Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 42 (2008) 822–827
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Spectroscopic analysis of the solar flare event on 2002 August 3 with the use of RHESSI and RESIK data

S. Gburek [a,*], T. Mrozek [b], M. Siarkowski [a], J. Sylwester [a]

[a] Space Research Centre, Polish Academy of Sciences, Solar Physics Division, 51-622 Wrocław, ul. Kopernika 11, Poland
[b] Astronomical Institute, University of Wrocław, ul. Kopernika 11, 51-622 Wrocław, Poland

Received 21 November 2006; received in revised form 24 April 2007; accepted 16 May 2007

Abstract

We use simultaneous observations from RESIK and RHESSI instruments to compare plasma properties of a major solar flare in its rise and gradual phase. This event occurred on 2002 August 3 (peak time at 19:06 UT). The flare had a very good coverage with RESIK data and well-resolved soft and hard X-ray sources were seen in RHESSI images. Spectra of X-ray radiation from RHESSI images are studied and compared with RESIK measurements in different flare phases. Result shows large differences in flare morphology and spectra between flare rise and gradual phase.

Keywords: Sun; Flares; X-rays; Spectra

1. Introduction

We perform spectroscopic analysis of two selected time intervals in the rise and the gradual phase of a major solar flare (GOES class X1.0) which occurred on 2002 August 3. The event took place in NOAA 0039 active region of $\alpha\beta\gamma$ magnetic configuration located at S15W70 heliographic coordinates. The flare lasted for about twenty minutes. This event has a particularly good coverage with data from different X-ray/EUV instruments. The available X-ray/EUV data set has been described and studied in Gburek et al. (2005) and Mrozek (2006). In particular the event evolution and location of EUV/X-ray emission sites were investigated there.

Here we focus on spectroscopic properties of this flare emission in its rise and gradual phase using X-ray data from REntgenovsky Spektrometr s Izognutymi Kristalami (RESIK) and Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) instruments. Detailed description of these instruments can be found in Sylwester et al. (2005) and Lin et al. (2002), respectively.

The data analysis is performed here in order to compare differences in morphology in the flare rise and gradual phase and to determine basic plasma parameters for X-ray sources observed in the selected time intervals. We also compare the proportions and spectral properties of the X-ray signal from the footpoints of the event and coronal source in the rise flare phase. Such proportions can be different significantly or even inverted depending on a particular flare (compare Brown et al., 2002; Veronig and Brown, 2004 and references therein).

2. Data analysis

RESIK is a Bragg crystal spectrometer launched in 2001 on the CORONAS-F spacecraft. RESIK has four energy channels within the range 3.3–6.1 Å. Nominal energy ranges for all RESIK channels are given in Table 3. RESIK data are used here in order to study the flare flux properties in softer X-rays.

RHESSI was launched on February 5, 2002. RHESSI's primary mission is to explore the basic physics of particle

* Corresponding author.
E-mail address: sg@cbk.pan.wroc.pl (S. Gburek).

0273-1177/34.00 © 2007 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2007.05.053

acceleration and explosive energy release in solar flares. RHESSI flare observations, used here, were taken with attenuators in state A1 (see Fig. 1) placed in the instrument field of view. Hence, the data in softer energy range (3–6 keV) may be substantially affected by instrumental effects.

However, it has been checked (Phillips et al., 2006a) that above 5 keV for A1 (as well as for A3) attenuator state the predicted and observed count rates can be made to agree for reasonable model parameters, as indicated by the normalized per degrees of freedom χ^2 values. Therefore we considered it worthwhile to use for analysis the RHESSI data in the energy range above 6 keV.

The analyzed flare has a very abrupt impulsive phase in which a hard X-ray emission is observed (around 19:04 UT) well above 100 keV level (see Fig. 1). The flare X-ray flux (12–25 keV) peaks at ~19:07 UT and then fades out gradually to the background level. For the analysis and comparison we selected two, about a minute long, time intervals. One in flare rise phase between 19:03:46 UT and 19:04:50 UT, covering the hardest peak observed by RHESSI in X-rays. The second selected interval extends well in flare decay phase starting from 19:14:20 UT and ending at 19:15:20 UT. The RESIK and RHESI light curves, with both analysis periods indicated, also are shown in Fig. 1. For both time intervals the RHESSI images, in various energy bands, were restored numerically.

