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ENERGY RELEASE DURING SLOW LONG DURATION FLARES

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Abstract. Slow Long Duration Events (SLDEs) are characterized by long duration of rising phase and smooth HXR emission with the lack of typical short lasting pulses. What is the cause of such behavior? To answer this question we investigated hard X-ray emission and morphology of selected SLDEs. In our analysis we utilized data from *RHESSI* and *GOES* satellites. Physical parameters of HXR sources were obtained from imaging spectroscopy and were used for the energy balance analysis. Characteristic time of heating rate decrease is very long, which explains long rising phase of these flares.

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

1. Introduction

A Long Duration Event (LDE) is a solar flare characterized by a slow decrease in soft X-ray (SXR) emission. LDEs in which the rise phase observed in Soft X-rays lasts more than 20 minutes are called Slow Long Durations Events (SLDEs). During such flares the impulsive phase is weak or does not exist (Hudson & McKenzie, 2000). In most cases Hard X-Ray (HXR) emission is observed without typical short lasting pulses. *Yohkoh*/HXT analysis of several slow LDEs (Bąk-Stęślicka, 2007) showed spatial correlation between sources of HXR emission in low energy channel and tops of loops seen in SXR images. In few cases high energy emission sources were observed near footpoints of loops. Bąk-Stęślicka & Jakimiec (2005) used *GOES* data to calculate temperature and emission measure of investigated flares. Observed time shift between the maximum of emission measure and the maximum of temperature confirmed long duration of rising phase. *Yohkoh*/SXT data were used to analyse morphology and to calculate physical parameters of loop-top sources (LTS) seen in SXR images (Bąk-Stęślicka & Jakimiec, 2005). The analysis of *Yohkoh* data indicate that most of the SLDEs have kernels at altitude $20-50$ Mm. Loop-top sources are characterizied by low temperature ($T < 10$ MK), low densities ($N \sim 10^{10}$ cm^3) and large sizes ($r > 7\times 10^8$ cm). The thermal energy release rate is small, below 1 erg cm^{-3} s^{-1} and decreases very slowly with time after reaching its maximum value. Because of limited sensitivity to hot plasma of SXT telescope and low spectral resolution of HXT telescope SLDEs can't be investigated in more detail. To overcome these instrumental limitations we decided to use *RHESSI* observations. This instrument allows us to investigate spatially resolved HXR emission of SLDEs with 1 keV spectral resolution, distinguish between the thermal and non-thermal nature of an LTS and calculate its physical parameters. In this paper we present an analysis of three SLDEs.

2. Observations

For our analysis we used observations from two satellites. *RHESSI* data (Lin et al., 2002) was used to calculate physical parameters characterizing loot-top sources. *GOES* fluxes were used to calculate temperature, emission measure and time shift between their maxima. *GOES*/SXI images helped us to investigate the morphology of analysed flares.

RHESSI is the rotating fourier imager which means that images are not obtained directly, but must be reconstructed with one of available algorithms (Hurford et al., 2002). We used PIXON method (Piña & Puetter, 1993) since it gives best estimation of sources intensities with very low background level. Images were reconstructed in narrow (1 keV) energy ranges and time intervals of $20-40$ s.

In each image we selected sources with an isophote equal to 50% intensity of a brightest pixel. Centroids of each source were calculated and used for estimation of the loop height. Source size was calculated as follows. First, we determined the area of HXR emission source within a 50% isophote in each image obtained for the same time interval and different energy ranges. We did not observe systematical changes of size with energy. Thus, a weighted mean of sizes was used to calculate the volume of emitting region.

With spatially resolved signals we were able to perform spectroscopy of individual HXR sources with the use of standard OSPEX package. Observed specra were fitted with a thermal component, lines (at 6.7 keV and 8.0 keV) and single power-law.

3. Data analysis

For all analysed flares we estimated the value of the heating function E_H for the loop-top sources seen in *RHESSI* images. In order to calculate heating rate of an LTS we considered its energy balance during the rise phase. Three major cooling processes where included into this balance: expansion, radiation and conduction:

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

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 loss due to thermal conduction, E_R is the radiative loss, and E_H is the heating rate or thermal energy release.The values of E_C, E_R and E_H are in erg cm^{-3} s^{-1}. We calculated:

- $\left(\frac{d\mathcal{E}}{dt}\right)_{ad} = 5kT\left(\frac{dN}{dt}\right)$,
- $E_C = 3.9 \times 10^{-7} T^{3.5}/(Lr)$ where r is the LTS radius and L is loop-length (Jakimiec et al., 1997). In case of SLDEs E_C is a dominant contributor in energy balance,
- $E_R = N^2\Phi(T)$ (where $\Phi(T)$ is the radiative loss function taken from Reeves & Warren (2002).

