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A SOLAR FLARE WITH EXTREMELY LONG PERSISTING HXR EMISSION

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Abstract. The *Yohkoh*/HXT observations of long duration events (LDEs) showed that the HXR thermal emission can be present for tens of minutes after the maximum of the flare. Hence, some heating process is expected to exist during that time. Using *RHESSI* data we are able to analyse LDEs in a more comprehensive way. *RHESSI* observations show that the very hot plasma exists long after the maximum of the LDEs. We found flares in which the emission above 12 keV was observed for six hours during the decay phase. Moreover, the very good spectral resolution allowed us to make a detailed analysis of HXR spectra and determine the nature of such long-existing emission. We found that, during the decay phase of LDEs, the HXR sources were located high in the corona. The presented observations suggest that the reconnection process and plasma heating are still effective even several hours after the maximum of the flare. This is crucial from the theoretical point of view, since the majority of existing models do not explain such a long energy release.

Key words: corona - flares - X-rays - gamma rays

1. Introduction

A long duration event (LDE) - a type of solar flares - is characterized by a slow decrease in brightness as seen in soft X-rays (SXR). Its decay phase lasts from several hours to more than a day. Much progress in studying LDEs was made by satellite observations in the ultraviolet and X-rays, such as those made during *Skylab*, *SMM* (Solar Maximum Mission) and *Yohkoh* space missions. The authors analysing this type of flares provided us with many interesting results (e.g. Sheeley *et al.*, 1975; Kahler, 1977; Feldman *et al.*, 1995; Harra-Murnion *et al.*, 1998; Czaykowska *et al.*, 1999; Shibasaki, 2002; Isobe *et al.*, 2002). One of the most important results is that continuous energy release and plasma heating must exist during the LDE decay phase to explain their evolution.

Loop-top sources (LTSs) are a remarkable feature of solar flares which are seen (in SXR and HXR) close to the flare loop apex. In all present-day solar flare models the energy release takes place above the loop-top sources (e.g. Kopp and Pneuman, 1976; Shibata, 1999; Hirose *et al.*, 2001) or even inside them (Jakimiec, 2002a,b). Thus, the detailed investigation of loop-top sources during the decay phase helps us to understand the energy release.

A detailed analysis of three LDEs with the use of *Yohkoh* data was made recently by Kołomański (2007a, b). The author performed an analysis of LTSs and concluded that the energy release in those events is present during their whole decay phase. Moreover, the energy balance was calculated and the typical value of heating was estimated to be of the order of $0.01 - 1\ \mathrm{erg\,cm^{-3}\,s^{-1}}$. Kołomański also reported that the loop-top HXR sources are present up to 50 minutes after the maximum of the flare. These sources were visible in the HXT/L channel ($14 - 23$ keV). As the observation was based on one, wide energy channel, the actual character (thermal or non-thermal) of the source cannot be reliably resolved. The sources were spatially well correlated with the SXR sources. This observation may provide an important clue that is needed to distinguish which model of the energy release during the decay phase of the flare is correct.

Other authors also reported HXR LTSs during the flare decay phase (Sato *et al.*, 1996; Harra-Murnion *et al.*, 1998; Khan *et al.*, 2006). The brightest HXR source is cospatial with (or slightly above) the loop-top source seen in the soft X-ray. It may be also located in the high-temperature cusp region. Masuda *et al.* (1998) observed HXR sources up to 30 minutes after the maximum of the flare. Their typical size was in the range of $1 - 2$ arcmin. Harra-Murnion *et al.* (1998) investigated two LDEs and concluded that HXR sources grow with time. Moreover, the HXR sources observed during the LDE flares were larger than the compact coronal sources discovered by Masuda (1994) by a factor of 5 and lasted a dozen of minutes. In one of those flares the HXR source was visible even 3 hours after the maximum of the flare.

