PRE-FLARE ACTIVITY AND MAGNETIC RECONNECTION DURING THE EVOLUTIONARY STAGES OF ENERGY RELEASE IN A SOLAR ERUPTIVE FLARE

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ABSTRACT

In this paper, we present a multi-wavelength analysis of an eruptive white-light M3.2 flare that occurred in active region NOAA 10486 on 2003 November 1. The excellent set of high-resolution observations made by RHESSI and the TRACE provides clear evidence of significant pre-flare activities for ~9 minutes in the form of an initiation phase observed at EUV/UV wavelengths followed by an X-ray precursor phase. During the initiation phase, we observed localized brightenings in the highly sheared core region close to the filament and interactions among short EUV loops overlying the filament, which led to the opening of magnetic field lines. The X-ray precursor phase is manifested in RHESSI measurements below ~30 keV and coincided with the beginning of flux emergence at the flaring location along with early signatures of the eruption. The RHESSI observations reveal that both plasma heating and electron acceleration occurred during the precursor phase. The main flare is consistent with the standard flare model. However, after the impulsive phase, an intense hard X-ray (HXR) looptop source was observed without significant footpoint emission. More intriguingly, for a brief period, the looptop source exhibited strong HXR emission with energies up to ~50–100 keV and significant non-thermal characteristics. The present study indicates a causal relation between the activities in the pre-flare and the main flare. We also conclude that pre-flare activities, occurring in the form of subtle magnetic reorganization along with localized magnetic reconnection, played a crucial role in destabilizing the active region filament, leading to a solar eruptive flare and associated large-scale phenomena.

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

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1. INTRODUCTION

Solar eruptive phenomena correspond to various kinds of transient magnetic activities occurring in the solar atmosphere in the form of flares, eruptive prominences, and coronal mass ejections. With the availability of multi-wavelength data, especially from space-based platforms, it has become apparent that these are different manifestations of a single physical process implicating the disruption of coronal magnetic fields (see, e.g., Lin et al. 2003a). There is also a near-universal consensus that magnetic reconnection plays a key role in the process of disruption of magnetic fields, as well as dissipation of stored magnetic energy in the corona (Lakhina 2000; Priest & Forbes 2002).

Flares mostly occur in a closed magnetic field configuration associated with active regions. Such closed magnetic structures may embrace one or more neutral lines in the photospheric magnetic flux. In a simplistic model, we can imagine the structure of a bipolar magnetic configuration in terms of an inner region, called the core field, and the outer region, called the envelope field (Moore et al. 2001). The core fields are rooted close to the neutral line while the envelope fields are rooted away from it. Before an eruption, the core fields can usually be traced by a dark filament in the chromosphere when viewed on the solar disk. The core fields are usually strongly non-potential in the pre-flare phase. In the initial stages of a large eruptive flare, the core fields containing the prominence erupt, stretching out the envelope fields. With the evolution of the eruption process, the stretched field lines reclose via magnetic reconnection beneath the erupting filament. Multi-wavelength observations of solar eruptive flares have revealed several key features of the eruption process: a rising arcade of intense (newly formed) soft X-ray (SXR) loops, hard X-ray (HXR) and Hα emission from the feet of the newly formed loops, and an X-ray coronal source at their summit. The standard CSHKP model of solar flares has been successful in broadly incorporating these multi-wavelength flare components (for a review see Hudson et al. 2004; Benz 2008; Schrijver 2009).

Although the standard flare model successfully describes several observational features of a large eruptive flare, the basic question about the triggering of the eruption remains unclear and debatable. 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 the 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. Here the eruption is initiated by reconnection at a neutral point located in the corona, well above the core region (Antiochos et al. 1999). In this manner, the former is built on the concept of an “internal reconnection” while the latter is suggestive of an “external reconnection” (Sterling et al. 2001).

In order to understand the triggering mechanism of solar eruption, it is essential to examine the pre-eruption phase and probe those features that might have played a vital role in the subsequent processes leading to fast energy release and
eruption. Observations of solar flares in SXR clearly indicate an enhancement in the flux before the flare, known as the X-ray precursor phase (Tappin 1991). There is evidence of active pre-flare structures in soft X-rays cospatial with the main flare, which develops several minutes or more before the onset of the flare (Fárník et al. 1996; Fárník & Savy 1998; Kim et al. 2008).

However, we should not ignore the fact that significant pre-flare activities may be present even before the X-ray precursor phase in other, longer wavelength observations such as Hα and EUV/UV. It has been suggested that the pre-flare brightening may occur as a result of slow reconnection and provide a trigger for the subsequent eruption (Moore & Roumeliotis 1992; Chifor et al. 2007). Here, it is worth mentioning that this pre-eruption reconnection may be very different from the post-eruption coronal reconnection, which is believed to lead to a two-ribbon flare (Kim et al. 2001).

