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On the fine structure of solar flare X-ray loop top sources

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Abstract. Solar flare X-ray loop top sources (LTSs) are known since early observations from Skylab.They are always present accompanying long duration events (LDE), but their nature remains unclear. One of the main unknowns is spatial structure of LTSs. Observations indicate that LTSs are large and diffuse, but several authors suggested that there is present a fine, internal structure within them which should be resolved even using present space instrumentation.We present an example for the solar flare well observed by SDO/AIA and RHESSI. The LTS was dynamic with an episode of splitting into two sources. We performed detailed analysis of X-ray sources morphology using restored RHESSI images. Moreover, we conducted a number of simulations taking into account various possible spatial distributions of X-ray emission. We have found that in case of the flare investigated RHESSI should be capable to detect the fine structure if present. However it is not visible on the restored images. Some of our simulations suggest that we can also miss large, diffuse sources in the X-ray observations which may eventually lead to misinterpretation of the observed X-ray features.

Keywords. Sun: corona, Sun: flares, Sun: X-rays, gamma rays

1. Introduction

Solar flare loop-top sources (LTS) visible in X-rays are common feature of solar flares known since Skylab observations (Kahler 1977). Regardless of flare size, duration or power, LTSs are similar. Their main characteristics (Vorpahl *et al.* 1977, Acton *et al.* 1992, Doschek *et al.* 1995, Feldman *et al.* 1995, Doschek & Feldman 1996, Jakimiec *et al.* 1998, White *et al.* 2002, Jiang *et al.* 2006, Kołomański *et al.* 2011) may be summarized as follow:

- they are filled with hot and relatively dense plasma;
- X-ray spectra are purely thermal, sometimes with trace of very weak non-thermal emission;
- physical parameters change smoothly with time;
- they contain large amount of energy released during flare;
- continious energy input/release must be present to explain LTS visible for several hours.

There is long-standing discussion concerning the fine structure of LTS. Observations in the range of 1-20 keV, reveals LTSs as large, and diffuse sources. Their sizes estimated with a use of SMM/HXIS, YOHKOH/HXT, and RHESSI data are changing from 200 up to 20000 arcsec^2 (Hoyng *et al.* 1981, Krucker & Lin 2008, Masuda *et al.* 1998, Preś & Kołomański 2009, Saint-Hillaire *et al.* 2009). In 1998 TRACE (Handy *et al.* 1999) has been launched, and thanks to its great spatial resolution instead of LTSs we saw filamentary loops in the EUV range. Therefore the question arised: are this different views connected with observations of co-spatial warm (approximately 1 MK) and hot (above

10 MK) structures which are physically different or there is only observational problem connected with differences in spatial and thermal resolutions of instruments? This problem became more severe after clarification of thermal response of TRACE 195 Å filter (Phillips *et al.* 2005). It was shown that images obtained with this filter may reveal hot (>10 MK) structures in EUV images. Such structures, if observed, were diffuse, without fine structure despite high spatial resolution of TRACE data. Similar situation was recorded with Hinode/EIS (Culhane *et al.* 2007) providing us with high spatial resolution (similar to TRACE) spectral images. Preś & Kołomański (2009) have shown that LTSs visible in EIS images have dual nature: warm structures are filamentary, and hot are diffuse. However this observation did not definetly resolve the problem because EIS has low temporal resolution. Each EIS image is obtained by rastering with a slit which takes some time. Therefore, if observed sources change their structure within observational time then details are blured and information about fine structure is lost.

In this paper we present an analysis of loop-top source of the SOL20111022T11:10 LDE observed simultaneously with RHESSI (Lin *et al.* 2002) and SDO/AIA (Lemen *et al.* 2012). This kind of event is characterized by slow evolution of physical parameters. Therefore it gives a chance that any internal structure, if present, may be observed for some time period because instrumental drawbacks may be less limiting.

2. Observational Data

Analyzed flare occurred in the active region NOAA 1314. According to GOES data it started at 10:00 UT and reached maximum brightness at 11:10 UT. The decay phase registered in 1–8 Å band lasted 10 hours. The solar X-ray flux returned to the pre-flare level at about 19:30 UT. The flare is a typical example of long duration event with the slow rise phase (sLDE) (Hudson & McKenzie 2000, Bak-Steslicka *et al.* 2011). Its location was close to the west solar limb, and it had a form of high arcade seen side-on. Such a geometry ensure minimization of projection effects with well resolved features occuring along arcade channel.

