LOOP-TOP ALTITUDE DECREASE IN AN X-CLASS FLARE

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UDC 523.985.3-735
Conference paper

Abstract. We study RHESSI X-ray source motions in the X3.9 flare of 2003 November 3. Particular attention is drawn to the apparent altitude decrease of a distinct loop-top (LT) source at the early flare phase before then changing to the commonly observed upward expansion of the flare loop system. We obtain that the downward motion is more pronounced at higher X-ray energies (peak values up to 50 km s\textsuperscript{–1}) consistent with recent findings by Sui et al. (2004). RHESSI spectra indicate that the emission process in the LT source is thermal bremsstrahlung from a super hot plasma (~40 MK) with high densities increasing from \(\sim10^{10}\) cm\textsuperscript{–3} early in the flare to several times \(10^{11}\) cm\textsuperscript{–3} at the end of RHESSI observations.

Key words: Sun – solar flares – X-rays

1. Introduction

The expansion of flare ribbons and the growth of the flare loop system in dynamical ("two-ribbon") flares belong to the most convincing observational signatures of magnetic reconnection in the solar corona. Recent findings from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al., 2002) indicate an apparent downward motion of the
X-ray loop-top (LT) source during the very early phase of a flare before then changing to the commonly observed upward expansion of the flare loop system (e.g. Sui and Holman, 2003; Sui et al., 2004; Liu et al., 2004). Sui and Holman (2003) and Sui et al. (2004) performed a detailed analysis of RHESSI observations of three homologous M-class flares that occurred during 2002 April 14–16. All three flares showed a distinct decrease of the LT altitude before and during the impulsive flare onset, whereby at higher X-ray energies the LT was located at higher altitudes and revealed a more pronounced decrease than at lower energies. These recent findings suggest that the altitude decrease of flare LT sources might be a common feature in the early phase of solar flares and is possibly closely related to the magnetic reconnection process.

Here we present RHESSI analysis of the source motions in the X3.9 flare that occurred on 2003 November 3 in NOAA 10488. The flare exhibits two strong foot points and a distinct X-ray LT source observed by RHESSI, which reveals a LT altitude decrease at the early phase as already reported by Liu et al. (2004). After the hot plasma cooled into the Hα bandpass, a distinct post-flare LT source was also observed in Hα by the Kanzelhöhe Solar Observatory.

2. Observations

Figure 3a shows RHESSI light curves in the 12–25 and 50–100 keV energy bands. The flare basically consists of two main particle injection phases observed in hard X-rays (consistent with a double peak recorded in GOES soft X-rays). Impulsive hard X-ray (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 and a second impulsive phase which starts at ∼09:57 UT and is still active at the the end of the RHESSI observations at 10:01:20 UT.

In Figure 1 we show a sequence of RHESSI images reconstructed with the CLEAN algorithm (Hurford et al., 2002) using front detector segments 3 to 8, which give an angular resolution of ∼7″. 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 imaged about 3–4 min prior to the impulsive HXR onset and foot point appearance. The 70–100 keV images show two distinct foot points separating from each other during the course
Figure 1: Sequence of RHESSI 15–20 keV (grey contours) and 70–100 keV (black contours) images of the loop-top (LT) and foot point (NF: Northern foot point, SF: Southern foot point) sources reconstructed with the CLEAN algorithm using grids 3 to 8. For the 15–20 keV images the contour levels at 65, 80, and 95% of each image’s peak flux are plotted. For the 70–100 keV images the contour levels are 55, 70, and 85%. Units of the \( x \)- and \( y \)-axis are arcsec.
of the flare. Note that before 09:48:00 and from 09:54:10 to 09:56:40 UT it was not possible to reconstruct foot point images.