We defined a background level for processing, all used here RHESSI data, from pre-flare RHESSI observed fluxes during the day-part of the satellite orbit. Full response matrix of RHESSI was used in order to reduce instrument observations. all RHESSI images were reconstructed using fluxes from 3F, 4F, 5F, 6F, 8F and 9F detectors.

For the rise phase interval, it was possible to obtain images with a good signal to noise ratio even above the energy level of 100 keV. For gradual phase interval a substantial X-ray emission was observed up to energy of 20 keV only. In the following analysis the images were converted to maps in order to show emission site location relative to the solar limb.

We used the RESIK spectra for the considered flare, for both selected time intervals, to complement the RHESSI spectra in the softer energy passband. The RESIK and the RHESSI data are used here in particular for studying the differences observed in spectra between the rise and gradual phases.

The RESIK and the RHESSI spectra for selected time interval in the flare impulsive and gradual phase are plotted together in Fig. 2. RHESSI observations were performed with attenuators inserted in the instrument field of view. Thus, the spectra below 6 keV may be somewhat biased (Smith et al., 2002) and therefore are not plotted in this Figure. Nonetheless the entire spectrum continuity looks consistent and thereby one would strongly suggest a global use of RESIK spectra in addition to RHESSI fluxes in the low energy (less than 6 keV) range where it is possible. Characteristic features of RHESSI spectral observations i.e. the iron line complex at ~6.7 keV and iron/nickel complex at ~8.0 keV appear well distinguished in the plot in Fig. 2. In the rise phase the hard X-ray flux is observed for energies above 100 keV. This provide an opportunity to see the high energy sources in RHESSI maps in the 110–140 keV energy range. A pronounced diffuse source seen in this energy range is shown in Fig. 3.

The morphology of the RHESSI images in the impulsive phase strongly changes depending on the energy band in which an image was obtained. For energies between 10 and 25 keV one can distinguish three intense, well separated emission sites. Two of them are on the disk. Using TRACE EUV observations it was checked that these sources well coincide with the sites where EUV projected loop ends are “rooted” in the denser layers of the solar atmosphere (Gburek et al., 2005). We will call these sources the southern and the northern “footpoints”. The third intense source seen in the 10–25 keV energy range is located above the solar limb, up in the solar corona. We will refer to it as to the kernel source. For energies lower

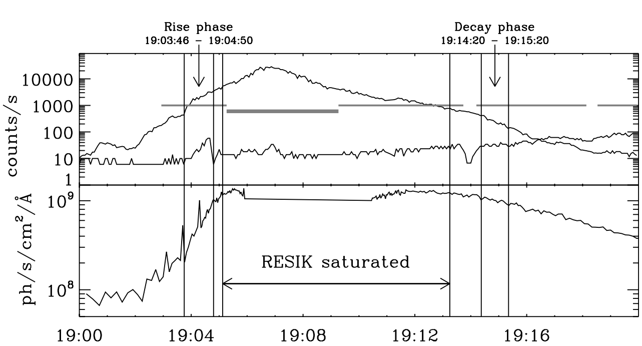

Fig. 1. Top panel: RHESSI light curves for 2002 August 3 flare. The lightcurves for the energy ranges 12–25 keV and 100–300 keV are plotted in thick and thin line, respectively. The arrows above the plot point to the time intervals which are analyzed in this contribution. The gray horizontal bars superimposed on the plot shows the time intervals when RHESSI attenuators were used (thin-gray line for A1 attenuator state and thick-gray line for A3). Bottom panel: RESIK lightcurve.