In this paper, we present a comprehensive multi-wavelength analysis of a well-observed M3.2 flare that occurred on 2003 November 1. The motivation of the present investigation is two fold: (1) to study the pre-flare activities and their relation with the eruption process, and (2) to understand the role of magnetic reconnection in the corona in the post-eruption phase. The study utilizes the excellent data sets from three space missions: RH\textit{ESSI}, TR\textit{ACE}, and SOHO. These observations were complemented by Hα and vector magnetic measurements from ground-based stations. Images of high temporal and spatial resolution at UV and EUV wavelengths coupled with 1 minute cadence \textit{SOHO} Michelson Doppler Imager (MDI) magnetograms have enabled us to look for the minute changes that took place in the pre-flare phase. RH\textit{ESSI} X-ray imaging and spectroscopic analysis was performed to understand the thermal and non-thermal characteristics of the flare emission. In Section 2, we present the data analysis and describe the multi-wavelength view of the event. In Section 3, we integrate and discuss the observations presented in the previous section. The conclusions of the present study are summarized in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Event Overview

The active region NOAA 10486 (along with 10484 and 10488) produced several powerful eruptions during the period of 2003 October–November. According to the solar region summary reports compiled by the Space Weather Prediction Center,\footnote{http://www.swpc.noaa.gov/} AR 10486 appeared between 2003 October 23 and November 5. The observations presented here correspond to the flare activity that occurred in AR 10486 on 2003 November 1 at the location S12 W60 showing GOES SXR intensity of M3.2 and Hα class of 1N.

According to \textit{GOES} reports, the flare took place between 22:26 and 22:49 UT with a peak at 22:38 UT. In Figure 1, we provide the \textit{GOES} light curves in 0.5–4 and 1–8 Å wavelength bands. Figure 2 provides multi-wavelength aspects of the active region. In Figure 2(a), we show a representative Hα filtergram obtained from the Udaipur Solar Observatory on 2003 November 1. The images shows three sunspots in the vicinity of the location where the filament erupted, which is marked by an arrow. In Figure 2(b), we show the RHESSI X-ray images overlaid by \textit{TRACE} white light (WL) images.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{RHESSI and \textit{GOES} light curves of the flare with a time cadence of 4 s and 3 s, respectively. In order to present different RHESSI light curves with clarity, the RHESSI count rates are scaled by factors of $1$, $1/4$, $1/5$, and $1/10$ for the energy bands of $6–12$, $12–25$, $25–50$, and $50–100$ keV, respectively.}
\end{figure}
Figure 2. Multi-wavelength view of the active region during pre-flare and flare timings. (a) Hα filtergram taken from USO at about \(\sim 13\) hr before the event. The filament that erupted during the flare is marked by an arrow. (b) White light observation of the active region by TRACE taken at the time of the Hα filtergram shown in panel (a). We find that the filament lies in the northwest part of the active region. (c and d) TRACE white light image and SOHO/MDI magnetogram during the impulsive phase of the flare. Red and blue contours represent co-temporal X-ray sources at 50–100 keV and 6–12 keV energy bands, respectively, and denote the region where the X-ray intensity is 60% of its peak value.

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

during the eruption process, we have analyzed the X-ray light curves and images (see Section 2.2) in four energy bands, namely, 6–12, 12–25, 25–50, and 50–100 keV. The RHESSI light curves, shown in Figure 1, are constructed by taking average count rates over front detectors 1, 3–6, 8, and 9 in each energy band. We note several important aspects of variation in X-ray fluxes that indicate important stages of the flare evolution: (1) X-ray count rates at 6–12 and 12–25 keV energy bands show a bump at \(\sim 22:26\) UT. At this time the X-ray flux at high energy bands (\(\gtrsim 25\) keV) is still at the background level. This bump indicates the precursor phase of the flare and is the most prominent in the 12–25 keV energy band. The RHESSI 12–25 keV light curve clearly describes the X-ray precursor phase between 22:24 and 22:28 UT. (2) GOES as well as RHESSI time profiles show a steady rise in the flux from \(\sim 22:28\) UT, which indicates the beginning of the flare impulsive phase. We observe a peak at \(\sim 22:30\) UT simultaneously in the three energy channels (12–25, 25–50, and 50–100 keV). This peak appears even sharper as we consider light curves of higher energy bands. This peak cannot be recognized in the GOES time profiles and RHESSI light curve in the 6–12 keV energy band. Hereafter we describe this peak as the first HXR burst. (3) The emission at high energy bands at energies \(\gtrsim 25\) keV further enhances after 22:31 UT and a second HXR burst is observed at \(\sim 22:33\) UT. (4) In low energy bands, there is a gradual rise in the count rates and the light curves peak several minutes after the second HXR burst. A third HXR burst occurred during the decline phase at \(\sim 22:39\) UT. Table 1 presents a summary of different phases of the flare evolution.

