermal bending of the TRACE guide telescope also leads to an unknown variation in the pointing of at least a few arcseconds (Fletcher et al. 2001; Alexander et al. 2006). In order to correct the TRACE pointing, we have co-aligned near-simultaneous TRACE and SOHO/EIT images observed at the same wavelength (i.e., 195 Å) using the method of Gallagher et al. (2002).

2.4.1. Pre-eruption Events

The availability of TRACE 195 Å images at high time cadence (~30 s) during most of the pre-eruption phase (16:00 and 17:22 UT) enables us to examine the minute changes in the activity site. In Figure 6, we present a few representative TRACE images do not appear very prominently (see, e.g., Liu et al. 2009; BaK-Stešlicka et al. 2011). We found that the TRACE pointing was offset by 2.7 ± 0.2 in the X direction and 6.8 ± 0.3 in the Y direction (see Figure 5).
the active region was relatively quiet (see Figure 6(a)). We find that a bright system of loops existed in the northern part of the active region, while its southern part lacked such coronal structures. Also, it is noteworthy that the active region did not exhibit very large, complex overlying field lines in EUV images despite its extended structure. This indicates a relatively simplified coronal structure in the active region.

After $\sim 16:07$ UT, an intense brightening occurred at the southern side of the loop system (see Figure 6(b)), marking the onset of the first event of the pre-eruption phase (or “pre-event I”). The brightening was observed until 16:22 UT with the maximum SXR intensity up to C2.2 at 16:14:30 UT. The flaring area grew rapidly and intense emission was produced at the looptop. At $\sim 16:12$ UT, a blob-like structure (i.e., plasmoid) was formed at the looptop, which became detached from the flaring loops (plasmoid is marked by arrows in Figures 6(b)–(d)). The plasmoid showed an upward motion that can be clearly seen in Figures 6(f)–(h)). We also note that the event occurred at the southern side of the filament, and part of it is cospatial with pre-event I. Compared to the two events described earlier, this event presented a very different morphological evolution. Initially (i.e., at $\sim 16:35$), a single low-lying loop system brightened up and expanded. This was followed by the brightening of another adjacent small loop system at the southern side of existing flaring loops (marked by arrows in Figures 6(i)–(n)). The coupled structure of two loop systems was visible up to $\sim 16:57$ UT. These EUV observations are consistent with the GOES profile that displayed a broad maximum phase followed by a gradual decline. RHESSI partially observed this phase up to $\sim 16:40$ UT. We find that X-ray sources are observed in $\lesssim 25$ keV energy bands from $\sim 16:36$ UT onward. The X-ray emission sources are spatially correlated with the flaring loops observed in EUV images (see Figure 6(k)).

In Figure 7, we show the evolution of X-ray sources in different energy bands during pre-events II and III. As discussed in Sections 2.1 and 2.3, pre-event II was very impulsive. It is noteworthy that the X-ray sources are compact in all the energy bands (i.e., 6–12 keV, 12–25 keV, and 25–50 keV) throughout this event (see the first and second rows of Figure 7). Due to the compactness of the flaring region as well as proximity to the limb (see also Figures 6(g)–(i)), it is hard to resolve the emission sources corresponding to the looptop and footpoint regions. However, in the decay phase (see Figures 7(e) and (f)), when the high-energy XHR source vanishes, we can recognize distinct looptop emission in the form of upward moving 6–12 keV and 12–25 keV sources. In Figures 7(g)–(l), we present RHESSI X-ray images in the 6–12 keV and 12–25 keV energy bands in the early phase of pre-event III. In the beginning, the source structure in both energy bands is broad. Especially from the 12 to 25 keV energy band images (see Figure 7(g)), we can clearly see an extended source with two centroids that likely represent emission from the looptop and footpoint locations. The extended source structure also indicates the presence of a larger volume of hot plasma and is consistent with the structure of the flaring region observed in EUV images. In the later stages, both X-ray sources move upward with the high energy source (12–25 keV) always located at higher altitudes in comparison to the low energy source (6–12 keV).