We took the altitude of an LTS above the photosphere h as an approximation for L in the expression for E_C. Value of h is smaller than L, so we calculated upper limit of E_H. The most uncertain parameter in energy equation is a source size and therefore density. Size determination is a common problem with the *RHESSI* data (Xu et al., 2008). Significant non-thermal component of HXR spectrum was observed only for the flare of 2005 July 13. We fitted this component with power-law function and calculated non-thermal energy using formula from a paper of Crosby et al. (1993). Obtained values are of the order of 10^{28} erg s^{-1}. For all selected flares we analysed time evolution of $E_H(t)$ and calculated characteristic time τ of the $E_H(t)$ decrease ($\frac{1}{\tau} = \frac{dlnE_H(t)}{dt}$).

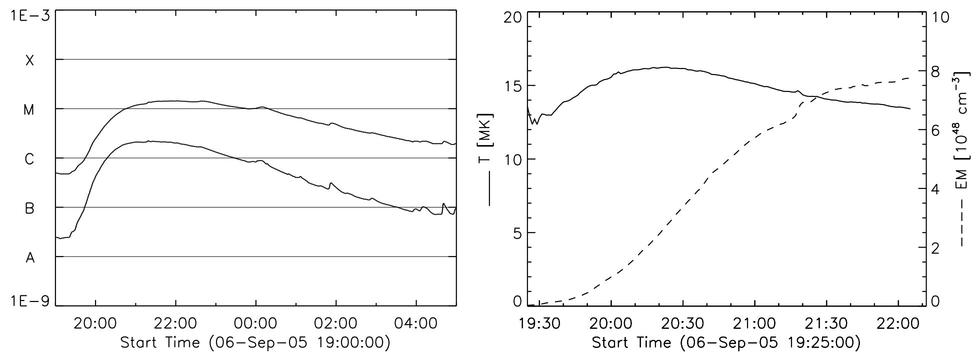

Figure 1: *Left: GOES* X-ray fluxes (upper curve: 1 − 8 Å, lower curve: 0.5 − 4 Å). *Right:* Temperature and emission measure during the rise phase of the 2005 September 6 flare obtained from the *GOES* data.

4. Results

4.1. 2005 September 6 flare

Flare of 2005 September 6 occured in an active region NOAA 10808 at the eastern limb. Flare (*GOES* class M1.4) began at 19:32 UT and reached its maximum at 22:02 UT (Fig.1, *left* panel). Temperature obtained from the *GOES* data reached the maximum (16.2 MK) at 20:23 UT and decreased during the long rise phase very slowly (see Fig.1, *right* panel). Emission measure reached its maximum at 22:04 UT. Difference between temperature and emission measure maxima is equal to 101 minutes (Fig.1, *right* panel) which is characteristic feature of SLDEs (Bąk-Stęślicka & Jakimiec, 2005).

HXR emission source is observed above loop seen in the SXI image (Fig.2, *left* panel). From the *RHESSI* PIXON images we determined size of the LTS ($\sim 16 - 20$ Mm) and height above the photosphere (> 70 Mm). Results are presented in Table I. We performed imaging spectroscopy for obtaining physical parameters of the LTS. Spectra with fitted model (thermal plus lines at 6 keV and 8 keV) are presented in Fig.2 (*right* panel). Obtained temperatures (~ 20 MK at the beginning and ~ 15 MK at the maximum) are higher than those obtained from the *GOES* data which is connected with a different temperature sensivity of these two instruments. Obtained

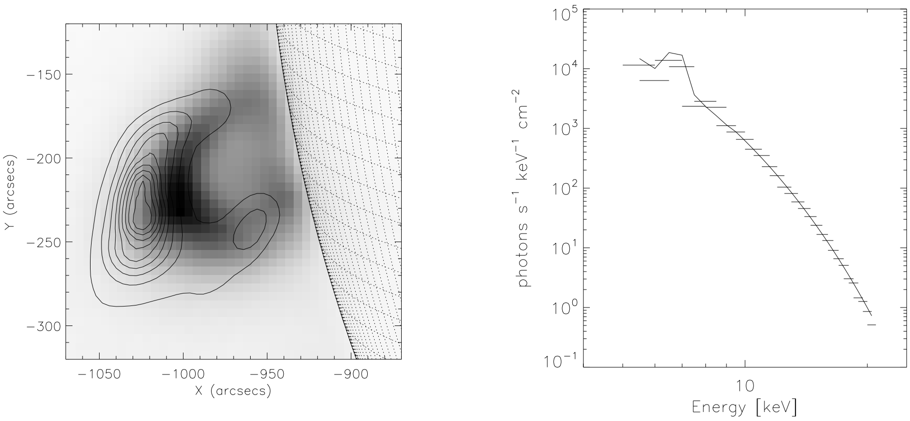

Figure 2: *Left: GOES*/SXI image showing flare of the 2005 September 6 during the rise phase. Contours show the emission in the $8-9$ keV range observed with *RHESSI*. The contours are for 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% of maximum emission. *Right: RHESSI* imaging spectroscopy of the LTS observed during the rise phase of the analysed flare (at 20:37 UT).