2.2. Multi-wavelength Imaging

2.2.1. X-Ray and E(UV) Observations

The RHESSI images have been reconstructed with the CLEAN algorithm with the natural weighing scheme using front detector segments 3–8 (excluding 7) in different energy bands, namely, 6–12, 12–25, 25–50, and 50–100 keV (Hurford et al. 2002). We compare RHESSI measurements with TRACE images in 195 Å and 1600 Å wavelengths. 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
Figure 3. Sequence of TRACE 195 Å images from pre-flare to post-flare stages. Panels (c) and (e)-(i) show co-temporal RHESSI X-ray images in 6–12 keV (blue), 12–25 keV (white), and 50–100 keV (red) energy bands overlaid on TRACE images. RHESSI images are reconstructed with the CLEAN algorithm using grids 3–8 and the natural weighing scheme. The integration time for RHESSI images is 30 s. The contour levels for RHESSI images are 60%, 75%, 85%, and 95% of the peak flux in each image.

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

Table 1
Summary of Different Phases of the Flare Evolution

| Phases         | Start Time–End Time (UT) | Observing Wavelength          |
|----------------|--------------------------|--------------------------------|
| Initiation phase | 22:19–22:24             | EUV and UV                     |
| Precursor phase  | 22:24–22:28              | X-ray (530 keV), EUV, and UV   |
| Impulsive Phase | 22:28–22:34              | X-ray (up to ~100 keV), EUV, and UV |
| Decay phase     | 22:34–22:49              | X-ray (up to ~100 keV), EUV, and UV |

TRACE 1600 Å channel is sensitive to plasma in the temperature range between \((4–10) \times 10^3\) K and represents a combination of UV continuum, C \(\text{iv}\), and Fe \(\text{ii}\) lines (Handy et al. 1999). Also the brightest and most rapidly varying features in the TRACE 1600 Å channel are likely to emit in the C \(\text{iv}\) lines (Handy et al. 1998).

It is known that the pointing of TRACE is not very accurate. Therefore, in order to compare RHESSI images and TRACE images, we need to correct the pointing information of TRACE images. This is achieved by considering the fact that the pointing information of RHESSI and SOHO is quite accurate. Therefore, we corrected TRACE pointing by comparing a TRACE WL image and a SOHO WL image observed at 22:23:29 and 22:23:33 UT, respectively. For the cross-correlation, we used the Solar SoftWare (SSW) routine, trace_mdi_align, developed by T. Metcalf (see also Metcalf et al. 2003).

We first describe the observations of TRACE in the 195 Å EUV channel along with co-temporal RHESSI X-ray images in Figure 3. TRACE images reveal a dark, elongated, inverted U-shaped structure that already existed in the flaring region that corresponds to the filament (this filament is marked in the H\(\alpha\) image shown in Figure 2(a)). The pre-flare 195 Å images reveal that the filament was thinner in the middle (cf. Figure 3(a)). Near the middle of the elongated filamentary structure, we observe the very first signatures of the flare in the form of brightenings at both sides of the filament material at \(\sim 22:19\) UT. It is noteworthy that this initial EUV flare brightening was observed \(\sim 4\) minutes before the start of the X-ray precursor phase. We call these
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which corresponds to the first HXR burst (cf. Figure 1). The next most prominently and intensely in the image at 22:29:58 UT, EUV structure and the two EUV kernels continued to become this time at energies below 25 keV (cf. Figure 3(c)). The arc-like Section 2.1 and Figure 1). We observe first clear X-ray sources at X-ray precursor phase (recognized during 22:24–22:28 UT; cf. Figure 5(a)). We call these the NW and SE ribbons. The most noticeable feature observed in EUV images at the early stage is the brightening at a relatively remote location (marked by an arrow in Figure 5(b)), close to the SE sunspot (cf. Figure 2), which continues during the main flare phase. This brightening cannot be seen in EUV images. We find that this near-sunspot brightening is connected to the SE flare ribbon by a less-bright, thin, elongated structure along which transient bright points appear. It is noteworthy that in the RHESSI 12–25 keV image we observe X-ray emission from this remote bright region for a short period at around 22:28 UT (cf. Figure 5(e)), which marks the beginning of the flare impulsive phase (cf. Figure 1 and Section 2.1). In UV images we observe sporadic brightening during ∼22:20–22:25 UT over a small region (at the western portion of the images) where EUV images show rapid changes in the configuration of short loops overlaying the filament. However, after ∼22:25 UT we see the formation of the arc-like structure, consistent with the flare evolution in the EUV wavelength, around the location of sporadic brightening (marked by an arrow in Figure 5(c)). From UV and EUV observations described previously, we collect several important pieces of information that clearly reveal an initiation phase of the flare between ∼22:19 and 22:24 UT, before the flare signatures in X-ray observations.