2.4.2. Activation of the Filament

After the pre-eruption events, the filament undergoes a very important stage of morphological evolution. This phase was observed between 17:05 and 17:19 UT, i.e., just after pre-event III (indicated by the gray shaded region in Figure 1). We present a sequence of TRACE 195 Å images in order to show a closer and clearer view of the filament activation in Figure 8. The growth of the filament is shown by placing a cross (“×”) at the top of the rising filament. From a linear fit to height–time data, we estimate the speed of the rising filament as $\sim 12$ km s$^{-1}$. After $\sim 17:11$ UT, we observe a localized brightening (indicated by arrows in Figures 8(j)–(n)) located at the top of a twisted flux rope, but below the apex of the filament. This brightening grows in successive images. We note another localized brightening below the rising filament at $\sim 17:18$ UT (indicated by another
Figure 6. Sequence of TRACE 195 Å images showing three successive flares during the pre-eruption phase (i.e., pre-events I, II, and III) corresponding to the three sub-peaks indicated in the GOES profile (see Figure 1). Note the intense brightening at the looptop (panel (b)) and the formation and ejection of the plasmoid (marked by arrows in panels (b)-(d)), which is accompanied by pre-event I (panel (e)). Following pre-event I, the filament rises (indicated in panel (f) by the black arrow). During the impulsive pre-event II, HXR sources of up to 40–60 keV could be reconstructed (panels (g)-(i)). Pre-event III is marked by successive brightening in two low-lying loops (marked by arrows in panels (l)-(n)). RHESSI images are reconstructed with the CLEAN algorithm. The contour levels for RHESSI images are 70%, 85%, and 95% of the peak flux in each image.

(A color version of this figure is available in the online journal.)
Figure 7. Evolution of RHESSI X-ray sources during pre-events II and III in 6–12 keV (black), 12–25 keV (green), and 25–50 keV (red) energy bands. RHESSI images are reconstructed with the CLEAN algorithm. The contour levels are 60%, 80%, and 95% of the peak flux in each image. (A color version of this figure is available in the online journal.)

Due to the unavailability of TRACE observations between 17:22 and 17:34 UT, we are unable to track the later phase of filament activation. RHESSI observations during this phase are not available.

2.4.3. Filament Eruption and the X1.8 Flare

TRACE observations of the event are available after 17:34 UT, i.e., ~4 minutes after the onset of the flare (GOES start time ~17:30 UT). By this time, the eruption of the filament had already begun (see Figures 10(b) and (h)). However, RHESSI observations are available from the beginning of the event (from 17:31 UT onward). In Figure 9, we present the evolution of HXR sources in four energy bands (i.e., 12–25 keV, 25–50 keV, 50–100 keV, and 100–300 keV). We note that the HXR emission at 12–25 keV (black contours) is associated with a compact, single coronal source throughout the flare that also exhibits “standard” upward movement. The HXR sources at higher energies (>25 keV) reveal a complicated evolution. We observe the onset of very high energy HXR emissions (25–50 keV, 50–100 keV, and 100–300 keV) from the earliest stages (Figures 9(a)–(c)), which are mainly from the footpoint regions. This is followed by an important phase, during which high-energy coronal HXR sources are observed. In particular, there are instances when HXR emissions of up
Figure 8. Sequence of \textit{TRACE} 195 \AA{} images showing the activation of the filament after the pre-eruption events. The filament shows rapid evolution between 17:05 UT and 17:19 UT. This interval is marked by the gray shaded region in Figure 1. The rise of the filament is shown by placing a cross ("\times") at the top. Note the brightenings occurring below the apex of the prominence from \(\sim 17:12\) UT onward (marked by arrows in panels (j)--(n)).

(A color version of this figure is available in the online journal.)

