X-RAY SOURCES AND MAGNETIC RECONNECTION IN AN X-CLASS FLARE

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ABSTRACT

In this paper, RHESSI X-ray source motions in the 2003 November 3, X3.9 flare are studied together with data from SXI, EIT, and Kanzelhöhe Hα. We particularly concentrate on the apparent latitude decrease of the RHESSI X-ray loop-top (LT) source early in the flare before changing to the commonly observed upward growth of the flare loop system. We find that at higher photon energies the LT source is located at higher altitudes and shows higher downward velocities than at lower energies, ranging from 14 km s\(^{-1}\) in the RHESSI 10–15 keV band to 45 km s\(^{-1}\) in the 25–30 keV band. For this flare, the LT altitude decrease was also observed by the SXI instrument with a mean speed of 12 km s\(^{-1}\). RHESSI spectra indicate that during the time of LT altitude decrease (pre-impulsive phase) the emission of the LT source is thermal bremsstrahlung from a “superhot” plasma with temperatures of \(\sim\)40 MK and densities of the order of \(10^{10}\) cm\(^{-3}\).

Key words: sun: flares, sun: X-rays.

1. INTRODUCTION

The expansion of flare ribbons and the growth of the flare loop system in dynamical “two-ribbon” flares are among the most convincing observational signatures of magnetic reconnection in the solar corona. In the standard magnetic reconnection model of two-ribbon flares (for a review see Priest & Forbes, 2002), a sheared or twisted coronal arcade containing a prominence rises slowly during the preflare phase. Then the structure rapidly erupts and the arcade field lines are stretched to form a vertical current sheet above the magnetic inversion line. When the sheet gets long enough, fast reconnection starts (e.g., Furth et al., 1963). In this scenario, first the “inner” field lines come into contact, and the downward-shrinking reconnected field lines form the first (lowest lying) flare loops. In the course of time, the field lines rooted successively farther away from the inversion line reconnect. Consequently, the flare loop system grows and the flare ribbons move away from the inversion line. This is evident from many observations (e.g., Švestka et al., 1987; Doyle & Widing, 1990; Tsuneta et al., 1992; Gallagher et al., 2002; Sui et al., 2004; Vršnak et al., 2004).

Here we present a multiwavelength analysis of the source motions in the X3.9 flare that occurred on 2003 November 3 with special emphasis on observations from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). The flare exhibits two strong footpoints and a distinct loop-top (LT) source in X-rays as observed by the RHESSI instrument. After the hot plasma cooled into the bandpass of the respective instruments, a distinct post-flare LT source was observed by the Soft X-ray Imager (SXI) onboard the GOES 12 satellite, the Extreme-ultraviolet Imaging Telescope (EIT) onboard the Solar and Heliospheric Observatory (SOHO) and in Hα by the Kanzelhöhe Solar Observatory (KSO). These observations enable us to study the plasma evolution during the impulsive and late phase flares.

Recent results from RHESSI indicate an apparent downward motion of the X-ray LT source during the early phase of a flare before changing to the commonly observed upward expansion of the flare loop system (Sui & Holman, 2003; Krucker et al., 2003; Sui et al., 2004; Liu et al., 2004; Ji et al., 2004). These observations were interpreted as being related to the formation of a large-scale current sheet above the flare loops (Sui & Holman, 2003; Sui et al., 2004). In the 2003 November 3 flare, also an apparent LT altitude decrease before the onset of the impulsive hard X-ray (HXR) emission is observed as already reported in Liu et al. (2004). Here, we use a multiwavelength approach with emphasis on detailed RHESSI analysis (imaging and spectroscopy) in order to find further observational details on this intriguing phenomenon and to understand how it might relate to the overall flare/reconnection process.


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2. OBSERVATIONS AND EVENT OVERVIEW

We study X-ray images and spectra from RHESSI (Lin et al., 2002), a NASA Small Explorer Mission designed to study high energy solar flare emission from 3 keV to 17 MeV, with high spectral and spatial resolution. The spectral resolution is 1 keV in the range from 3 to several hundred keV. The spatial resolution is as high as 2"/3 with a full-Sun field of view (Lin et al., 2002). Throughout the flare, the RHESSI thick attenuators were in the field of view causing a rapid drop of the effective detector area at low photon energies (Smith et al., 2002). Thus, we did not consider RHESSI observations below 10 keV.