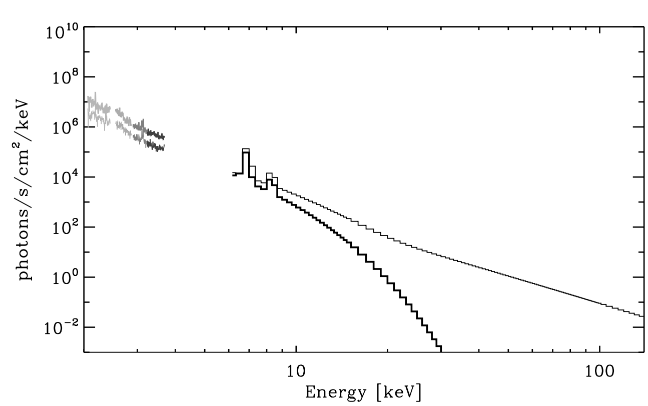

Fig. 2. RESIK and RHESSI spectra for the analyzed event. The spectra for the rise and decay phase are plotted in thin and thick line, respectively. Spectra for RESIK channels 1, 2, 3 and 4 are plotted in energy-progressive gray intensities (the darker the curve the lower the channel number).

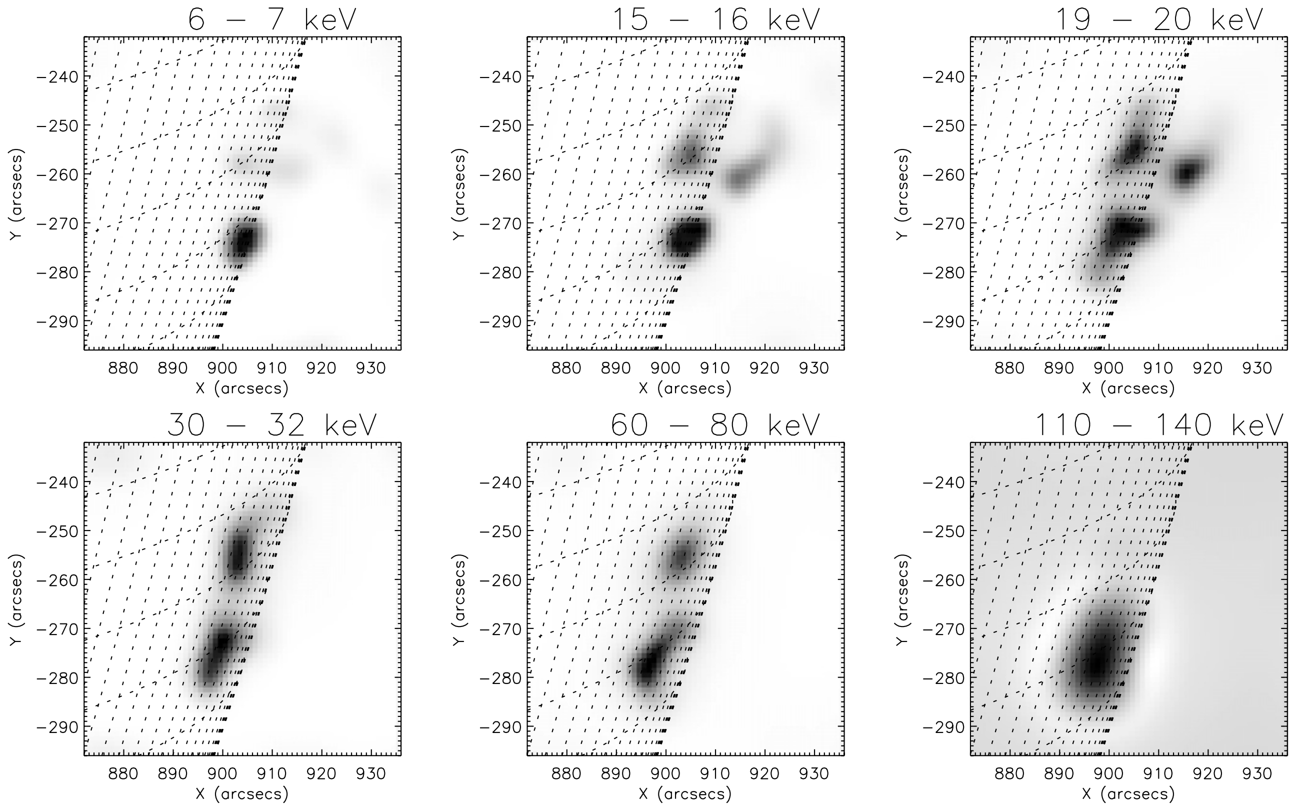

Fig. 3. RHESSI X-ray intensity map reconstructed with the use of pixon algorithm during the flare rise phase.

than 10 keV, the emission comes mainly from one site located near the southern footpoint (see RHESSI image in Fig. 3). This emission (compare the RHESSI images for 6–7 keV and 15–16 keV in Fig. 5) may come from the plasma which started to evaporate from the southern footpoint and therefore is not located exactly in the same place.