Figure 2 shows a sequence of Hα images recorded at the Kanzelhöhe Solar Observatory from the beginning to the late phase of the flare (from 09:44 to 13:00 UT). The images in panels (1) and (11)–(28) are taken in the centre of the Hα spectral line, whereas images (2)–(10) are recorded in the red wing of the Hα spectral line (at the off-band centre wavelength of Hα + 0.4 Å). At the impulsive flare onset, three foot points and a curved ribbon are seen in Hα. After about 09:55 UT only two distinct foot points which coincide with the foot points observed by RHESSI are remaining. After 10:00 UT, in addition to the two foot points a post-flare LT source is observed in the Hα images and can be followed for about three hours, first against the disk and later (>11:30 UT) above the solar limb.
3. Results

From the RHESSI image sequences reconstructed at different energy bands, we derived the centroid positions of the LT and foot point sources. Note that although the angular resolution in the reconstructed RHESSI images is \(~7\arcsec\), the emission centroids can be determined with an accuracy of \(<1\arcsec\) (Sui et al., 2004). In Figure 3b, the distance of the LT source along its main axis of motion for the 10–15, 15–20, 20–25 and 25–30 keV energy bands is plotted, respectively. The main axis of motion was determined from a linear least-squares fit to the LT centroid data and is offset from the radial direction by 18° toward North. Also drawn is the separation of the two RHESSI foot points reconstructed at 70–100 keV energies.

It can be seen that during the impulsive phase, the foot point separation and LT progression to greater heights in the corona show a similar evolution and that the LT source reconstructed at higher energies is systematically located at higher altitudes. However, during the very early flare phase (i.e. before the impulsive increase of the hard emission and before foot points can be imaged), the LT altitude decreases.

Figure 3c shows the velocity of the RHESSI LT source obtained as the time derivative of the LT centroid data shown in panel 3b. For the downward motion, peak values up to \(-50\) 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 HXR peaks of the first impulsive phase (cf. Figure 3a,c) which is consistent with magnetic reconnection models of solar flares. 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 HXR emission. However, during \(~09:54–09:57\) UT where only weak HXR emission and no foot points are observed, velocities in the range 15 to 20 km s\(^{-1}\) are obtained, whereas during the second impulsive phase with distinct HXR spikes comparatively low velocities of about 5 km s\(^{-1}\) are obtained.

As an alternative velocity estimation, we applied linear fits to the LT centroids during the time of downward motion using 10 images reconstructed in each energy band during the period 09:45:58 to 09:48:24 UT. The fit results are summarized in Table I. 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 as high as 45 km s\(^{-1}\) (which corresponds to a decrease of the initial LT height of 47%). Furthermore, from the linear fits we obtain that the initial LT heights are systematically larger 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). At the end of the downward motion, the LT centroids in the different energy bands are all within 1 Mm (between 7.3 and 8.2 Mm).

In Figure 4 we show spatially integrated, background subtracted RHESSI spectra derived during three time intervals of the very early flare phase together with the applied spectral fits. The spectra were derived with 1-keV bins accumulated over 20 s using all RHESSI front detector segments.
Table I: Parameters of the LT altitude decrease as derived from a linear fit to the LT centroids during 09:45:58–09:48:24 UT.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Initial Altitude (Mm)</th>
<th>Final Alt. (Mm)</th>
<th>Alt. Decrease (%)</th>
<th>Velocity (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–15</td>
<td>10.1</td>
<td>8.2</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>15–20</td>
<td>11.7</td>
<td>7.5</td>
<td>36</td>
<td>29</td>
</tr>
<tr>
<td>20–25</td>
<td>12.1</td>
<td>7.7</td>
<td>36</td>
<td>30</td>
</tr>
<tr>
<td>25–30</td>
<td>13.8</td>
<td>7.3</td>
<td>47</td>
<td>45</td>
</tr>
</tbody>
</table>

except 2, 5, and 7, and were corrected for pulse pile-up (Smith et al., 2002). During the integration times of the spectra shown in Figure 4, the emission is predominantly from the loop-top and no RHESSI foot points can be imaged. During this early phase, we obtain acceptable fits (i.e. the reduced \(\chi^2 \sim 1\)) with solely an isothermal component in the energy range 10–30 keV.