The energy release during the decay phase may be investigated in the HXR range in two ways: indirect and direct. As the characteristic cooling time of hot (above 10 MK) plasma is of the order of 10 minutes, the observation of HXR sources existing for a dozen minutes after the flare maximum is the indirect indication of the energy release. The alternative signature is the HXR non-thermal component which is direct evidence of particle acceleration during the energy release process. Despite the nature of the HXR source, its presence strongly suggests that energy release during the decay phase does exist.

Gallagher *et al.* (2002) observed LTS evolution using *RHESSI* and *TRACE* data. The HXR emission was observed in the $12 - 25$ keV even 4 hours after the maximum of the flare and almost 11 hours in the $6 - 12$ keV. The observed LTS was large and its altitude was increasing with speed gradually decreasing from 10 to 1.7 km s^{-1}. The higher energy emission ($12 - 25$ keV) was located above the lower energy ones ($6 - 12$ keV and $3 - 6$ keV) and all HXR emission was located above the tops of the loops observed in the EUV range (*TRACE* 195 Å).

In the *Yohkoh* era we were able to detect HXR radiation in four, wide energy bands. Most of the previous observations of the long-persisting HXR LTSs were made in the $14 - 23$ keV range (L channel). One observational point in such a wide range give us limited information about the nature (thermal or non-thermal) of the observed source. Especially as in this range both components, the thermal and non-thermal, strongly influenced the measured flux. Surprisingly, this situation did not change even with *RHESSI* observations - the analysis presented in papers is usually restricted to wide (several keV) energy intervals.

In our analysis we used the *RHESSI* instrument which provides us with data of high spectral resolution. It gives opportunity for the detailed analysis of the thermal and non-thermal components of the long-persisting HXR LTSs. Moreover, the sensitivity and dynamical range of *RHESSI* is much better than the sensitivity and dynamical range of previous instruments. In this paper we present the preliminary results of the analysis of one LDE observed by *RHESSI*.

2. Observations

Our analysis is based on the *RHESSI* data (Lin *et al.*, 2002) supported with the *TRACE* (Handy *et al.*, 1999) observations. *RHESSI* is a rotating Fourier imager located on a low orbit (600 km). Its great dynamic range is achieved mainly due to the use of attenuators which decrease the signal in the low energy range during the strong events. Unfortunately, the attenuators can seriously complicate the spectral analysis (Smith *et al.*, 2002) especially in the lowest energies. During one orbit *RHESSI* passes through the radiation

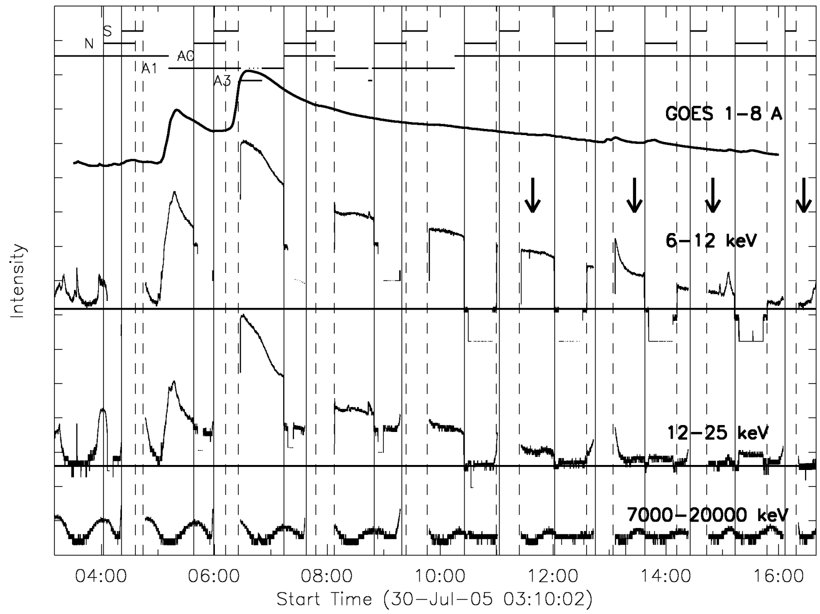

Figure 1: *GOES* and *RHESSI* light curves of the entire event. Vertical lines represent borders of the night (N) and the SAA (S) periods. Horizontal, solid lines represent the approximate background levels for 6 − 12 keV and 12 − 25 keV. Four arrows represent time intervals in which the analysis was performed. The curves were shifted vertically for better presentation.

