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ELUSIVE NATURE OF X-RAY FLARE LOOP-TOP SOURCES

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Abstract. Loop-top sources (LTSs) are remarkable X-ray features of solar flares. They are diffuse, bright regions seen close to a flare loop apex. They form before the flare maximum, and may last many hours. Loop-top sources were first recorded in images taken from the Skylab space station almost forty years ago. More recent observations made by the *Yohkoh* satellite showed that LTSs are common characteristics of solar flares regardless of a flare's size, duration or power. Nevertheless the sources are still not well understood. Moreover we are not sure if LTSs are diffuse but coherent regions or their diffuse appearance is 'formed' by instrumental imperfection. Can present-day space instruments help us to solve the mystery of LTSs? We use data from *RHESSI* to study geometrical properties of LTSs of nine flares. We found that the size-altitude relation discovered for LTSs based on *Yohkoh*/SXT data is valid also for LTSs observed by *RHESSI*. Our results seem to support the possibility that loop-top sources have a diffuse nature.

Key words: solar flares - hard X-rays - coronal sources - energy release

1. Introduction

Loop-top sources (LTSs) are remarkable X-ray features of solar flares. They appear as diffuse, bright regions seen close to a flare loop apex. LTSs form at the beginning of a flare and may last many hours (e.g. Feldman *et al.*, 1995; Kołomański, 2007a). The sources were first recorded on images taken from the *Skylab* space station. Kahler (1977) reported that in arcade flares a 'bright linear feature' runs along the tops of the loops. The linear structure was sometimes resolved into a system of knots (sources). In the paper by Vorpahl *et al.* (1977) the authors discovered that loop top sources last long and are the brightest, hottest and densest parts of flaring loops. To explain the observed properties the authors suggested that it is necessary to add

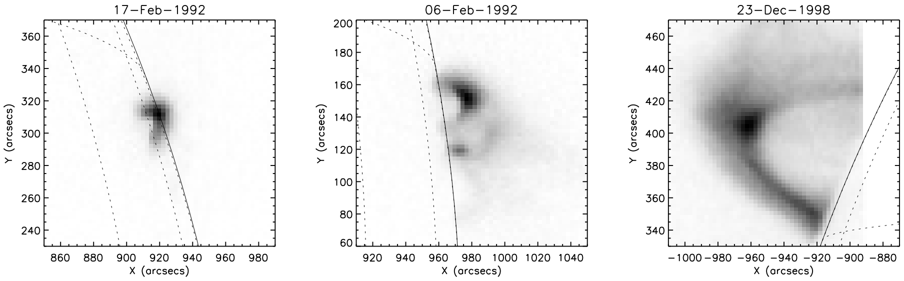

Figure 1: Three examples of flares with loop-top sources observed by *Yohkoh*/SXT. X-ray class of the flares is similar (from the left to the right: M1.9, M7.6, M2.3) but they differ in geometrical size. Field of view is the same in each image, 140 × 140 arcsec.

mass and energy to LTSs and to restrict mass and energy outflows from the sources during the whole duration of a flare.

More recent observations made by the *Yohkoh* satellite showed that LTSs are common characteristics of solar flares regardless of the flare size, duration or power (see Figure 1). Investigation of LTSs carried out by many authors using X-ray images from *Yohkoh*, led to several important conclusions (Acton *et al.*, 1992; Doschek *et al.*, 1995; Feldman *et al.*, 1995; Doschek and Feldman 1996; Jakimiec *et al.*, 1998; White *et al.* 2002; Kołomański 2007ab):

- hot plasma (about 20 MK) is concentrated in a volume at loop tops (in LTSs),
- LTSs are visible throughout the whole duration of a flare (up to several hours in long-duration flares),
- their contribution to the total flare emission is of the order of 40 % (in soft X-rays),
- energy should be added to LTSs continuously,
- mass and energy outflow should be restricted (this was confirmed by radio data - electrons need to be trapped at loop tops),
- temperature distribution in LTSs is quite uniform (different sections of LTSs must be in physical contact),
- LTSs probably cannot be modelled using simple 1D numerical approximation of a loop.

Preś and Kołomański (2007) studied geometric and physical parameters of a large sample of LTSs. The authors found several interesting statistical relations between the parameters. It turned out that basic observables of LTSs separate into two independent pairs: (area projected on the image, i.e. size, altitude above the photosphere) and (mean temperature, total emission measure). The relation in the first pair indicated that the higher the altitude, the bigger the size of an LTS. The size measured as projected area, A, of an LTS distinctly rises with its altitude, h (Figure 2). The relation is a power-law with index 1.13 ± 0.04. This relation has a power index 0.56 for the source mean radius, and 1.69 for the volume. The size-altitude relation (SAR), i.e. higher flares should have bigger LTSs, seems to be obvious (big flare syndrome), but it is not. If we assume that the source is a part of the hosting loop, then the loop cross-section area must show the same relation as SAR for the source mean radius. This means that higher flare loops are not linearly scaled version of smaller loops, i.e. a loop diameter is not proportional to a loop length, but rather to its square root. The higher loops must be systematically narrower than the smaller ones.