Near the first HXR burst (∼22:30 UT) we observe two strong 50–100 keV X-ray sources that lie over the two UV flare ribbons. At this time we also find that a loop-like structure evolves that connects the two UV flare ribbons. The intensity and thickness of the loop increase rapidly. We mark the loop system by an arrow in Figure 5(h). During the second HXR burst (∼22:33 UT) we again find two high-energy X-ray sources at 50–100 keV. The association of UV flare ribbons with the strong HXR sources suggests that the two HXR sources mark the conjugate FPs of a loop system. The HXR emissions from the FPs of flaring loops are traditionally viewed in terms of the thick-target bremsstrahlung process (Brown 1971) in which the X-ray production at the FPs of the loop system takes place when high-energy electrons, accelerated in the reconnection region, come along the guiding magnetic field lines and penetrate the denser transition region and chromospheric layers (cf. Kontar et al. 2010). We observe a low-energy X-ray source (below 25 keV), below the erupting arc-like structure, throughout the comparison of the two images shows several interesting new developments: the arc-like structure becomes fainter and moves toward the southwest (marked by white arrows), a new intense source develops close to the NW kernels (marked by a blue arrow), bright patches of emission are seen between the new source and the arc-like structure (marked by a yellow arrow), and a bright loop system is observed (marked by a red arrow). At the eastern part of the loop system, a group of bright points appear that are likely to represent the emission from the footpoints (FPs) of the loop system. The next image available to us is after a gap of ∼6 minutes, which shows the bright and closed system of loops having a simplified structure (compare Figure 3(i)). The brightness of the closed loop system decays slowly and the loops become more structured in the later stages.

In Figure 5, we present the UV observations of the flare taken in the TRACE 1600Å passband along with co-temporal RHESSI X-ray images. The careful examination of UV images suggests that the initial flare brightening occurred at ∼22:19 UT in the form of two bright kernels, very similar to that of EUV measurements. However, within 2 minutes, the two kernels rapidly evolve into ribbon-like structures (indicated by arrows in Figure 5(a)). We call these the NW and SE ribbons. The most noticeable feature observed in UV images at the early stage is the brightening at a relatively remote location (marked by an arrow in Figure 5(b)), close to the SE sunspot (cf. Figure 2), which continues during the main flare phase. This brightening cannot be seen in EUV images. We find that this near-sunspot brightening is connected to the SE flare ribbon by a less-bright, thin, elongated structure along which transient bright points appear. It is noteworthy that in the RHESSI 12–25 keV image we observe X-ray emission from this remote bright region for a short period at around 22:28 UT (cf. Figure 5(e)), which marks the beginning of the flare impulsive phase (cf. Figure 1 and Section 2.1). In UV images we observe sporadic brightening during ∼22:20–22:25 UT over a small region (at the western portion of the images) where EUV images show rapid changes in the configuration of short loops overlaying the filament. However, after ∼22:25 UT we see the formation of the arc-like structure, consistent with the flare evolution in the EUV wavelength, around the location of sporadic brightening (marked by an arrow in Figure 5(c)). From UV and EUV observations described previously, we collect several important pieces of information that clearly reveal an initiation phase of the flare between ∼22:19 and 22:24 UT, before the flare signatures in X-ray observations.

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Figure 5. Sequence of TRACE 1600 Å images from pre-flare to post-flare stages. Panels (b) and (c), (e)–(g), (i), and (k) show co-temporal RHESSI X-ray images in 6–12 keV (green), 12–25 keV (white), and 50–100 keV (blue) energy bands overlaid on TRACE images. The contour levels for RHESSI images are 60%, 75%, 85%, and 95% of the peak flux in each image. RHESSI image parameters are the same as in Figure 3.

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

flare. We therefore interpret that the low-energy X-ray source indicates the region of X-ray emission from the top of the hot loops.

In Figure 6, we present RHESSI images in 6–12 keV, 12–25 keV, 25–50 keV, and 50–100 keV energy bands to show the temporal and spatial evolution of X-ray sources. We find that the origin and evolution of the X-ray sources during the precursor phase is very interesting and requires careful examination. Since the X-ray time profiles indicate significant emission below 30 keV (cf. Figures 1 and 10(d)), we investigate the morphology of the series of images in 6–12 keV and 12–25 keV during this phase. Although the X-ray flux starts to rise at ∼22:24 UT, the clear structure of X-ray sources was observed from 22:26 UT onward, i.e., from the peak of the X-ray precursor phase. The evolution of X-ray sources between 22:26:00 UT and 22:28:30 UT reveals several interesting features. At the beginning, the emission at 6–12 keV originates in the form of X-ray flare ribbons (compare Figure 6(a)) which are formed at both sides of the filament (Figure 3(c)). The next image at 22:26:30 UT shows a similar morphology, although now ribbons contract and rather resemble FP sources. Here it is noteworthy that the X-ray source at high energy, i.e., 12–25 keV, lies in between 6–12 keV X-ray ribbons/FPs (compare Figure 6(b)). The next images
seem to show a looptop (LT) but again the FP emission dominates. This scenario is further supported by comparing X-ray source locations with TRACE UV images (cf. Figure 5(e)). The TRACE EUV images during this interval indicate a continuous evolving bright feature (called earlier an arc-like structure) above the filament. Therefore we find that the multi-wavelength analysis of the initiation and precursor phases provides clear evidence of subtle activity and magnetic reorganization before the flare onset.