Figure 10, we present a few representative \textit{TRACE} 1600 \AA{} (panels (a)--(f)) and 195 \AA{} (panels (g)--(l)) images. We have overplotted co-temporal \textit{RHESSI} X-ray PIXON images at the 12--25 keV and 50--100 keV energy bands in selected panels to compare the location of HXR coronal and footpoint sources with respect to the phases of the erupting filament. At the start of the \textit{TRACE} observations at 17:34 UT, we observe the expansion and stretching of a flux rope that rapidly evolves into a \(Y\)-shaped structure (see Figures 10(b) and (c)). We observe intense brightening along the leg of the erupting structure in the form of an \(E\)UV structure (see Figure 10(c)). This bright feature is also seen in the 195 \AA{} images (see Figures 10(h) and (i)). It is noteworthy that the HXR coronal sources in the 50--100 keV energy band lie over this elongated bright (E)UV structure (marked by arrow in Figures 10(c) and (h)). During 17:35--17:36 UT (see Figures 10(d) and (j)), we find the detachment of the stretched flux rope from the solar source region and its upward propagation. From the linear fit to height–time measurements of the erupting filament observed in 1600 \AA{} images, we estimate the speed of the erupting filament to be \(\sim 270\) km s\(^{-1}\). We note that during the detachment of the flux rope, HXR emission at 50--100 keV is observed from an extended source that covers the footpoint and coronal regions (see Figures 10(d) and (i)). During this phase, the \textit{RHESSI} light curves indicate three consecutive HXR bursts (see Figure 4). After the eruption, we observe a closed post-flare loop system with HXR emission from the coronal loops (see Figures 10(e), (f), (k), and (l)).

2.5. \textit{RHESSI} X-Ray Spectroscopy

We have studied the evolution of \textit{RHESSI} X-ray spectra during the pre-eruption phase as well as the eruptive X1.8 flare. We first generated a \textit{RHESSI} spectrogram with an energy
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**Figure 9.** Evolution of RHESSI X-ray sources during the eruptive X1.8 flare (see Figure 1) in 12–25 keV (black), 25–50 keV (green), 50–100 keV (blue), and 100–300 keV (red) energy bands. RHESSI images are reconstructed with the CLEAN algorithm. The contour levels are 55%, 70%, 85%, and 95% of the peak flux in each image.

(A color version of this figure is available in the online journal.)

We computed spatially integrated, background subtracted RHESSI spectra accumulated for 20 s of integration time during pre-events II and III (this time interval is indicated by gray strips in Figure 3). A few representative spectra during this interval are shown in Figures 11(a)–(f). We find that during pre-event II, the X-ray emission exhibited a very fast spectral evolution, with the peak HXR emission between 16:23 and 16:24 UT. Due to fast spectral evolution of the flare, we decided to select the maximum energy value for fitting by comparing the flux during the flare with that of the background level for each time interval. This can be easily achieved by selecting the fitting option Auto-Set-Max in the OSPEX software. The maximum value of energy used for fitting is indicated by a dashed line in each spectrum shown in Figures 11(a)–(c). The lower energy value selected for fitting was 6 keV. In Figures 11(d)–(f), we show a few representative RHESSI spectra derived during the early part of pre-event III. The spectra were fitted in the energy range of 6–30 keV. In Figures 11(g)–(i), we show a few representative RHESSI spectra derived during the X1.8 flare. The spectra were fitted in the energy range of 6–150 keV. Time evolution of various spectral parameters (temperature ($T$), emission measure ($\text{EM}$),
3. RESULTS AND DISCUSSION

We present a multi-wavelength study of four successive flares that occurred in NOAA AR 10656 on 2004 August 18 over a period of 2 hr. Three class C flares occurred before the eruption, and the last event was a major X1.8 eruptive flare. The pre-eruption events occurred in the vicinity of the filament and were localized in nature. The filament became unstable and eventually erupted, producing an X-class flare. Table 1 presents an observational summary of flare activity and associated phenomena. We discuss the multiple flare activity in terms of two evolutionary stages.

3.1. Pre-eruption Phase

The pre-eruption phase is characterized by three localized flares (i.e., pre-events I, II, and III) along with the heating, activation, and rise of the filament. Pre-event I exhibited intense brightening of a low-lying loop system observed within a very confined volume (see Figures 6(b)–(e)). However, this

and power-law index ($\gamma$) obtained from fits to the RHESSI spectra, integrated over consecutive 12 s intervals, is shown in Figure 12.
Figure 11. RHESSI X-ray spectra derived during various time intervals covering the pre-eruption events II and III (first and second rows, respectively) and the X1.8 eruptive flare (last row), together with applied fits. The spectra were fitted with an isothermal model (dash-dotted line) and a functional power law with a turnover at low energies (dashed line). The gray (solid) line indicates the sum of the two components. The maximum energy used for fitting each spectrum during pre-event II is denoted by a vertical dashed line (top row only).