From many studies based on *Yohkoh* data it seemed that in the case of LTSs we deal with a diffuse, coherent region, physically different from the rest of a hosting loop and from so-called post-flare loops. However, data from new instruments have complicated the situation.

2. *TRACE* versus *Hinode*

TRACE (Handy *et al.* 1998), launched in 1998, cast doubts on the diffuse nature of LTSs. This EUV telescope has higher spatial resolution than *Yohkoh*/SXT. In *TRACE* images of solar flares a set of sharp loops is seen instead of diffuse loop-top sources (Figure 3). Although *TRACE* is the most sensitive to plasma at quite different temperatures (1 – 2 MK) than SXT (∼ 10 MK) it was suggested that diffuse appearance of LTSs comes from the insufficient spatial resolution of SXT and that the sources are in fact composed of multitude of tops of filamentary loops.

Nevertheless, some *TRACE* observations of solar flares, especially in the 195 Å band, reveal diffuse structures located above narrow loops. Location of these diffuse structures corresponds well with the *Yohkoh* loop-top sources (see e.g. Figure 2 in Warren *et al.*, 1999). Thus, the diffuse nature of LTSs is not caused by low spatial resolution. However, there is another instrumental

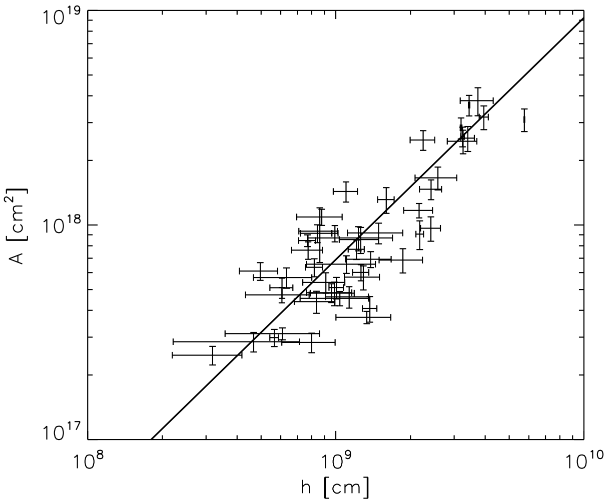

Figure 2: Relation between the projected LTS area (A) and its altitude above the photosphere (h) for the time of maximum LTS brightness as seen in SXT images. From Preś and Kołomański (2007).

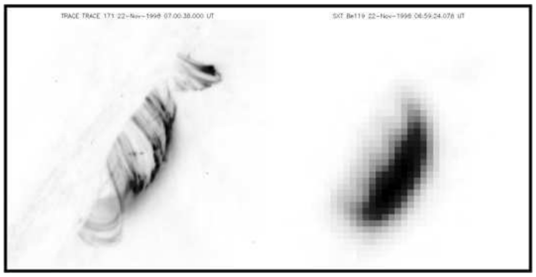

Figure 3: Comparison of structure of SOL1998-11-22T06:42 limb flare as seen in the *TRACE* 171 Å (left) and the SXT Be119 (right) filters. Loop-top source visible as diffuse structure in the SXT image appears to consist of many filamentary loops seen in the *TRACE* image.

factor that may lead to diffuse appearance of these sources in *TRACE* images. Plasma in solar flares is multithermal. A thermal response of the 195 Å channel has two distinct maxima (see Figure 3 in Phillips *et al.*, 2005). The higher maximum comes from FeXII line, that forms at temperatures from 1 to 2 MK whereas the second one is produced by FeXXIV line in temperatures from 10 to 30 MK. Due to different thermal widths, from the multitude of loops with different temperatures the cooler maximum selects much less loops while the hotter maximum sees many overlapping loops forming a diffuse region. Despite very good spatial resolution, *TRACE* had insufficient thermal resolution for hot, flare plasma. Thus concluding anything about the structure of hot LTSs from this data is quite risky. Nonetheless it was suggested that LTSs are observed as large, diffuse sources only due to instrumental imperfection, i.e. too low resolution.