We note that already at this early flare phase, i.e. before the impulsive increase of emission at high energies, the RHESSI spectra are indicative of a “super-hot” (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. Between 09:44:20 and 09:46:20 UT, the emission measure derived from RHESSI thermal fits increases from \(3 \times 10^{46}\) to \(14 \times 10^{46}\) cm\(^{-3}\) (see Figure 4). During the main flare, the emission measure then increases by three orders of magnitudes up to a peak value of about \(6 \times 10^{49}\) 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 determined the source volume \(V\) observed by RHESSI and emission measures \(EM\) from RHESSI spectral fits, and calculated the density as \(n = (EM/V)^{1/2}\) (assuming a filling factor of 1). From RHESSI images we derive that the LT source has a radial extend of about 15". Since at these energies the LT source is the only emission source observed by RHESSI, we estimate the emitting source volume by approximating the LT source as a sphere with a diameter of 15" and obtain \(V \approx 7 \times 10^{26}\) cm\(^3\). Thus, for the density of the hot flare plasma we find a peak value as high as \(3 \times 10^{11}\) cm\(^{-3}\). For the very early phase of the flare, i.e. during the time of LT altitude decrease, we obtain plasma densities of the order of \(10^{10}\) cm\(^{-3}\).
Figure 4: RHESSI background-subtracted, spatially integrated photon spectra (crosses with error bars) derived during the very early flare phase (the start time of the integration is annotated in each panel). The full line indicates the fit to the data which is the spectrum of an isothermal plasma.

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

4. Summary and Conclusions

For the LT downward motion observed early in the 2003 November 3 flare, we found that the initial altitude of the LT source is larger and the mean velocities (as high as 45 km s$^{-1}$) are higher at higher X-ray energies which is consistent with the results of Sui et al. (2004) for the flares on 2002 April 14–16. These systematic differences obtained for different X-ray energies and its occurrence at the early flare phase argue for a physical origin of the phenomenon of LT altitude decrease (and not, e.g., a projection effect). Furthermore, RHESSI spectra indicate that the emission in the LT source is thermal bremsstrahlung of a “super hot” plasma ($\sim$40 MK) with high densities (with peak values of several times $10^{11}$ cm$^{-3}$). Hα observations of the post-flare LT source in emission against the disk are also indicative of
very high densities in excess of $10^{12}$ cm$^{-3}$.

Within the magnetic reconnection process in solar flares, several scenarios can possibly explain the observed LT altitude decrease: the relaxation of reconnected field lines, “shrinking” down to form a system of closed loops (Švestka et al., 1987; Lin et al., 1995; Forbes and Acton, 1996); the change from slow X-point to fast Petscheck-type reconnection which would push downward the lower bound of the current sheet (Sui et al., 2004); plasma processes in shrinking magnetic structures as described in collapsing magnetic trap models (Somov and Kosugi, 1997; Karlický and Kosugi, 2004). Work is in progress in order to compare simulation results from a collapsing magnetic trap model with the observational findings of the LT altitude decrease.

Acknowledgements

This research was supported by Grant IAA3003202 of the Academy of Sciences and Grant 205/04/0358 of Grant Agency of the Czech Republic as well as by the Austrian Science Fund (FWF project P15344).

References

A.M. VERONIG ET AL.: FLARE LOOP-TOP ALTITUDE DECREASE

SNIZAVANJE VISINE VRHA PETLJI U JEDNOM BLJESKU X - KLASI

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UDK 523.985.3-735
Izlaganje sa znanstvenog skupa

Sažetak. Istražuju se gibanja RHESSI izvora X-zraka u X3.9 bljesku od 3. studenog 2003. godine. Posebna se pažnja posvećuje prividnom smanjenju visine održenog izvora na vrhu petlje (LT) u ranoj fazi bljeska prije nego što dođe do ubičajene ekspanzije sustava petlji. Ustanovljeno je da je gibanje prema dolje izraženije za veće energije X-zraka (do 50 km s⁻¹), što je u skladu s nalazima Sui et al. (2004). RHESSI spekttri ukazuju na to da je proces emisije u LT izvoru termičko zakočeno zračenje supervrutce plazme (~40 MK) velike gustoće koja se povećava od ~10¹⁰ cm⁻³ na početku bljeska do nekoliko puta 10¹¹ cm⁻³ pri kraju opažanja pomoću sonde RHESSI.

Ključne riječi: Sunce - bljeskovi - X-zrake