Small flare is remarkable in that it was associated with a plasmoid ejection. The formation of the plasmoid at the top of the flare loops and its upward motion are readily visible from EUV images. Another significant observation is the presence of the 10–15 keV HXR LT source at the flare maximum, indicating intense plasma heating. The upward-moving blob of hot plasma along with the HXR LT source provides evidence for the magnetic reconnection. It is likely that the ejection of plasma and magnetic fields, observed as a plasmoid, is caused by weaker overlying magnetic fields and lower density above the flare loops. Plasmoid ejection is believed to be a consequence of magnetic reconnection. We emphasize that the
rise of the filament began after this small flare, which occurred at its southern leg, suggesting a causal relation between the flare event and filament rise. It is likely that the magnetic reconnection caused a weakening of overlying field lines, making the expansion of the filament possible.

Pre-event II corresponds to the very rapid variation of the GOES flux that lasted for only $\sim 7$ minutes. This highly impulsive and compact event took place at the northern leg of the filament (see Figures 6(g)–(i)). Despite the impulsiveness of the event, we clearly identified that the peak of the HXR flux ($16:23:50$ UT in the $25–50$ keV energy band) occurred before the thermal SXR peak ($16:25:00$ UT in GOES 1–8 Å). The timing of the peaks of the HXR and SXR fluxes suggests that high-energy HXR emission is associated with processes that are intimately linked with the primary energy release (i.e., magnetic reconnection), while the SXR flux with a delayed maximum is attributed to the thermal emission from hot flare loops. The series of cospatial EUV and X-ray images readily confirm this picture. The EUV images reveal fast expansion of a loop system within a confined yet elongated region. We note that HXR emission was clearly observed up to $60$ keV above the background level. It is noteworthy that X-ray spectra during the peak timings indicate hot thermal plasma ($\sim 23$ MK) with lower emission measure values (see Figures 11(a)–(c)), indicating intense plasma heating within a confined environment (Joshi et al. 2011). At this point, the HXR spectrum reveals strong non-thermal characteristics at energies $>15$ keV with a photon spectral index of $\gamma \simeq 4$. It is remarkable that in such a short-lived and confined event, we clearly recognize a soft–hard–soft spectral evolution, providing evidence of particle acceleration (Benz 1977; Grigis & Benz 2004; Joshi et al. 2011).

Compared to the previous events, pre-event III showed a very different morphological evolution. The TRACE EUV observations suggest that this event is associated with the successive brightening of two systems of low-lying loops, which are located side by side (see Figures 6(j)–(n)). The partially available RHESSI observations indicate the emission from coronal loops along with an upward movement of the LT source (Figure 7), an important feature of the standard flare model (see, e.g., Joshi et al. 2007). RHESSI X-ray spectroscopy analysis reveals lower values of temperature and emission measure during this event compared to pre-event II (Figure 11).

During the time between events I and III, the evolution of the filament was very slow. However, we emphasize that the filament’s slow evolution in the pre-eruption phase is temporally and spatially associated with flaring activity. We observe more significant morphological changes associated with the rising filament after the pre-eruption events (Figure 8). The changes started to occur just after pre-event III and were continuously observed during the rest of the pre-eruption phase. During this interval, the filament exhibited a continuous rise with a speed of $\sim 12$ km s$^{-1}$. Before the main eruption, we find brightenings within the twisted filament channel, which is also reflected in