belts and the South Atlantic Anomaly (SAA) which has also a significant influence on the measured HXR fluxes. We focused our attention on the very late phase of LDE when the analysed signals were weak and they should be carefully inspected. Moreover, the majority of the flare flux was observed in the low energy range which could be highly affected by attenuators. For these reasons we decided not to analyse time intervals when attenuators were in or when *RHESSI* was passing through the SAA. Images obtained during passage through the radiation belts could be analysed carefully since the signal from the radiation belts is not modulated - it should not contaminate the actual source flux in the reconstructed image.

The analysed long-duration flare observed on the July 30th 2005 occurred in the active region NOAA 10792, close to the eastern solar limb. *RHESSI* light curves of the entire flare are presented in the Figure 1. The whole event consists of two flares which were observed within the same active region. Both were connected with the eruptions of different parts of the

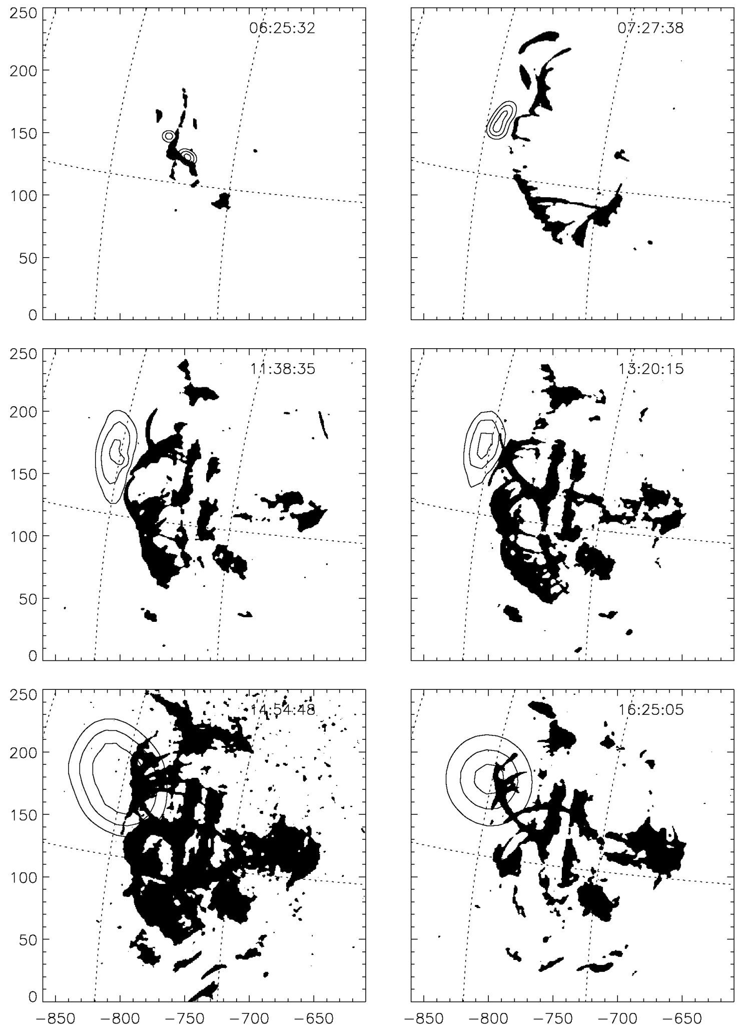

Figure 2: *TRACE* 171 Å images illustrating the overall evolution of the analysed flare. Upper left panel: rise phase, close to the maximum; the HXR sources (contours) were reconstructed in the 50 − 70 keV range. Upper right panel: one hour after the maximum of the flare; contours present the HXR emission in the 7 − 8 keV range. Middle and bottom panels: four investigated time intervals; contours present the HXR emission in the 7 − 8 keV range. All presented contours are for 50%, 70% and 90% of the maximum.