Hα images of the flare were acquired at the Kanzelhöhe Solar Observatory (KSO), Austria, which routinely takes full-disk Hα images with a time cadence of ~5 s and a spatial resolution of 2"/2/pixel (Otruba & Pötzi, 2003). Furthermore, the flare was recorded by the Soft X-ray Imager (SXI; Hill et al., 2005; Pizzo et al., 2005) onboard the GOES 12 spacecraft and in Fe XII 195 Å by the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière, 1995) onboard SoHO.

The X3.9 flare of 2003 November 3 took place in active region NOAA 10488, one of the three large and flare-active regions (NOAA 10484, 10486, 10488) that produced the major flares during the October/November 2003 period of very high solar activity. NOAA 10488 was an extremely fast emerging and evolving active region. Fig. 1 shows continuum images and longitudinal magnetic field maps of NOAA 10488 observed on 2003 October 31 and November 3 with the Michelson Doppler Imager (MDI; Scherrer et al., 1995) onboard SoHO. In total, NOAA 10488 produced 2 X-class flares, 7 M-class flares, and numerous smaller events. Both X-class flares occurred on 2003 November 3 (X2.7 flare, start: 01:10 UT; X3.9 flare, start: 09:40 UT), when the active region was close to the solar limb (cf. Fig. 1).

The GOES soft X-ray flux of the X3.9 flare on which we concentrate here shows a fast rise with a double peak followed by a long decay phase (cf. Fig. 4, top panel). The flare basically consists of two main particle injection phases observed in RHESSI HXRs, consistent with the double peak observed by GOES (cf. the RHESSI light curves in Fig. 5a). Impulsive HXR emission with two major peaks is observed between ~09:48 and 09:53 UT, followed by a comparatively “quiet” phase between 09:53 and 09:57 UT. A second impulsive phase starts at ~09:57 UT and comprises five individual peaks up to the end of the RHESSI observations (when still strong HXR was emission present).

In Figure 2 we show a sequence of RHESSI images reconstructed with the CLEAN algorithm using detectors 3 to 8 (Hurford et al., 2002). The images obtained in the 15–20 keV energy band show a strong LT source which is present over the whole flare duration and can be im-
Figure 3. Sequence of Hα images from the Kanzelhöhe Solar Observatory. Units of the x- and y-axis are arcsec from disk center. In panels (a)–(c) the contours of the RHESSI footpoints (blue) and LT (red) are drawn.

Figure 3 shows a sequence of Hα images taken at KSO. At the impulsive flare onset (cf. panel a), three footpoints (each associated with one of the three large spots of the active region denoted as S1, S2 and S3 in Fig. 1) and a curved ribbon associated with S2 and the small preceding spot group S4 (both have negative polarity) are seen in Hα. After about 09:55 UT only the two distinct footpoints associated with S1 (positive polarity) and S2 (negative polarity) are remaining. These footpoints coincide with the footpoints seen by RHESSI (cf. Figs. 2 and 3). After 10:00 UT, in addition to the two footpoints a rising post-flare LT source is observed in the Hα images which can be followed for at least three hours, first against the disk and later (11:30 UT) above the solar limb.

Finally, we note that the event was associated with a fast CME (~1400 km s⁻¹), a diffuse Moreton wave, an EIT wave, a moving type IV burst and a complex type II burst extending to the heliometer wavelength range (see Dauphin et al., 2005; Vršnak et al., 2005a,b).

3. RESULTS

3.1. LT Source Motion

Figure 4 (bottom panel) shows the evolution of the LT source during the impulsive and long decay phase of the flare as seen by the different instruments, i.e. RHESSI, SXI, EIT, and KSO Hα. To determine the flare LT position in RHESSI, we constructed sequences of RHESSI images in the 10–15, 15–20, 20–25, and 25–30 keV energy bands. All RHESSI images were derived with the CLEAN algorithm using front detector segments 3 to 8, which give an angular resolution of ~7′′, and were accumulated over consecutive 16.2 s intervals. From these images we determined the LT position as the centroid of emission of all pixels above 70% of each image’s peak flux. Note that although the reconstructed RHESSI images give a FWHM angular resolution of ~7′′, the emission centroids can be determined with an accuracy of <1′′ (Hurford et al., 2002). The post-flare LT sources observed in soft X-rays by SXI, in Fe xii 195 Å by EIT and in Hα were measured by visual inspection.