### Table 1

Observational Summary of Activities During the Pre-Eruption Phase and Eruptive X1.8 Flare

| Phases | GOES Interval in UT (Peak Time) | Activity | RHESSI |
|--------|--------------------------------|----------|--------|
| Pre-event I (C2.2) | 16:07–16:22 UT (16:14 UT) | Localized brightening along with plasmoid ejection at the southern leg of the filament, filament slowly rises | Contaminated by particle event, compact source in 10–15 keV |
| Pre-event II (C6.7) | 16:23–16:30 UT (16:25 UT) | Confined flare at the northern leg of the filament | HXR source up to 50–80 keV detected with significant non-thermal emission ($\gamma \simeq 4.0$) |
| Pre-event III (C7.3) | 16:35–17:05 UT (16:45 UT) | Sequential brightening in two low-lying loops followed by arcade formation | Partially observed up to $\sim 16:40$ UT, mostly thermal emission from the looptop up to $\sim 30$ keV Not available |
| Filament activation | 17:05–17:19 UT | Rise of filament along with localized brightenings | Multiple HXR bursts with strong non-thermal HXR emission, high-energy coronal HXR sources |
| Filament eruption and X1.8 flare | 17:30–19:00 UT | Filament eruption, formation of bright elongated coronal structure below the erupting prominence |

![Figure 12](image-url)
GOES observations as a small bump at $\sim$17:18 UT (Figure 1). The localized brightenings at two different locations below the apex of the prominence are likely caused by heating due to magnetic reconnection (Chifor et al. 2007). We further note that as the brightening increased, the filament appeared less structured, probably due to the change from absorption of EUV radiation to emission caused by the fast heating of plasma within the filament (Filippov & Koutchmy 2002).

3.2. Filament Eruption and the X1.8 Flare

This phase is marked by the onset of the X1.8 flare, during which the activated filament underwent a transition into the dynamic phase and erupted. This phase is characterized by a fast rise of the prominence ($\sim$270 km s$^{-1}$) and strong HXR non-thermal emission.

The evolution of the HXR flux during the X-class flare is very interesting. It displayed four distinct episodes of flux enhancement; the first peak was very broad (labeled phase I; see Figure 4) and gradual, while the other three peaks were impulsive (labeled phase II; see Figure 4). More importantly, these peaks were observed at very high energies of up to $\sim$100–300 keV. During phase I of the prolonged HXR emission (17:31 UT–17:33 UT), the X-ray emission above $\sim$20 keV followed hard power laws with a photon spectral index $\sim$3.5 (Figure 12). The spectra continued to be harder throughout this phase. The spectra increased in hardness again during the next three HXR bursts (indicated by vertical dashed lines in Figure 12). We note a very important phase of prominence eruption in EUV observations between the second and third HXR peaks (at $\sim$17:35 UT). With the rapid expansion of the prominence, intense brightening is observed in EUV images below the erupting structure (Figures 10(c) and (h)). It is remarkable that this important stage of prominence eruption is spatially and temporally associated with high-energy HXR emission in the form of an extended coronal HXR source observed in the 50–100 keV energy band. We further note that the temperature rose to very high values with a maximum value of $\sim$31 MK at $\sim$17:34 UT during the HXR bursts that occurred between 17:34 and 17:36 UT. This period of high plasma temperature matches the appearance of an elongated bright EUV structure and an extended HXR coronal source.

This stage of multiple HXR bursts concluded with the final detachment of the prominence from the solar source region, with the closed post-flare loops remaining on the solar limb. We also note that the thermal emission dominates during the decay phase with a slow rise in emission measure.

After the first HXR burst ($\sim$17:32–17:33), we observe strong HXR coronal emission at energies $\geq$25 keV (Figures 9(d)–(i)), which was detected until the late phases of the flare. Moreover, HXR images at 50–100 keV clearly indicate coronal emission between 17:35 and 17:38 UT. Such a high-energy coronal HXR emission has recently been detected in several flares by RHESSI during their different evolutionary phases (Veronig & Brown 2004; Krucker & Lin 2008; Joshi et al. 2009, 2011). However, the physical mechanism for this strong non-thermal source in the tenuous corona is still not clearly understood.

4. SUMMARY AND CONCLUSIONS

Solar eruptions are complex phenomena that involve a diversity of physical processes during their various stages. The observation of multiple flare activity from AR 10656 on 2004 August 18 provides us with a unique opportunity to understand some of the aspects of the eruption process, namely, the role of the pre-eruption magnetic reconnection, triggering mechanism, particle acceleration, and large-scale reconnection during the main phase of the eruption, which are summarized as follows.