same dark filament. The second, stronger (X1.3 *GOES* class) flare had a long lasting decay phase. Its maximum was observed at 6:35 UT and its decaying was visible until 16:30 UT when another strong flare masked it. Thus, the decaying phase lasted more than 10 hours in the 6 − 12 keV range. The overall evolution is illustrated in Figure 2 with several *TRACE* 171 Å images.

The HXR sources were overlaid on *TRACE* images. The *TRACE* pointing correction was made through the method based on the cross-correlation between *TRACE* 171 Å images and the *Extreme ultraviolet Imaging Telescope* (EIT) images taken in the same energy band[1].

Four investigated time intervals are marked with arrows in Figure 1. The typical influence of the radiation belts and SAA can be seen on light-curves. Usually the SAA influence is observed as the rise of the signal observed several minutes before and after the passage through the SAA. The influence of radiation belts is visible as the waving of the signal in the 7–20 MeV range (the lowest light curve in the Figure 1). This influence is well observed in the high energy range although it is also important in lower ranges. We estimated the actual (outside radiation belts and SAA) background level using time intervals when the satellite was in the Earth shadow and the entire emission from the Sun was completely blocked. The examples of such background levels are presented with horizontal lines for two energy ranges in Figure 1.

3. Analysis

It is very difficult to obtain reliable HXR images in case of a very weak flux. We failed with the standard method based on the grids from the 3rd to 9th (without the 7th) for any reconstruction algorithm available in the *RHESSI* software. The cause is the actual size of the source. Namely, if the actual size of the source is comparable with the resolution of the given grid then there is an insignificant information contained in the modulation (Hurford *et al.*, 2002). Thus, the image obtained with such a grid is dominated by the noise. We tried to handle this problem in the following way. In the first step, we reconstructed images for each grid separately taking a wide field of view (8" pixel, images of the size of 256×256 pixel) and using the back-projection algorithm (Hurford *et al.*, 2002). An example for three time intervals and four grids is presented in the Figure 3. Next, we used these images for determining which grid provided us with reliable images of the source. It can be seen in Figure 3 that for some time intervals there is only noise in the narrow grids. Moreover, we observed that this behaviour could be a function of time. Namely, for further time intervals we observed sources in wider grids only, which means that the observed source had been