Around the first and second HXR bursts, the X-ray emission in 25–50 keV and 50–100 keV energy bands originates from two distinct FP sources. It is to be noted that the separation between the two FPs around the second HXR burst is less than that of the first HXR bursts (Figure 6). On the other hand, emission at energies below 25 keV is confined to a single LT source that slowly moves toward the southwest side of the activity site. It is noteworthy that from ~22:34 UT onward, X-ray emission at the 25–50 keV energy band also originates from the location of the LT source and we can observe a single X-ray source simultaneously in 6–12 keV, 12–25 keV, and 25–50 keV energy bands. Between ~22:34 and ~22:38 UT, the HXR flux in the 50–100 keV energy band becomes very weak and we cannot see source structure. However, at ~22:39 UT HXR flux enhances (compare Figure 1) and a strong HXR source appears that is cospatial with the LT source observed at low energies (see Figure 6(p)). In Figure 7, we plot the altitude evolution of the RHESSI LT source in different energy bands as well as the separation of the two 50–100 keV FP sources. For 6–12, 12–25, and
25–50 keV measurements, the LT altitude is defined as the distance along the main axis of motion between the centroid of the LT source and a reference point on the Sun (the center of the line between the two FPs seen in the RHESSI 50–100 keV image at 22:29 UT). The LT source is defined as the region with emission above 85% of the peak flux of each image. In Figure 7, we also plot the height of the 50–100 keV LT source which is seen only for a short period during the third HXR burst at ∼22:39 UT. In this case, we determine the LT source by selecting a region with emission above 75% of the peak flux.

2.2.2. X-Ray and WL Observations

This flare also produced signatures in WL observations. We examined a series of TRACE WL images that are available typically every minute. The WL channel of TRACE has a very broad response, from 1700 Å to 1 μm, making it sensitive to emission in the transition region, the chromosphere, and the photosphere (Handy et al. 1999). We find flare-related brightening in WL images from ∼22:29 UT that lasted for ∼7 minutes. Figure 8 shows a few representative WL images.

These images clearly reveal that brightenings occurred at three locations: a WL ribbon very close to the western sunspot that is cospatial with the NW HXR source (one of the FPs), another WL ribbon close to the eastern sunspot that is cospatial with the SE HXR source (second HXR FP), and a bright patch of emission visible only for ∼2 minutes between the two HXR bursts (indicated by an arrow in Figure 8(c)). The fact that HXR FP sources correlate well with the WL brightenings suggests this event to be a type I WL flare (Fang & Ding 1995). We also notice that initially the northern edge of the NW WL ribbon touched the sunspot while in the later stages the ribbon separated from the sunspot.

2.3. RHESSI X-Ray Spectroscopy

We have studied the evolution of RHESSI X-ray spectra during the flare over consecutive 20 s intervals from the precursor to the decline phase (i.e., between 22:25:00 UT and 22:40:00 UT). For this analysis we first generated a RHESSI spectrogram with an energy binning of 1/3 keV from 6–15 keV and 1 keV from 15–80 keV. We only used the front segments of the detectors, and excluded detectors 2 and 7 (which have lower energy resolution and high threshold energies, respectively). The spectra were deconvolved with the full detector response matrix (i.e., off-diagonal elements were included; Smith et al. 2002).

In Figure 9 we show spatially integrated, background-subtracted RHESSI spectra derived during six time intervals of the flare together with the applied spectral fits. These six time intervals are marked in Figure 10(d) where we have plotted 6–30 keV and 30–80 keV RHESSI light curves. The plot reveals
that during the precursor phase, emission originates only at low X-ray energies (i.e., 6–30 keV). We find a rapid increase in the X-ray flux in the 30–80 keV energy band only with the onset of the impulsive phase at ∼22:28 UT. Therefore, we have restricted the spectral fitting during the precursor phase (between 22:25:00 and 22:28:20 UT) in the energy range 6–30 keV. The spectra derived after the impulsive phase (between 22:28:20 and 22:40:00 UT) were fitted in the range 6–80 keV.