The SDO/AIA consists of a set of four 20 cm, normal-incidence telescopes. It provides observations with high angular (1.5 arcsec) and temporal (12 s) resolutions in 10 wavelenghts bands. We investigated morphology of the event and its evolution using SDO/AIA images obtained with 131 Å filter. The filter's thermal response has two narrow maxima: warm (1 MK) and hot (10 MK). As both maxima are almost equal in sensitivity (Boerner *et al.* 2012) we may expect that a hot component of flare emission is not overwhelmed by a warm component. Moreover, the 131 Å band has high thermal resolution for hot maxima. The resolution is as good as for the warm maxima, and much higher than the TRACE 195 Å band resolution for hot plasma. Such characteristics of the 131 Å band made it be a good choice to study LTSs.

RHESSI is a rotating Fourier imager with nine germanium detectors. Detectors are large and cooled to about 75 K, ensuring great sensitivity of the instrument, and allowing for investigation of very low solar flare fluxes that are observed during the decay phase of LDE events. Geometry of the event was investigated with a use of images reconstructed using PIXON algorithm (Pina & Puetter 1993). We used grid selection method (Kołomański *et al.* 2011) which allows to reconstruct reliable HXR images for late decay phase of LDEs.

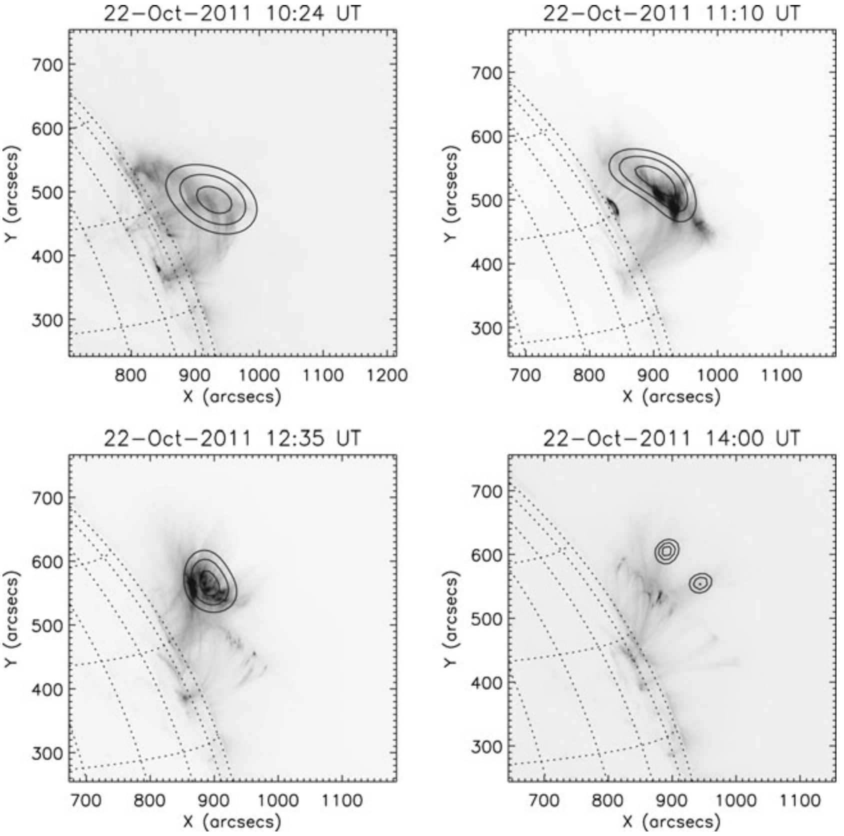

Figure 1. EUV images (grayscale) with X-ray sources (contours) are given in Fig 1 for four moments in time: rise phase (10:24 UT), maximum (11:10 UT), early decay (12:35 UT), and late decay (14:00 UT).