For energies in the range 25–80 keV footpoint signals dominate. The kernel emission disappears completely in the images obtained for energies higher than 30 keV. Both footpoints are visible up to energies of 80 keV but in the highest energy band only the southern footpoint gives contribution to the measured flux. Since all three sources are well resolved in the RHESSI images we made imaging spectroscopy for each of them separately. Each source was enclosed in the rectangular box (of the same dimensions for all sources) and only the signal in the box was used for RHESSI spectra computation. Box definitions and comparison of the obtained spectra are shown in Fig. 4. The spectrum calculated from the entire image is also plotted there.

All the calculations of the RHESSI spectra were performed using Object Spectral Executive[1] OSPEX package which is an integrated tool for spectral analysis in the SolarSoft[2] environment. We also used the OSPEX capability of fitting spectra with different models to find basic plasma parameters such us temperatures, emission measures, electron fluxes and spectral indices.

For both footpoints and the kernel source spectra (Fig. 4) in the impulsive flare phase the best OSPEX fits were obtained with the models including one thermal plasma component, thick target bremsstrahlung component and line component. We fitted also thick target models and thermal model with lines to the spectrum obtained from entire images (Fig. 4) for the rise flare phase.

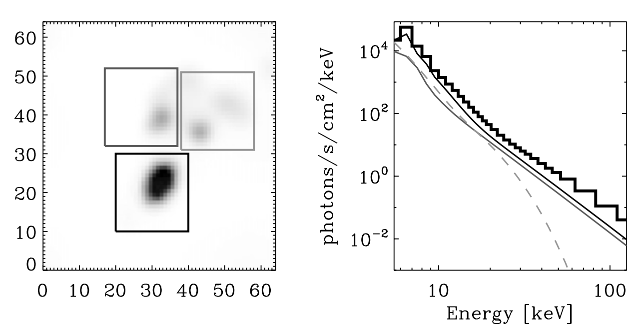

Fig. 4. Left: RHESSI image obtained in the energy range 8–9 keV during flare impulsive phase. Right: RHESSI spectra for corresponding sources seen in the image to the left. Spectrum for the entire image area is plotted in thick black line. Kernel loop-top source spectrum (in the light gray box in the image) is plotted in gray-dashed line. The spectrum for the southern footpoint (area in the black box in the image) is plotted in thin-black-solid line. The spectrum of the northern footpoint is plotted in thin-gray-solid line.

[1] http://hesperia.gsfc.nasa.gov/ssw/packages/spex/doc/ospex_explanation.htm

[2] http://www.lmsal.com/solarsoft.