Spectral fits were obtained using a forward-fitting method implemented in the OSPEX code. The OSPEX allows the user to choose a model photon spectrum, which is multiplied with the instrument response matrix and then fitted to the observed count spectrum. The best-fit parameters are obtained as output. We used the bremsstrahlung and line spectrum of an isothermal plasma and a power-law function with a turnover at low X-ray energies. The negative power-law index below the low-energy turnover was fixed at 1.5. In this manner, there are five free parameters in the model: temperature ($T$) and emission measure (EM) for the thermal component, and power-law index ($\gamma$), normalization of the power law, and low-energy turnover for the non-thermal component. From these fits, we derive the temperature and EM of the hot flaring plasma as well as the power law index for the non-thermal component. Figure 10 shows the time evolution of these parameters obtained from fits to the RHESSI spectra integrated over consecutive 20 s intervals.

The spectra during the precursor phase suggest that hot thermal emission with temperature $T > 24$ MK already existed at the very start (compare Figure 10(a)). The comparison of RHESSI images with UV and EUV observations indicates that this intense plasma heating corresponds to localized brightenings at three regions in the form of two X-ray ribbons/FPs along with an LT source. However, the temperature decreases afterward for a short period (between 22:26:50 and 22:27:50 UT). The temperature again increases with the onset of the impulsive phase (after 22:27:50 UT) and peaks (∼30 MK) at 22:28:50 UT. The temperature does not increase any further in the later stages. The EM shows a gradual increase during the precursor phase (between 22:25:10 and 22:27:50 UT) followed by a decrease for a short duration. The EM further shows a gradual rise with the start of the impulsive phase until the end of the HXR emission. Around the peak of the precursor phase, we observe significant HXR emission. During this time interval, the spectra at energies $\varepsilon \gtrsim 10$ keV can be fitted by a power law with photon spectral index $\gamma$ in the range of ∼6–7.

The spectra reveal quite different characteristics during the impulsive and decay phases. During the period
in Figure 11(b). The comparison of panels (a) and (b) suggests that S1 and S2 are sunspots of negative polarity while S3 is a positive polarity sunspot. The sequence of magnetogram images of the activity site reveals the emergence of magnetic flux in a region close to sunspot S3. This emerging flux region (EFR) is marked in Figure 11(d) by an arrow. From the figure it is apparent that the EFR is of positive polarity. However, we cannot be certain of the intrinsic magnetic polarity of the EFR because of its location at W60. In Figure 12, we plot emerging magnetic flux through EFR by selecting a rectangular box of size 28′′ × 20′′ (compare Figure 11(d)). The important observation is that the magnetic flux of the EFR starts to rise in one polarity at ~22:25 UT, which coincides with the onset of the X-ray precursor phase.

In Figure 11(c), we show the location of X-ray emission during the flare impulsive phase over the co-temporal magnetogram. We find the NW and SE HXR FPs are associated with the positive polarity region (S3) and the negative polarity region (F−), respectively.

In Figure 13, we show a vector magnetogram of the active region NOAA 10486 on 2003 November 1 at 14:08 UT. The magnetogram data have been taken from the vector magnetograph facility of the Marshall Space Flight Center (Hagyard et al. 1982). The 180° azimuthal ambiguity has been resolved by using the minimum energy method (Metcalf 1994; Leka et al. 2009). The transverse vector fields are indicated by green arrows in the figure. The region associated with flaring activity is shown inside the red box in Figure 13. The direction of transverse vectors between the negative polarity regions (associated with sunspots S1 and S2) and the positive polarity region (associated with sunspot S3) indicates that magnetic field lines are highly sheared. To quantify the non-potentiality of the field lines in the activity site, we compute the spatially averaged signed shear angle (SASSA; Tiwari et al. 2009), which represents the average deviation of the observed transverse vectors from that of the potential transverse vectors. Over the region of interest (described by the red box in Figure 13), we obtain the value of SASSA as ~15°. Such a high value of SASSA indicates that the region was highly stressed and capable of driving major eruptions (Tiwari et al. 2010).

3. RESULTS AND DISCUSSION

We divide the whole flare activity into four distinct evolutionary stages and discuss important characteristic features of each phase.

3.1. Initiation Phase (~22:19–22:24 UT)

The initiation phase is readily visible at UV and EUV wavelengths. UV images indicate the initial brightenings at two locations, one on each side of the filament. This brightening looks much like flare kernels. It is noteworthy that the main flare occurred at this location only. EUV images reveal rapid changes in the configuration of short loops embedding the filament. We observed interactions among short EUV loops, which resulted in the opening of field lines. Vector magnetogram and EUV images suggest that the magnetic field is highly sheared at this site. We further notice that the discrete, localized brightenings can be identified in both UV and EUV images.