3. Simulations of LTS Fine Structure

The overall evolution of the SOL20111022T11:10 flare is quite typical for sLDE event. It was accompynied by an eruption, footpoints were barely visible in HXRs, and supra-arcade downflows were observed. EUV images (grayscale) with X-ray sources (contours) are given in Fig 1 for four moments in time: rise phase (10:24 UT), maximum (11:10 UT), early decay (12:35 UT), and late decay (14:00 UT). During entire event we observed HXR sources located close to EUV loop tops. Around 12:30 UT we observed one, large X-ray source which was spatially correlated with set of hot EUV sources. We used this interval to search for signs of fine structure in X-ray source, and to check the grid selection method sensitivity to scenario in which LTS consists of several small-scale sources.

Generally speaking, the grid-selection method is based on checking RHESSI single-grid images for any sign of modulation, selection of such grids, and using them for final image reconstruction. If source size is comparable to or larger than grid angular resolution then modulation of signal dissapears. However, we have to remember that if HXR emission is coming from number of small sources, occupying relatively small area, then we cannot see modulation in RHESSI finer grids (high resolution), and misinterpret reconstructed source as a real large source.

We have no information about real structure of observed LTS. Therefore we decided to use AIA 131 Å image as a proxy of possible distribution. In Figure 2 (left panel) we

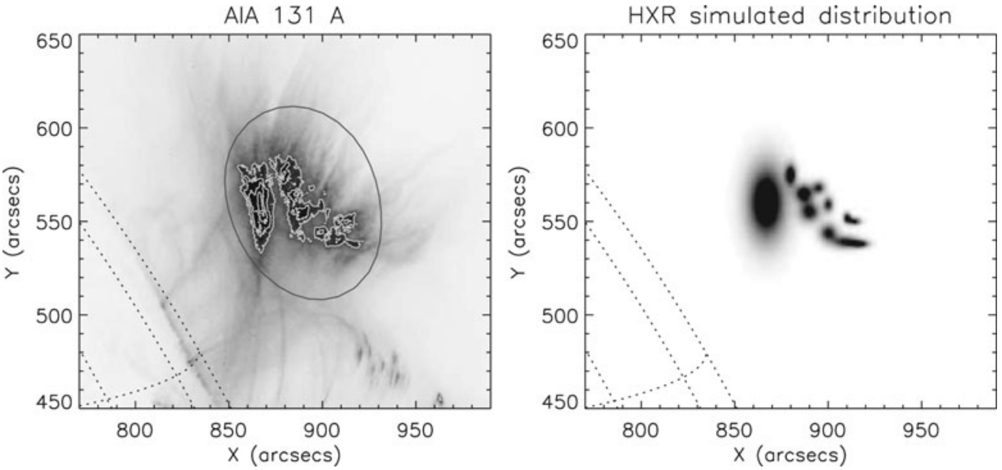

Figure 2. Left panel: AIA 131 Å image taken on 12:35:33 UT. Dark contour represent 50% of maximum of RHESSI source reconstructed for 2-minutes long time interval (12:35-12:37 UT). White contours are drawn for EUV emission with levels of 60, 70, 80, and 90% of the brightest pixel. Right panel: simulated distribution of eleven X-ray sources with sizes, locations, and relative intensity similar to EUV sources visible in left panel.

present AIA 131 Å image taken on 12:35:33 UT. Dark contour represent 50% of maximum of RHESSI source reconstructed for 2-minutes long time interval (12:35-12:37 UT). White contours are drawn for EUV emission with levels of 60, 70, 80, and 90% of the brightest pixel. EUV sources were stable in position and in brightness for several minutes. Taking into account thermal response of AIA 131 Å filter and looking into AIA images obtained in other wavelengths we assumed that LTS may have fine structure similar to observed EUV emission. On the basis of this filter we defined synthetic LTS with sizes, locations, and relative intensity similar to EUV sources. The result is presented in Figure 2 (right panel).

This artificial distribution of X-ray sources was used for testing if RHESSI data and available image reconstruction algorithms are capable to resolve fine structure. After several preliminary reconstructions we decided to use CLEAN and PIXON algorithms which gave most stable results.