[1] http://hesperia.gsfc.nasa.gov/~ptg/trace-align/

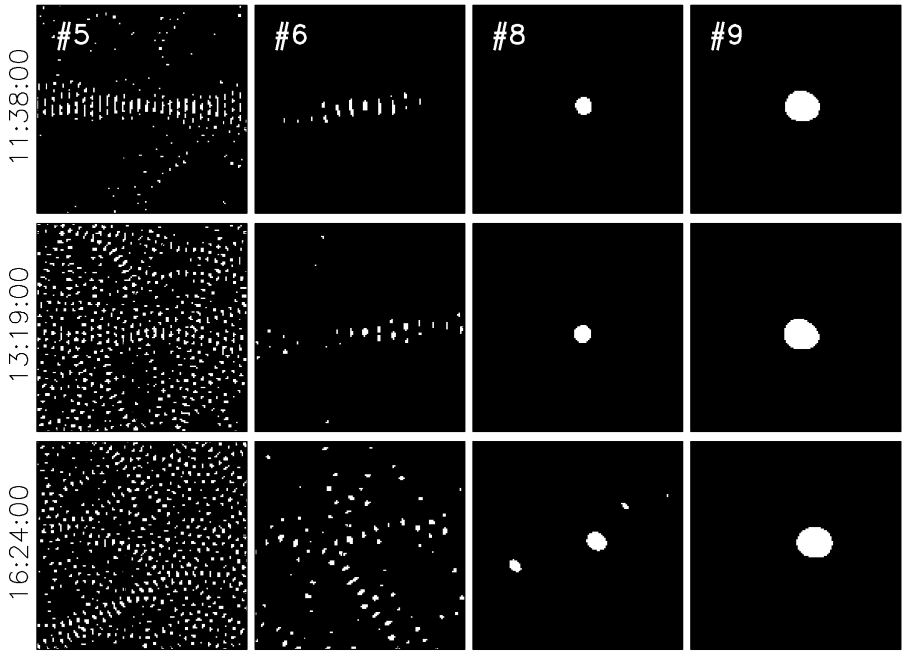

Figure 3: The 6 – 7 keV images reconstructed for single grids (Nos. 5,6,7,8) and three time intervals with the use of back projection algorithm. The field of view for single frame is 1100 × 1100 arcsec.

expanding. A similar characteristic of the HXR sources observed in the early decay was found using *Yohkoh* data (Masuda *et al.*, 1998; Harra-Murnion *et al.*, 1998).

Taking the above into account we decided, for a given time interval, to select only those grids which showed a reliable source in the single grid image. Thus, for the first time interval we used grids number 5,6,8,9 for the second – 6,8,9 and for the third and the fourth – 8,9. With such a flexible selection of the grids we were able to obtain PIXON images with an energy resolution as good as 1 keV for energies lower than 10 keV and 2 keV for energies greater than 10 keV.

The location of the HXR emission source during the late decay phase is presented in the last four panels of Figure 2. The HXR source (7 – 8 keV) was marked on each panel. The source is located above an arcade of post-flare loops cooled into the *TRACE* 171 Å passband (≈ 1 MK). It is a large structure with the FWHM size greater than 1 arcmin. We estimated positions of the LTS by calculating its centroid within the 50% isointensity contour (relative to the brightest pixel in the *RHESSI* image). Errors in the centroids locations change from 4 arcsec (first time interval) to 10 arcsec (fourth time interval). We found that, within the errors, the LTS seen in different energies at a given time has the same position.

This result is interesting from the theoretical point of view. Figure 4 presents the spatially integrated spectrum obtained for the time interval 11:38-11:40 UT. We fitted several different models to the spectrum. In every case we used one thermal component and single Gaussian as a line representation. As a model for the higher energies flux (above 10 keV) we tried one of the following: the second (hotter) thermal, the power-law, the thick target or the thin target models. We obtained the best fit for the power-law with index $\gamma = 9.7$ and cut-off energy equal to 12 keV. However, we had almost the same chi-squared for the fit with two thermal functions. The second thermal component is hot with a temperature of 20 MK. Both fits are presented in Figure 4. Regardless of its nature (thermal or non-thermal) the emission observed in the $10 - 18$ keV range is qualitatively different from the emission observed in the $3 - 10$ keV range. Remembering, that both emission components came from the same LTS this result is a challenge for existing solar flare models. First, the HXR emission above 10 keV is observed six hours after the maximum of the flare. Second, two different emission components are cospatial. If they both were thermal it would mean that some mechanism preventing from fast mixing of the hotter and cooler plasma within this LTS should exist. Moreover, the hotter component should be continuously supported by some heating mechanism. If one component is thermal and the second is non-thermal the problem is similar i.e. we need an energy release process working within the hot (10 MK) and dense ($10^9 - 10^{10}$ cm^{-3}) region. The only model which can explain long-persisting HXR emission and spatial correlation between low and high energy components is the turbulent LTS model proposed by Jakimiec (1990) and further developed by Jakimec and Fludra (1991) and Jakimiec *et al.* (1998).