1. Our observations imply that pre-eruption events essentially represent discrete episodes of magnetic reconnection that play an important role in filament evolution toward eruption. The evidence for localized magnetic reconnection and particle acceleration is observed in the form of plasmoid ejection, HXR emission, and soft–hard–soft evolution of the HXR spectra. The sequence of activities suggests that the localized and short-lived episodes of magnetic reconnection that occurred near the filament tend to weaken the overlying magnetic structure. It is important to note that the decrease in the overlying magnetic field is a crucial factor that permits the successful eruption of an unstable flux rope (Török et al. 2004; Török & Kliem 2005). Observations presented here reveal an early quasi-static, slowly evolving phase of the filament before the onset of the more dynamic activation phase. The activation phase of a filament associated with slow rising and heating has been recognized as an important precursor before an eruption (Sterling & Moore 2005; Liu et al. 2008; Sterling et al. 2011).

2. These observations also reveal that the initiation of the eruption is essentially linked with the EUV/X-ray emissions that originate at the lower corona and/or chromospheric heights rather than reconnection occurring in higher coronal loops above the prominence. The HXR emission also suggests that the pre-eruption reconnection occurred close to the leg of the prominence. The heating of the rising prominence during its activation phase essentially resembles the precursor phase brightenings that are generally observed from a few to tens of minutes prior to a large flare in the form of an increase in SXR and EUV emissions (Magara & Shibata 1999). From these observations, we infer that the mechanism leading to pre-eruption flares and precursor emissions caused the onset of the filament activation and eruption. Our present interpretation of the initiation of the prominence eruption is consistent with the tether-cutting mechanism (Moore & Roumeliotis 1992). The onset of the X1.8 flare marks the fast-rise phase of the filament. Sterling & Moore (2005) suggested that the transition to the fast-rise phase would occur when the lowlying reconnection that initiated the slow-rise phase inflated the overlying filament-carrying fields to the point that they became unstable and violently erupted, perhaps due to an MHD instability or runaway tether cutting.

3. The filament eruption was accompanied by an X1.8 flare. The flare was marked by four distinct HXR peaks up to 100–300 keV energies. We observed strong and prolonged non-thermal HXR emission at the flare onset, showing evidence of an extended phase of particle acceleration (see, e.g., Joshi et al. 2012 and references therein) related to the early stages of filament eruption. We therefore interpret that the initial ejection of a filament is associated with the formation of a current sheet underneath, which then reconnects to cause the subsequent eruption and non-thermal emission (see, e.g., Alexander et al. 2006). RHESSI and TRACE observations during the next three HXR bursts are consistent with this interpretation and reveal a thin, elongated, bright structure in EUV images copspatial with 50–100 keV extended coronal HXR sources. Within the scope of the standard flare model, we believe that the
extended coronal HXR emission associated with a bright, thin (E)UV structure is a direct consequence of magnetic reconnection in the current sheet formed below the erupting prominence. This is further supported by the fact that at this very interval, the temperature attained the highest value of \textasciitilde 31 MK. These three impulsive HXR bursts clearly showed soft–hard–soft spectral evolution, suggesting distinct events of particle acceleration associated with the early phase of CME initiation. The appearance of strong HXR coronal and footpoint emissions during the impulsive phase implies rapid dissipation of magnetic energy in the current sheet as a result of an increase in the rate of magnetic reconnection (see, e.g., Sui & Holman 2003).

Understanding the triggering mechanism of solar eruptions is still a challenging topic of research in contemporary solar physics. The investigation of filament evolution in the pre-eruption phase and the associated small-scale reconnection events could provide special insight into the processes that lead to the initiation of CMEs. We are in the process of analyzing suitable data with superior resolution observed at several E(UV) channels from the Solar Dynamics Observatory to learn about the multiple stages of the eruptive phenomena more precisely. Probing the thermal and non-thermal characteristics of the relatively mild X-ray emissions during the pre-eruption phase is very crucial for such studies. We hope that the observation of the proposed Solar Low-energy X-ray Spectrometer (SoLEXS) experiment (Sankarasubramanian et al. 2011) with a very high spectral resolution will be useful in understanding the small-scale pre-flare activity.

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