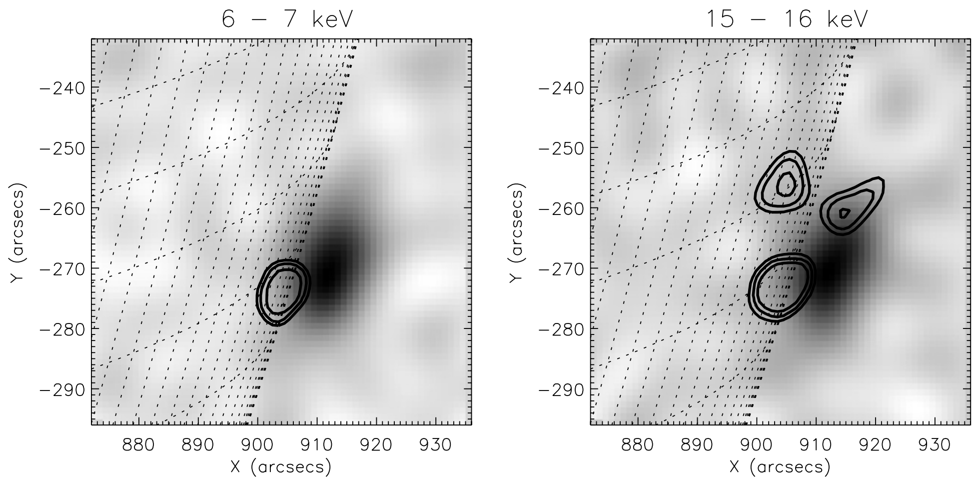

Fig. 5. RHESSI maps obtained during the flare gradual phase. For comparison the contours of map from the flare rise phase (Fig. 3, top-left and top-middle panel) are superimposed on the maps. The contours are plotted at 0.5, 0.7 and 0.9 of the maximum intensity.

For the source in the gradual flare phase (Fig. 5) the best fit was obtained using single thermal model and line components. All fits had the (normalized per degree of freedom) χ^2 values below one. Fit results for all flare sources analyzed are summarized in Table 1.

From comparison of the spectra shown in Fig. 4 it follows that the southern footpoint has stronger X-ray emission than the northern footpoint. Both footpoints have similar ''hardness'' of the electron spectra (compare δ indexes in Table 1 for footpoint sources) but the electron flux for the southern footpoint is much higher than in the northern footpoint. This could explain the observed footpoint X-ray emission asymmetry.

The total footpoint signal is higher than the kernel source in the flare rise phase (see Fig. 4). This again is caused by the strong emission of the southern footpoint. The northern footpoint has weaker emission from the kernel in a few keV long energy interval centered at about 10 keV (Fig. 4).

The kernel source emission in the rise phase have been found to come from almost thermalized plasma of the temperature of 20.0 MK. However OSPEX fits to RHESSI data indicate that some residual X-ray bremsstrahlung radiation could be produced in this source. The bremsstrahlung effects in the kernel source are much weaker than in the footpoints.

Table 1
Results of spectral fits for the sources observed in the flare impulsive and gradual phase

No.	Source	T	EM	F	δ	E_c	χ^2
1	Southern footpoint	19.5	0.147	34.8	4.83	11.1	0.39
2	Northern footpoint	10.3	1.610	23.6	4.95	11.8	0.12
3	Kernel	20.0	0.09	2.35	8.17	22.7	0.02
4	1 + 2 + 3	29.6	0.066	48.2	4.35	10.0	0.53
5	Gradual phase source	19.0	0.225	—	—	x	0.55

Here the temperature T is given in MK, emission measure EM in units of 10^{49} cm^{-3}, nonthermal electron flux F in units of 10^{35} electrons/s, cutoff energy E_c is in keV and δ stands for electron spectral index.

The single temperature trial fits for the kernel source gave worse fit quality than these with bremsstrahlung component however. Thus the X-ray emission of the kernel source can not be explained assuming only isothermal plasma conditions in this kernel.

The morphology of the RHESSI images calculated for the gradual phase is much simpler than for the impulsive phase. There is only one extended source seen in the image. This source in the two selected energy bands is shown in Fig. 5. The source shape is almost independent on the energy and is pronounced in the RHESSI frames up to 20 keV only.

OSPEX fits showed (Table 1) that the spectra of the source in the gradual flare phase can be well approximated assuming isothermal plasma model with temperature of ($T \sim 19$ MK).

The differences of thermal plasma conditions during the selected intervals in the rise and gradual flare phases also are clearly seen in the RESIK spectra plotted in Fig. 6. The spectral intensities and the continuum levels are substantially higher in the gradual phase. Fig. 6 shows that line intensities are different in both flare phases. This feature is particularly well visible in RESIK observations in vicinity of the argon triplet lines which are shown in details in Fig. 7. Also the intensities of parent to satellite lines 5.68 Å/5.86 Å are strikingly different (see Fig. 6). This last ratio is very sensitive to plasma temperature as it was shown by Phillips et al. (2006b).