Table I: Physical parameters of the LTS of the 2005 September 6 flare: h – altitude, r – mean source radius, T – temperature, EM – emission measure, E_H – heating rate.

Time [UT]	19:58	20:17	20:37	21:34	21:49	22:05
h [Mm]	72.1	72.4	76.8	83.6	84.1	82.0
r [Mm]	19.8	16.4	17.7	19.0	19.4	20.3
T [MK]	20.3	20.8	20.4	16.8	16.2	15.2
EM [10^{48} cm^{-3}]	0.15	0.43	0.84	1.5	1.5	1.9
E_H [erg cm^{-3} s^{-1}]	1.02	1.34	1.1	0.47	0.41	0.32
τ [s]			4430			

value of heating rate is low (Table I) and decrease with the characteristic time of 4430 s, which can explain very long rising phase.

Table II: Physical parameters of the LTS of the 2005 July 13 flare: h – altitude, r – mean source radius, T – temperature, EM – emission measure, E_H – heating rate.

Time [UT]	14:16	14:23	14:32	14:39
h [Mm]	38.3	40.6	39.0	40.1
r [Mm]	8.5	9.0	9.3	9.8
T [MK]	23.5	22.1	22.0	20.1
EM [10^{48} cm^{-3}]	2.3	4.7	7.1	10.0
E_H[erg cm^{-3} s^{-1}]	7.4	5.3	5.3	3.6
τ [s]		2000		

4.2. 2005 July 13 flare

Flare of 2005 July 13 occured in active region NOAA 10786, near to the western limb (N11W90). Flare started at 14:01 UT. SXR flux increased slowly and reached the maximum at 14:49 UT (*GOES* class M5.0). Temperature reached the maximum (19 MK) at 14:19 UT. Maximum value of emission measure (2.6×10^{49} cm^{-3}) attained at 14:58 UT. Time difference between these two maxima is 39 minutes.
During the rise phase emission in the range of $100 - 300$ keV was observed. According to the *RHESSI* the emission came from footpoint sources. At the same time LTS was observed in the energy range up to 40 keV. Using PIXON images height of the source ($\sim$ 40 Mm) and its size ($\sim$ 9 Mm) were determined. From the spectra fitting we calculated temperature ($>$ 20 MK), emission measure, and non-thermal component parameters. The heating rates are listed in Table II. Large value of τ ($\sim$ 2000 s) explains long rising phase. Density of the non-thermal electron energy is highest at the beginning of the observations and is equal to 20 erg cm $^{-3}$ s^{-1} and is about 3 times larger than value of the heating rate. This difference is caused by uncertainty of non-thermal component parameter determination. Near the flare maximum density of the non-thermal electron energy is comparable to the heating rate ($\sim 4 - 5$ erg cm $^{-3}$ s^{-1}).

Table III: Physical parameters of the LTS of the 2007 January 25 flare: h – altitude, r – mean source radius, T – temperature, EM – emission measure, E_H – heating rate.

Time [UT]	06:47	06:55	07:00
h [Mm]	27.0	28.7	28.9
r [Mm]	12.8	12.4	14.0
T [MK]	15.8	13.7	12.9
EM [10^{48} cm^{-3}]	0.11	1.5	2.4
E_H[erg cm^{-3} s^{-1}]	1.61	1.01	0.74
τ [s]		1110	

4.3. 2007 January 25 flare

Flare of 2007 January 25 occured in active region NOAA 10940, close to the eastern limb (S08E88). SXR started to increase at 06:33 UT and reached the maximum at 07:14 UT. Flare was weaker (*GOES* class C6.3) than two previous ones. Time difference between temperature (12.8 MK at 06:57 UT) and emission measure (5×10^{48} cm^{-3} at 07:26 UT) maxima is equal to 29 minutes, which is the lowest value for all analysed flares.

RHESSI observed this flare from the beginning up to ~ 07:10 UT. There was no significant emission above 25 keV during the entire flare. Only two weak pulses ($25 - 50$ keV) were observed close to 06:47 UT. From PIXON images we obtained location of the source, size and height above the photosphere. From the spectra fitting we calculated temperature (< 16 MK), emission measure of the LTS and energy release during this flare. Heating rate decreases with the characteristic time of 1100 s. All parameters are presented in Table III.

5. Summary

Our analysis can be summarized as follows:

- Long duration rise phase of the SLDEs is confirmed by times shift between maximum of temperature and maximum of emission measure. Based on *GOES* data time shift is of the order of some dozen minutes.

- Obtained values of E_H are larger than previous estimations based on *Yohkoh*/SXT data (Bąk-Stęślicka & Jakimiec, 2005). This difference is caused by the fact that SXT telescope had limited sensitivity to hot plasma ($>$ 10 MK) which usually led to underestimation of a flare plasma temperature. *RHESSI* data enable us to estimate much more reliable (higher) value of plasma temperature and therefore higher values of E_H.

- Long duration of the SLDEs rising phase is caused by very slow decrease of the E_H during that phase. Characteristic time of E_H decrease is larger than 1000 s.

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