Physical parameters of the plasma inside the LTSs were obtained by fitting to the spectrum obtained for observed sources. Except the first time interval (11:38-11:40 UT) we observed only one thermal component. The values for all analysed time intervals are collected in Table I.

As we mentioned in the Introduction, the presence of HXR emission from LTS during the decay phase is evidence for energy release at that time. In

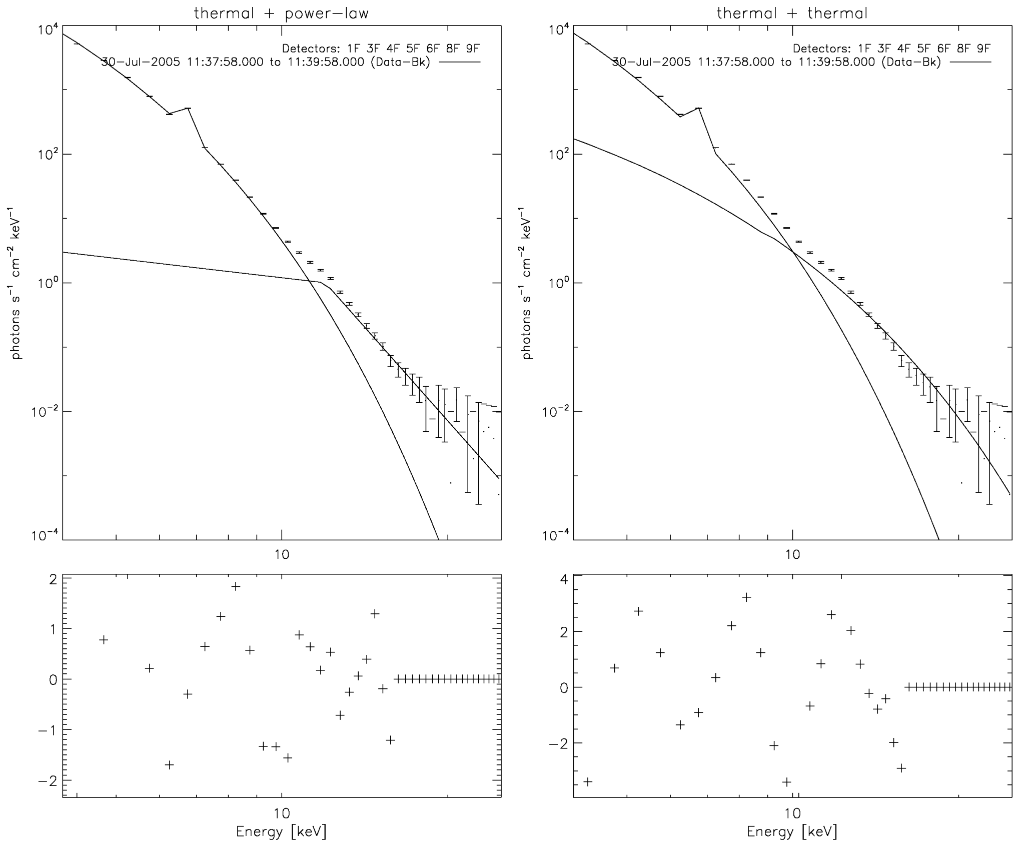

Figure 4: Spatially integrated *RHESSI* spectra obtained in the first of the analysed time intervals. Upper panels present two fitted models. The first is the thermal plus power-law (left). The second is the double thermal model (right). Residuals are presented in bottom panels.

order to calculate the heating rate of the loop-top source we considered its energy balance during the decay phase. Into this balance three major cooling processes where included: expansion, radiation and conduction:

$$\left(\frac{d\mathcal{E}}{dt}\right)_{obs} = \left(\frac{d\mathcal{E}}{dt}\right)_{ad} - E_C - E_R + E_H \qquad (1)$$

where $\mathcal{E} = 3NkT$ is thermal energy density, $\left(\frac{d\mathcal{E}}{dt}\right)_{obs}$ is the decrease of $\mathcal{E}$ per second estimated from temperature (T) and density (N) values, $\left(\frac{d\mathcal{E}}{dt}\right)_{ad}$ is the decrease due to the adiabatic expansion of plasma in a source, E_C is the energy losses due to thermal conduction, E_R is the radiative losses and E_H is the heating rate or thermal energy release (E_C, E_R and E_H