The RESIK spectra where used to calculate differential emission measure distributions with temperature DEM(T) in the analyzed time intervals. The detailed description of the method used for DEM(T) calculations can be found in Sylwester et al., 2008. Double-peaked DEM(T) distributions were obtained indicating the presence of at least two thermal plasma components in both flare phases. The colder component which peaks at 5 MK is present in the rise and in the gradual flare phase. The temperatures of the hotter component are different in the rise ($T = 21.8$ MK) and the decay ($T = 17.4$ MK) phases. The

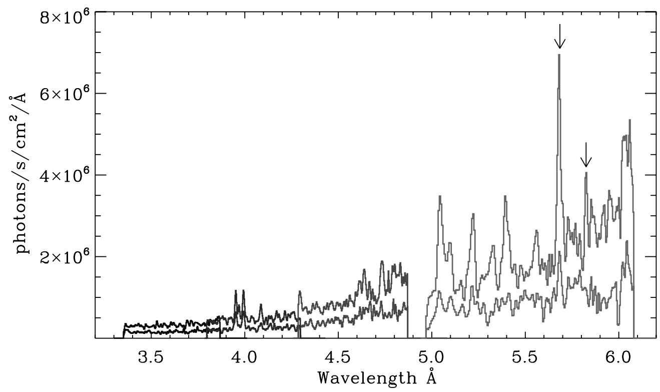

Fig. 6. Comparison of RESIK spectra obtained during flare gradual phase (upper gray lines) and rise phase (bottom gray lines). Spectra for RESIK channels are plotted in gray intensities (the darker the curve the higher is the energy). Arrows point at the RESIK spectra at wavelengths of 5.68 Å and 5.86 Å where silicon parent and satellite lines are seen, respectively.

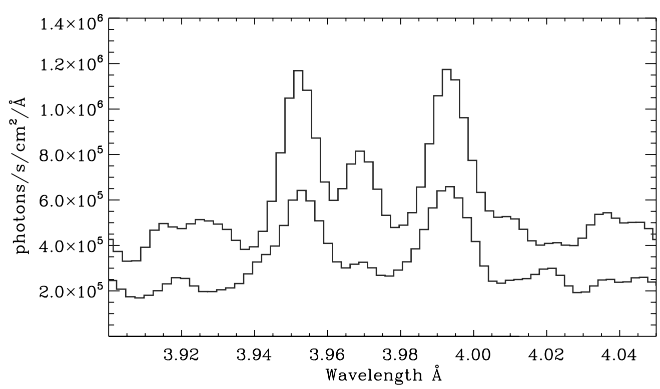

Fig. 7. Argon triplet as observed in the third RESIK channel during the flare rise phase (upper line) and the gradual phase (bottom line).

Table 2
Results of RESIK spectra analysis

Flare phase	T_{cold}	EM_{cold}	T_{hot}	EM_{hot}
Rise	5.0	7.8	21.8	0.24
Gradual	5.0	14.0	17.4	0.55

The temperatures T_{hot} and T_{cold} with respective emission measures EM_{hot} and EM_{cold} are shown here. Both temperatures are given in MK and emission measures in units of 10^{49} cm^{-3}.

Table 3
RESIK energy channels and wavelength ranges

Channel No.:	1	2	3	4
Energy range (keV)	3.26–3.65	2.90–3.24	2.55–2.85	2.05–2.48
Wavelength range (Å)	3.40–3.80	3.83–4.27	4.35–4.86	5.00–6.05

emission measures of the hotter components are of about 30 times lower than for colder ones (Table 2) in both flare phases. The temperatures and emission measures determined from RESIK data for colder and hotter plasma components are shown in Table 2.

3. Conclusions

A well observed event has been identified for a common detailed analysis in soft/hard X-rays using RESIK and RHESSI data. The results presented here indicate for an excellent cross-calibration of sensitivities between RESIK and RHESSI. Inclusion of RESIK spectra into the analysis of RHESSI observations will possibly better reveal the role of non-thermal particles present during the rise phase as concerns the excitation of soft X-ray lines. On the other hand RESIK spectra may allow for a better modeling of the thermal component of the RHESSI spectra. RHESSI images provide direct information on location of the soft X-ray emission contributing to RESIK spectra. This will allow for good estimates of an upper limit for the emitting plasma volume and therefore place a lower limit for the plasma density as determined from RESIK emission measure model for the flare sources.