From each of the image sequences of the different instruments, i.e. RHESSI, SXI, EIT, and Hα, we derived the main direction of motion of the flare and post-flare LT source by a linear least-squares fit to the centroid data resulting in a direction of motion which is offset from the radial direction by 15–19° toward North. The distance calculated along this main axis is plotted in the bottom panel of Fig. 4. The graph shows the rise of the flare and post-flare loop system for about 11 hours. Moreover, the LT heights are clearly structured with temperature, i.e. higher temperature plasma is located above lower temperature plasma.¹ The figure also shows that the velocity of the LT rise is highest (20–30 km s⁻¹) at the rising phase of the GOES flux. For the late decay phase between

¹The RHESSI instrument is particularly sensitive to flare plasmas in excess of 10 MK. SXI’s maximum sensitivity is primarily in the temperature range 1–10 MK. For the LT kinematical measurements we used four different SXI analysis filters sensitive to different temperatures (Hill et al., 2005; Pizzo et al., 2005): open filter position (2.9–3.4 MK), the thin polyimide filter (3.8 MK), the medium polyimide filter (3.8–4.0 MK), and the thin beryllium filter (5.0 MK). The bandpass of EIT Fe xii (195 Å) is narrow with a peak formation temperature of 1.6 MK (Delaboudinière, 1995). In Hα we see plasma at temperatures of about 10,000 K (e.g. Heinzel & Karlický, 1987).
14 UT and 21 UT, we find from SXI and EIT measurements upward velocities still as high as \( \sim 1-2 \text{ km s}^{-1} \).

In the inset of Fig. 4, a zoom into the flare initial and impulsive phase is shown. RHESSI as well as SXI measurements indicate an initial altitude decrease of the LT source before 09:49 UT. This phenomenon is studied in more detail in Figure 5. Figure 5a shows RHESSI light curves in the 12–25 and 50–100 keV energy bands for the flare impulsive phase. In Figure 5b, the distance of the RHESSI LT source along its main axis of motion for the 10–15, 15–20, 20–25 and 25–30 keV energy bands is plotted. Figure 5c shows the velocity of the RHESSI LT source obtained as the time derivative of the LT centroid data in panel b. For the downward velocity, peak values up to \(-50 \text{ km s}^{-1}\) are reached. The highest upward velocities of the LT source (up to 35 km s\(^{-1}\)) are observed close in time to the two highest XHR peaks of the first impulsive phase (cf. Fig. 5, panels a and c), which is consistent with the standard reconnection model. If the LT upward motion reflects progressive magnetic reconnection, then higher upward velocities are associated with higher reconnection rates (in case of a uniform magnetic field). On the other hand, higher reconnection rates are associated with more efficient particle acceleration and thus more XHR emission.

As an alternative velocity estimation, we applied linear fits to the LT centroids during the time of downward motion using 10 RHESSI images reconstructed in each energy band during the period 09:45:58 to 09:48:24 UT. The fit results are summarized in Table 1. We find a systematic increase in the mean downward velocity with energy: in the 10–15 keV band it is 14 km s\(^{-1}\) whereas in the 25–30 keV band the mean downward velocity is 45 km s\(^{-1}\). Furthermore, from the linear fits we find that the initial LT heights are systematically higher in higher energy bands (ranging from 10.1 Mm in the 10–15 keV band to 13.8 Mm in the 25–30 keV band), whereas at the end of the downward motion all LT centroids are within a range of 1 Mm. From a linear fit to the four earliest SXI data points which show the LT centroid, we derive a mean downward velocity of 12 km s\(^{-1}\). This value is in agreement with the trend found from RHESSI observations that at lower photon energies the speed of LT altitude decrease is smaller.