Table I: Physical parameters of the analysed sources: h - altitude, r - source radius, T - temperature, EM - emission measure, (E_H) - heating rate

Time [UT]	11:39	13:20	14:54	16:25
h [Mm]	84.3	91.5	98.0	100.2
r [Mm]	13.4	17.5	33.4	30.3
T [MK]	11.6	8.8	7.9	7.1
EM [10^{47} cm^{-3}]	3.2	2.9	2.6	1.9
$(E_H)_{max}$[erg cm^{-3} s^{-1}]	0.3337	0.0675	0.0250	0.0165
$(E_H)_{min}$[erg cm^{-3} s^{-1}]	0.0001	0.0005	0.0004	0.0000

are in erg cm^{-3} s^{-1}). We calculated $\left(\frac{d\mathcal{E}}{dt}\right)_{ad} = 5kT\left(\frac{dN}{dt}\right)$, $E_C = 3.9 \times 10^{-7}T^{3.5}/(Lr)$ (Jakimiec *et al.*, 1997) where r is the LTS radius and L is the loop-length - we took an altitude of an LTS above the photosphere (h) as an approximation of L, $E_R = N^2\Phi(T)$, where $\Phi(T)$ is the radiative loss function taken from Reeves and Warren (2002). In our calculations, the energy of nonthermal electrons was not included except in the first interval.

Assuming that we observe the non-thermal component in the time interval of 11:38-11:40 UT we can estimate the non-thermal component in the energy balance. Assuming the thick-target model we obtained that the density of the non-thermal electron energy is of the order of 0.07 erg cm^{-3} s^{-1}. The result is similar to Czaykowska *et al.* (2001) who showed that during the decay phase this component could be omitted because it is much smaller than E_C.

From Equation 1 we calculated the upper and lower limits for E_H. The upper limit, $(E_H)_{max}$, is calculated directly from Equation 1. However, it was shown that the actual conductivity may be smaller than the Spitzer conductivity (Luciani *et al.*, 1983). Therefore the lower limit, $(E_H)_{min}$, is obtained under the assumption $E_C = 0$. This limit is rather hypothetical – it seems to be impossible that conductive losses are completely switched off. The results of the energy balance calculations are presented in Table I. Although $(E_H)_{min}$ is almost equal to zero, but it was calculated under an unreal assumption. Concluding, the actual value of E_H must be larger than $(E_H)_{min}$ implying that the energy release takes place even 10 hours after the flare maximum.

To estimate the altitude of a LTS we need to know its position in the *RHESSI* image and find the point above which the source is situated (reference point). The source position was defined, as we mentioned, by the position of its centroid. To locate the reference point we had to reconstruct images in higher energies during the impulsive phase in order to obtain locations of foot point (FP) sources (Figure 2, upper left panel). The reference-point location was taken as the mean value of FP sources coordinates corrected to account for the solar differential rotation. Finally, the LTS altitude was calculated as the distance between its centroid and the reference point. The obtained altitudes are corrected for projection effects.

The actual size of the LTS was determined in the following way. The lower limit was obtained with the use of single grid images. It was mentioned above that the relation between the thickness of the grid and the actual size of the source did exist. Namely, if the source is resolved with the given grid and is not resolved with neighbouring narrower one it means that the actual size must be larger than the FWHM resolution of the narrower grid. For estimating the upper limit of LTS size we used the PIXON images reconstructed with the use of all grids in which we observed the source at a given time. The upper limit was assumed as the FWHM size of the source. Such a method gives only a rough estimation of LTS size. We must keep this in mind when calculating the energy balance. The mean values of an LTS radius are collected in Table I.