The observed emission asymmetry of footpoint sources during flare rise phase can be explained by the amount of the non-thermal energetic electrons reaching each footpoint. From imaging spectroscopy analysis performed using OSPEX package it follows that higher amount of these electron reaches the southern footpoint thus giving more energy for conversion into X-ray radiation in that footpoint. The overall X-rays emission from the footpoints is stronger than emission from the kernel source observed in the flare rise phase. However, the northern footpoint has weaker emission in X-rays from the kernel in a few keV long energy interval centered at about 10 keV. The plasma of the kernel source in the flare rise phase has an isothermal component of the temperature of about 20 MK as it is seen from RHESSI data. Some bremsstrahlung effects are observed also in the kernel source. These are weaker than the ones observed in footpoints however.

The comparison of results obtained from RESIK (Table 2) and RHESI (Table 1, position 4) data shows the presence of hotter plasma component with temperatures above 20 MK in the rise phase of the event. RESIK spectra analysis shows in addition the presence of the colder plasma component ($T = 5$ MK) in that phase.

The emission from the diffuse source seen in RHESSI images in the gradual phase can be well approximated assuming only isothermal conditions with temperature of 19 MK. However DEM(T) distributions calculated from RESIK spectra shows a presence of two the hotter ($T = 17.4$ MK) and the colder ($T = 5.0$ MK) plasma components in the decay of the flare. Thus the X-ray emission observed for the source in the gradual flare phase can not be realistically explained assuming only isothermal plasma condition.

The determined from RHESSI and RESIK measurements plasma parameters supports the scenario in which energetic nonthermal electrons heat the plasma in the footpoints in the flare rise phase. Then evaporating from the footpoints plasma fills the overall flare magnetic loop system and forms an extended source seen in the gradual phase what gives an explanation to the observed in RHESSI images change in the source configuration and morphology.

Acknowledgements

RESIK is a common project between NRL (USA), MSSL and RAL (UK), IZMIRAN (Russia) and SRC (Poland) RHESSI is a NASA Small Explorer. This work was supported by the Polish Ministry of Science and Higher Education Grants 1.P03D.017.29 and N203 1937 33.

References

Brown, J., Aschwanden, M., Kontar, P. Chromospheric height and density measurements in a solar flare observed with RHESSI I. Theory. Solar Phys. 210 (1), 373–381, 2002.

Gburek, S., Sylwester, J., Sylwester, B., Dennis, B., Phillips, K.J.H. Multi-wavelength study of a strong impulsive solar limb flare on 2002 August 3. Adv. Space Res. 35 (10), 1728–1731, 2005.

Lin, R.P., Dennis, B.R., Hurford, G.J., Smith, D.M., Zehnder, A., Harvey, P.R., et al. The Reuven Ramaty high-energy solar spectroscopic imager (RHESSI). Solar Phys. 210 (1), 3–32, 2002.

Mrozek, T. RHESSI investigation of solar flare footpoints. Adv. Space Res. 38 (5), 962–967, 2006.

Phillips, K.J.H., Chifor, C., Denis, B.R. RHESSI observations of the solar flare iron-line feature at 6.7 keV. Astrophys. J. 647, 1480–1490, 2006a.

Phillips, K.J.H., Dubau, J., Sylwester, J., Sylwester, B. Si XII X-ray satellite lines in solar flare spectra. Astrophys. J. 638 (2), 1154–1161, 2006b.

Smith, D.M., Lin, R.P., Turin, P., Curtis, D.W., Primbsch, J.H., et al. The RHESSI spectrometer. Solar Phys. 210 (1), 33–60, 2002.

Sylwester, J., Gaicki, I., Kordylewski, Z., Kowalinski, M., Nowak, S., Plocieniak, S., et al. Resik: a bent crystal X-ray spectrometer for studies of solar coronal plasma composition. Solar Phys. 226 (1), 45–72, 2005.

Sylwester, J., Sylwester, B., Landi, E., Phillips, K.J.H., Kuznetsov, V.D. Determination of K, Ar, Cl, S, Si and Al flare abundances from RESIK soft X-ray spectra. Adv. Space Res. 42 (5), 838–843, 2008.

Veronig, A., Brown, J. A coronal thick-target interpretation of two hard X-ray loop events. Astrophys. J. 603 (2), L117–L120, 2004.