Figure 3 presents an example of CLEAN and PIXON image reconstruction for three examples of sets of grids. Reconstructed image show a complex of small sources barely compared to what we simulated. Unexpected result is that we did not see the largest of simulated sources. We performed several other tests in which we tried other scenarios with one large source and various combinations of smaller ones. Even for two-source scenario (one large, and one small) we obtained an image which contained only small source. It is rather unexpected result, not mentioned in previous papers testing performance of various image reconstruction algorithms (Dennis & Pernak 2009, Aschwanden *et al.* 2004). From interpretation point of view this result has serious consequences. It may be possible, that reconstructing images of HXR emission from real observations we may not see large, diffuse sources when smaller sources are present.

Despite a lack of modulation visible in narrow grids, we decided to reconstruct images with grids 3-6, 8, and 9 for the SOL20111022T11:10 flare. Obtained results were compared to image reconstructed, with the same parameters as for real data, for simulated distribution. Using overlapping energy intervals of 6-7, 6.5-7.5, and 7-8 keV we wanted to see if any of reconstructed sources are visible in the same location. Sources

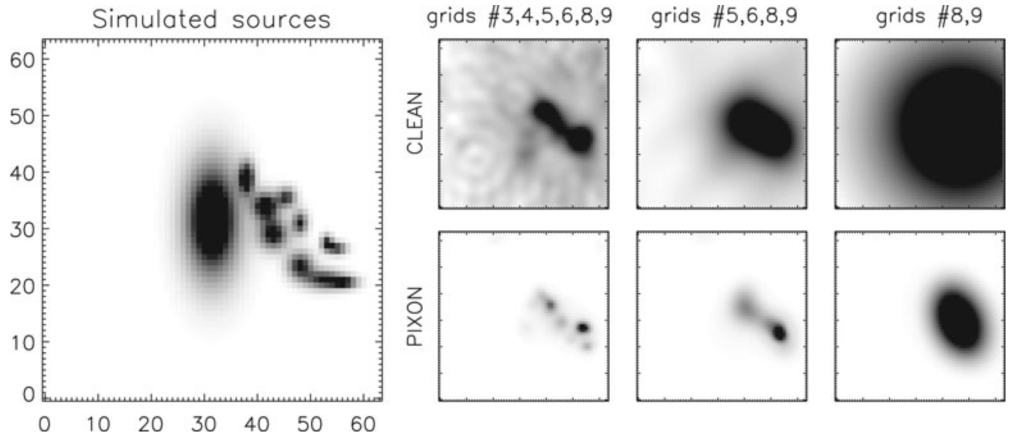

Figure 3. Left panel: Simulated distribution of eleven X-ray sources. Right panels: Results of reconstruction of simulated sources with a use of two algorithms and three sets of grids.

reconstructed for real data present almost no repeatability suggesting that fine structure is absent. However, the same situation is observed for sources reconstructed from simulated distribution. It means that even when the fine structure exist then it is not possible to reconstruct its real distribution.

It is worth to mention that PIXON "is trying" to reconstruct the fine distribution which is visible as sources with sizes comparable to their simulated values, despite different positions. For real data we did not observe such behavior. Images with grid #3 reveals large sources that are significantly larger than resolution of grid #3. Moreover, we reconstructed PIXON images for real data with grid #1 and obtained almost the same picture as for grid #3. We interpret this result as a lack of fine structure in observed source. However, it should be noticed that in a case of many small sources, which intensity changing fast (distribution of "blinking" sources), may produce similar result (Longcope *et al.* 2010).

4. Summary

Investigated the SOL20111022T11:10 flare showed suitable geometry, location and gradual evolution for performing some tests and excercises concerning the existence of fine structure in X-ray loop-top sources. Images reconstructed with grid selection method and PIXON algorithm revealed one or two large sources spatially correlated with EUV emission sources visible in AIA 131 Å. Assuming that there is some relation between EUV and X-ray emission sources we constructed artificial fine-structured X-ray source. Next, we reconstructed images with a use of real and simulated RHESSI data. Obtained results may be summarized as follow:

- Reconstruction algorithms have signifant problems when sources differ in size significantly (more than order of magnitude). Large source is not reconstructed when small ones are present.
- Sources reconstructed for real data present almost no repeatability suggesting that fine structure is absent. However, the same situation is observed for sources reconstructed for simulated distribution. It means that even when the fine structure exist then it is not possible to reconstruct it.
- Small-scale structure of LTS can not be decisively excluded, but they are less likely.

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