4. Conclusions

Previous results of the investigation of long-persisting HXR LTSs were based on the data which had given rough information of the physical parameters of the source. The channel L in the *Yohkoh*/HXT gave a flux integrated over a wide energy band, namely 14–23 keV. Using the *RHESSI* data we had, for the first time, the possibility to analyse the HXR flux and images with energy resolution as good as 1 keV.

The flux for energy above 12 keV was detected for almost 6 hours during the decay phase while the 8 keV emission was observed even 10 hours after the maximum of the flare. The flux above 12 keV is a part of the component which is clearly different from the thermal component dominating the range below 10 keV. The best fit to the observed spectrum (Figure 4, left panel) we obtained for the thermal (10 MK) and non thermal ($\gamma = 9.7$) components.

Similar chi-squared we obtained in the case of two thermal components: of 10 MK and a hotter of 20 MK. However, systematic changes of residuals observed in this case suggest that the double-thermal model is worse. Regardless of its nature (thermal or non-thermal) the existence of the emission above 12 keV even six hours after the maximum of the flare suggests that some process of energy release long after the maximum of the flare should exist.

The above conclusion is confirmed by the energy balance calculation. The actual value of E_H is larger than zero in all intervals which means that the energy release takes place even 10 hours after the flare maximum.

Existing models of a solar flare do not explain such long timescales of the energy release. The so called 'standard model' (Shibata *et al.*, 1995) is based on the scenario in which the main driver of the flare is the eruption of the filament. In the flare analysed in this Paper we observed such an eruption. It was observed only during the impulsive phase which means that it could not influence the energy release observed several hours after the maximum of the flare.

Similarly, models in which we assume the trapping of particles do not give a solution for this kind of events. In this model the continuous acceleration of particles should be present to balance the energy losses of the observed HXR LTS. The particle is efficiently accelerated due to multiple interactions with upward-moving magnetic mirrors located in the lower parts of the loop. The required velocities of mirrors should be of the order of hundreds $\mathrm{km\,s^{-1}}$ - about 1% of the thermal velocity of the 10 MK plasma. Let us assume a velocity equal to $500\,\mathrm{km\,s^{-1}}$. In the analysed flare we obtained the half length of the observed structures equal to about 100000 km. Taking into account the assumed velocities we estimated that the mirrors should meet at the top of the loop within 4 minutes only. Obviously, the other problem with acceleration of particles trapped within the flaring structure is connected with the high density of the observed sources. We estimated the density to be of the order of $10^9 - 10^{10}\,\mathrm{cm^{-3}}$ which means that the free path of the electrons is much smaller than the size of the observed LTS. In such conditions the acceleration of trapped particles is unefficient.

Some different mechanism of the energy release during the long lasting decay phase has to be considered. The turbulent LTS model (Jakimiec, 1990; Jakimiec *et al.*, 1998) provides an explanation of this problem. In this model the LTS is turbulent which means that the magnetic field within the

LTS is highly tangled. In such configuration the energy release is caused by the multitude of small current sheets (Jakimiec, 2002a,b). The main energy release and the formation of a turbulent LTS takes place during the impulsive phase. After the maximum there is still enough energy stored in the magnetic field inside the LTS to produce a significant amount of energy due to the great number of small reconnections. Obviously, the rate of these reconnections decreases with time however, this decreasing is not as fast as it would be in the case of one current sheet. Recently Jiang *et al.* (2006) analysed several short duration events using *RHESSI* data. The authors concluded also that the LTSs should be turbulent to explain their observed properties.

We report only one well observed event. In the next phase of our investigation we will analyse a larger number of flares. Moreover, we are going to include the radio data which will give us a better insight into the non-thermal particle population existing within long persisting HXR LTSs. The analysis is in progress.

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