It is evident that the initiation phase represents the initial energy release at distinct locations in a region of highly sheared magnetic fields close to the filament, i.e., the “core” of the erupting region. It is likely that during this phase a small volume

\[ \gamma \sim 3.6 \]

\[ (\text{top to bottom: plasma temperature, emission measure, photon spectral index)} \]

\[ \gamma \sim 3.6 \]

\[ n_{\text{Em}} \sim 10^{10} \text{ cm}^{-3} \]

\[ T \sim 10^7 \text{ K} \]

\[ \gamma \sim 3.9 \]

\[ \eta \sim 0.6 \]

\[ n_{\text{Em}} \sim 10^{24} \text{ cm}^{-3} \]

\[ T \sim 10^6 \text{ K} \]

\[ \gamma \sim 3.1 \]

\[ \eta \sim 0.5 \]

\[ n_{\text{Em}} \sim 10^{14} \text{ cm}^{-3} \]

\[ T \sim 10^5 \text{ K} \]

\[ \gamma \sim 3.0 \]

\[ \eta \sim 0.4 \]

\[ n_{\text{Em}} \sim 10^{13} \text{ cm}^{-3} \]

\[ T \sim 10^4 \text{ K} \]

\[ \gamma \sim 2.9 \]

\[ \eta \sim 0.3 \]

\[ n_{\text{Em}} \sim 10^{12} \text{ cm}^{-3} \]

\[ T \sim 10^3 \text{ K} \]
Figure 11. (a) SOHO white light image close to flare onset. The three sunspots identified near the flaring region are marked by arrows and denoted as S1, S2, and S3. (b)–(d) MDI magnetograms showing magnetic field evolution during the event. The negative flux region in between the sunspots is marked as F$^-$ in panel (b). The emerging flux region of the positive polarity near the sunspot S3 is marked as EFR in panel (d). Red and blue contours in panel (c) represent co-temporal X-ray sources at 50–100 keV and 6–12 keV energy bands, respectively, and denote the region where the X-ray intensity is 70% of its peak value. The rectangular box of size 28$''$ × 20$''$ shown in panel (d) defines the EFR. The temporal evolution of emerging magnetic flux through this region is shown in Figure 12.

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

of plasma is heated up at different locations, which is insufficient to produce the detectable level of X-ray emission.

3.2. Precursor Phase (∼22:24–22:28 UT)

The precursor phase shows significant X-ray emissions below 30 keV, while the count rates at higher energies (≥30 keV) are still at the background level. We find an EFR within the core region and the very first signatures of the eruption in the form of a bright arc-like feature in UV/EUV images. Since an EFR may destabilize the sheared magnetic structures leading to solar eruption (Choudhary et al. 1998), it is likely that the onset of the eruption is intimately connected to the emergence of magnetic flux. Furthermore, the initial eruption took place at the location where EUV loops interacted during the initiation phase.

The plasma temperature was very high at the beginning of the precursor phase, but the EM was still low and increased gradually (compare Figure 10). This indicates that the low-energy X-ray emission at this stage originated from discrete volumes of hot plasma. This fact is further confirmed with EUV/UV images that still display localized brightenings that are cospacial with the X-ray sources and correspond to emission from X-ray ribbons/FPs and LT. We find that around the peak of the precursor phase HXR emission follows a power law, which provides evidence for electron acceleration.

To synthesize the initiation and precursor phases, the initial energy release took place in the form of localized brightenings in the highly sheared core region and is associated with the early signatures of eruption. It has been suggested that the X-ray precursor phase, with distinct, localized brightenings, can be understood in terms of localized magnetic reconnection that acts as a common trigger for both flare emission and filament eruption (Chifor et al. 2007).

3.3. Impulsive Phase (∼22:28–22:34 UT)

The impulsive phase is represented by the onset of high-energy (≥30 keV) HXR emission at 22:28 UT, indicating the impulsive release of a large amount of energy. The plasma temperature also rises impulsively and attains a maximum value of ∼30 MK at 22:28:50 UT. The temperature slowly decreases in the later stages throughout the flare while EM gradually increases. It implies that now the flare involves a larger volume with the filling of hot plasma in the loop system (Uddin et al. 2003).

At the time of maximum plasma temperature, the EUV images show a major reorganization in the structure of the
flaring region as indicated in Figure 4. The multi-wavelength signatures observed at HXR, UV, and WL measurements at this stage show consistency with the standard flare model (see, e.g., Joshi et al. 2007, 2009). Spatial correlation between HXR FP sources and WL emitting regions suggests that WL emission is closely connected with the flare energy deposition by non-thermal particles in the chromosphere (Hudson 1972; Metcalf et al. 2003).

It is important to note that the converging motion of HXR FPs at the beginning of the impulsive phase is marked by rapidly evolving EUV loops into a simplified structure, indicating a possible connection between the two processes. We interpret this as evidence for the relaxation of highly sheared magnetic loops (Ji et al. 2007; Joshi et al. 2009).