In Figure 5d we plot the ratio of the LT emission in the 20–25 and the 15–20 keV bands revealing a distinct spectral change during the time where the decrease in the LT height is observed. If the emission in the LT source is the bremsstrahlung from an (iso-)thermal plasma, then the increase of this ratio would indicate that the temperature is increasing. On the other hand, if the LT emission is due to nonthermal bremsstrahlung of fast electrons then it would indicate that the injected electron spectrum is hardening. Each scenario as well as a combination of both, i.e. temperature increase and spectral hardening during the flare initial phase is physically plausible. In Sect. 3.2 we show RHESSI spectroscopy in order to obtain further information on the predominant emission process in the LT source.

<table>
<thead>
<tr>
<th>Energy Band</th>
<th>Initial Altitude (Mm)</th>
<th>Final Altitude (Mm)</th>
<th>Downward Velocity (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHESSI 25–30</td>
<td>13.8</td>
<td>7.3</td>
<td>45</td>
</tr>
<tr>
<td>RHESSI 20–25</td>
<td>12.1</td>
<td>7.7</td>
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</tr>
<tr>
<td>RHESSI 15–20</td>
<td>11.7</td>
<td>7.5</td>
<td>29</td>
</tr>
<tr>
<td>RHESSI 10–15</td>
<td>10.1</td>
<td>8.2</td>
<td>14</td>
</tr>
<tr>
<td>SXI</td>
<td>8.6</td>
<td>7.0</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1. Parameters of the LT altitude decrease as derived from linear fits to the RHESSI and SXI LT centroids. The initial and final height of the LT source above the solar surface is listed as well as the mean speed of the apparent downward motion. Initial and final LT altitudes refer to the times 09:45:58 and 09:48:24 UT.
3.2. RHESSI X-ray spectroscopy

Our main emphasis lies on the very early phase, i.e. the time of altitude decrease of the LT source. In Figure 6 we show spatially integrated, background-subtracted RHESSI spectra derived during three time intervals very early in the flare together with the applied spectral fits. The spectra were derived with 1-keV bins accumulated over 20 s (the start time is indicated in each panel) using all front detector segments except 2, 5, and 7 (since they have lower spectral resolution and/or high threshold energies, respectively) and were corrected for pulse pile-up (Smith et al., 2002) using a "tweak" factor of 0.6. For these early (pre-impulsive) phase we obtain acceptable fits, i.e. the reduced \( \chi^2 \) \approx 1, with solely an isothermal component in the energy range 10–30 keV, whereas in all later spectra an additional power-law component at higher X-ray energies was needed. Based on RHESSI images, we can interpret the spatially integrated spectra obtained at this early flare phase as spectra solely of the LT source.

We note that already at the very early phase of the flare, i.e. before the impulsive increase of emission at high energies, the RHESSI spectra are indicative of a "superhot" (Lin et al., 1981) plasma with temperatures increasing from 35 MK at 09:44:20 UT to a peak value of 45 MK around 09:48:00 UT. At the very early stage between 09:44:20 and 09:46:20 UT, the emission measure derived from RHESSI thermal fits increases from \( 3 \cdot 10^{46} \) to \( 14 \cdot 10^{46} \) cm\(^{-3} \). During the main flare, the emission measure then increases by three orders of magnitudes up to a peak value of about \( 6 \cdot 10^{49} \) cm\(^{-3} \) at the end of RHESSI observations (10:01 UT), whereas the temperature does not further increase after 09:48 UT.

To obtain an estimate of the density \( n \) of the hot flare plasma in the LT, we infer the emitting source volume \( V \) from RHESSI images and emission measures \( EM \) from RHESSI spectral fits, and calculate the density \( n = (EM/V)^{1/2} \) under the assumption of a filling factor of one. From RHESSI images reconstructed with the PIXON algorithm (Hurford et al., 2002) in the 15–20 keV band (using a 50% contour level), we estimated the emitting LT source volume to be \( V \approx A^{3/2} \approx 7 \cdot 10^{26} \) cm\(^3 \). RHESSI spectral fits reveal a peak emission measure at the end of RHESSI observations of about \( 6 \cdot 10^{49} \) cm\(^{-3} \) which implies peak densities of the hot flare plasma as high as \( 3 \cdot 10^{11} \) cm\(^{-3} \). During the very early phase of the flare, i.e. the time of LT altitude decrease, the RHESSI emission measure increases from about \( 10^{46} \) to \( 10^{47} \) cm\(^{-3} \), which implies plasma densities in the LT of the order of \( 10^{10} \) cm\(^{-3} \). If the filling factor was smaller than one, this would increase the density. Thus, the derived density values can be considered as lower limits.