The X-ray spectra exhibit a significant non-thermal component throughout the impulsive phase with the hardest X-ray emission at the time of the second HXR burst. In general, we note a distinct anti-correlation between the evolution of HXR flux and photon spectral index (compare Figures 10(c) and (d)). Such behavior indicates that each non-thermal emission peak represents a distinct acceleration event of the electrons in the flare (Grigis & Benz 2004).

### 3.4. Decay Phase (~22:34–22:49 UT)

During this interval, GOES SXRs attain the maximum phase. We found an HXR source at 25–50 keV at the top of the EUV flare loop system throughout the decline phase, which shows continuous upward motion, consistent with the standard flare model. However, it is noteworthy that the HXR LT source is observed without an FP component. The high-energy HXR LT source is believed to be closely associated with the site of electron acceleration in the corona (Krucker et al. 2007; Krucker et al. 2008a, 2010). Moreover, we observed an HXR burst in this late phase, at ~22:39 UT, during which the spectrum shows significant non-thermal emission with $\gamma = 3.9$. At this time a single 50–100 keV HXR source was detected for a brief period, which is co-spatial with the 25–50 keV LT source and shows movement in the same direction. Furthermore, it is located away from the HXR FP sources detected earlier during the impulsive phase (compare Figure 6). Therefore, we interpret the HXR emission at 50–100 keV at this time as originating from the LT. Coronal HXR emission has been reported in some of the recent RHESSI observations (Lin et al. 2003b; Veronig & Brown 2004; Veronig et al. 2005; Krucker et al. 2008b; Krucker & Lin 2008). However, the physical mechanism for such a strong non-thermal source in the tenuous corona is still not clearly understood. Here it is very interesting to see that the strong HXR emission from the LT source between 22:34 and 22:46 UT is temporally associated with the steep rise in the magnetic flux emergence (cf. Figure 12). Furthermore, we find that the LT source seems to be

![Figure 12. Temporal evolution of emerging magnetic flux through the EFR which is defined in Figure 11(d) by a rectangular box of size 28″ × 20″.](image-url)
spatially located within the EFR region (Figure 11). Therefore it is likely that the new magnetic flux was continuously fed to the magnetic reconnection site in the corona causing the prolonged non-thermal LT emission.

4. CONCLUSIONS

The availability of excellent high-cadence multi-wavelength data has enabled us to make a detailed investigation of the physical processes that led to the M3.2 flare on 2003 November 1 and the associated eruption. The main emphasis of this study lies in understanding the pre-flare activity that manifested for \( \sim 9 \) minutes before the onset of the flare impulsive phase. The early pre-flare activities are characterized in the form of an initiation phase, recognized in EUV and UV wavelengths, which is followed by a more energetic X-ray precursor phase. The main activity during the initiation phase is the localized brightenings at three locations close to a filament in a highly sheared magnetic field region. The main flare showed emissions exactly at the same locations. Another important observation of the initiation phase is the rapid changes in the configuration of short EUV loops followed by the opening of field lines. The very first signature of eruption was seen during the X-ray precursor phase at the location where EUV loops interacted.

The onset of the X-ray precursor phase coincided with the flux emergence. The X-ray precursor phase is characterized by high plasma temperatures, with a maximum temperature \( \sim 28 \) MK, and corresponding EUV/UV images showed enhanced brightening along with plasma eruption. More importantly, we find HXR non-thermal emission, which suggests that electron acceleration occurred during the precursor phase. We therefore conclude that pre-flare brightenings correspond to events of localized magnetic reconnection in the core region, i.e., close to the neutral line where the filament lies. It is likely that the interactions among short EUV loops, overlaying the filament and followed by the flux emergence, played a crucial role in driving the eruption and successive large-scale magnetic reconnection that resulted in the main flare.

The impulsive phase of the flare is mostly consistent with the standard flare scenario. However, an HXR LT source is observed during the impulsive as well as decay phase. It is noteworthy that the HXR LT source became stronger in the decay phase and showed non-thermal emission. Further, the HXR LT source at the decay phase is rather unusual in that there is no significant FP emission.

The present study indicates a causal relation between pre-flare activity and the main flare. It also follows that the signatures of magnetic reconnection during the initiation and precursor phases occur in the form of localized instances of energy release. In this manner, one can differentiate pre-eruption reconnection from the post-eruption coronal reconnection that is generally understood in the framework of the standard flare model. Our understanding of the pre-eruption reconnection is still limited because of observational constraints. However, we should keep in mind that sometimes the earliest pre-flare activities can be anticipated with EUV/UV measurements well before the X-ray precursors. The new data sets from the Solar Dynamic Observatory, with superior resolution, would be very useful for such investigations.

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