It is also worth noting that only very rarely are H\( \alpha \) loops seen in emission against the disk and that such observations imply high electron densities in the post-flare H\( \alpha \) loops in excess of \( 10^{12} \) cm\(^{-3} \) as revealed from theoretical studies (Heinzel & Karlický, 1987; Švestka et al., 1987).

4. DISCUSSION AND CONCLUSIONS

Our kinematical results are in agreement with those obtained by Sui & Holman (2003) and Sui et al. (2004) for three homologous M-class flares on 2002 April 14/15, 15, and 16. These authors report speeds of the altitude decrease of \( \approx 15–25 \) km s\(^{-1} \) in the 6–12 keV energy band, and \( \approx 20–30 \) km s\(^{-1} \) in the 12–25 keV band which are comparable to the velocities we derived for the 2003 November 3 X3.9 flare (see Table 1). In our case, however, the LT source could be observed at even higher energies, and in the 25–30 keV band we obtained a mean speed as high as \( 45 \) km s\(^{-1} \). This velocity is higher than the largest upward velocity observed later in the flare (\( \approx 35 \) km s\(^{-1} \)). We also stress that in this energy band, the decrease in LT altitude was almost 50% of the initial altitude (over a time range of only 2–3 min).

The LT altitude decrease observed early in the flare is a relatively new phenomenon revealed by RHESSI observations of at least five flares.\(^2\) This is too few flares to allow any firm statistical conclusions to be drawn but in all cases the LT source was very strong with high plasma densities (peak values of a few times \( 10^{13} \) cm\(^{-3} \)) and the flare occurred close to the solar limb. The plasma density is a crucial parameter since the X-ray productivity depends strongly on density for both the thermal and nonthermal emissions. Thus, the observation of the phenomenon of the LT altitude decrease is restricted to LT sources which have a high enough density already at the earliest flare phase.

\(^2\) 2002 April 14/15 M3.7, April 15 M1.2, and April 16 M2.5 events cf. Sui & Holman (2003), Sui et al. (2004) and Veronig & Brown (2004). 2002 July 23 X4.8 flare cf. Holman et al. (2003), Lin et al. (2003) and Krucker et al. (2003). 2003 November 3 X3.9 flare see Liu et al. (2004) and the present paper. An altitude decrease of a RHESSI LT source is also mentioned for the M2.3 flare on 2002 September 9 by Ji et al. (2004) but no RHESSI images or LT measurements are presented in their paper. Furthermore, a RHESSI LT altitude decrease was also noticed for the X1.5 flare of 2002 April 21 (Dennis, unpublished).
One possible explanation of the observed LT altitude decrease is a geometrical effect caused, e.g., by the projection of successive brightnesses along an arcade. However, an altitude change is suggested by the systematic findings that the phenomenon occurs only early in the flare, and that higher energies are located higher in the corona and reveal larger downward velocities (see also Sui et al., 2004).

Within the magnetic reconnection process in solar flares it is expected that newly reconnected field lines relax, “shrinking” down to form a system of closed loops (Švestka et al., 1987; Lin et al., 1995; Forbes & Acton, 1996; Lin, 2004). Sui et al. (2004) suggested that the observed altitude decrease of the LT source might also be related to the change from slow X-point to fast Petschek-type reconnection which would not only increase the energy release rate but also push the lower bound of the current sheet downward. Karlický et al. (2005) and Veronig et al. (2005) presented simulations of the LT altitude decrease in the frame of a collapsing magnetic trap model (Somov & Kosugi, 1997; Karlický & Kosugi, 2004) embedded in a standard 2-D reconnection flare model. An important advantage of this model is that it provides a prediction of the X-ray emissivity that can be compared with the observations. In these papers it was found that the magnetic trap model can reproduce the key observational findings of the LT altitude decrease (i.e. height structuring and velocity profiles at different energies) in case that the predominant emission process in the LT source is thermal bremsstrahlung.

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