The EUV Imaging Spectrometer (EIS) is one of the three scientific instruments aboard *Hinode* (Culhane *et al.*, 2007). EIS provides observations in many spectral lines from two wavelength ranges: 170–210 Å and 250–290 Å. High spectral resolution EIS images can be obtained by rastering with a slit. Moreover, the images are taken in several spectral lines simultaneously. The instrument has not as high angular resolution (about 2 arcsec) as *TRACE* but it can record emission of hotter plasma. Among several spectral windows, the 'hottest' EIS band is the one that includes line of CaXVII at 192.82 Å. The line forms at a temperature $4.5 - 7.5$ MK, i.e. it can reveal a cooler component of a flare emission. Moreover, the thermal resolution in this line is much higher than the *TRACE* thermal resolution for hot plasma.

Preś and Kołomański (2009) analysed EIS observations of the long-duration flare SOL2006-12-17T17:12. The authors reported that the flare emission was seen in the form of sharp filamentary loop structures in lines with formation temperatures below 3 MK (e.g. FeXII 195.12 Å), as in typical *TRACE* images. But in the Ca XVII image, there is an additional set of sharp loops with a distinct, diffuse LTS (see Figure 4). Thermal resolution of the CaXVII line is as high as of the FeXII line observed both by EIS and *TRACE*. Thus, diffuse appearance of the LTS of SOL2006-12-17T17:12 cannot be explained by overlapping of many independent loops as it was suggested in the case of *TRACE*. Preś and Kołomański (2009) estimated for the LTS its projected area, A, and altitude, h, and compared the obtained results with the SAR relation found for *Yohkoh*/SXT (see Figure 7). Even with higher thermal resolution of EIS, the LTS appears to follow the SAR relation from SXT. This could mean that LTSs have diffuse nature, but much more observations from EIS is needed to draw such a conclusion. Unfortunately, due to low solar activity in the recent years and due to some characteristics of EIS observing modes it is hard to find suitable data. Therefore we decided to use *RHESSI* observations.

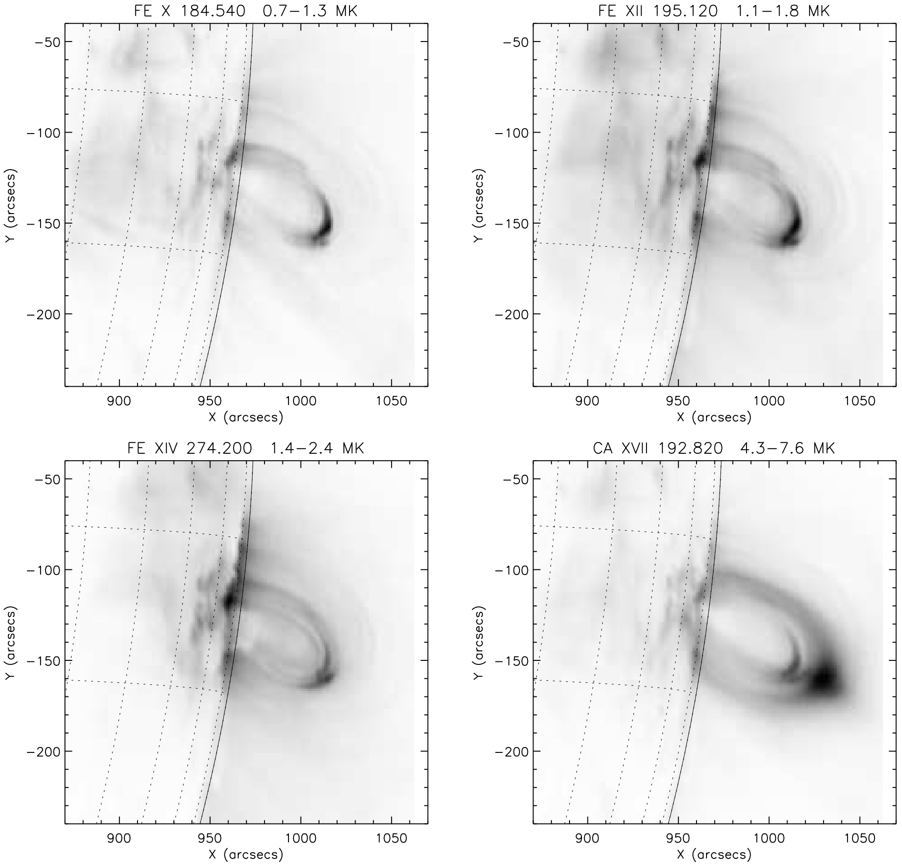

Figure 4: EIS intensity maps of the SOL2006-12-17T17:12 flare for 4 lines emitted by FeX, FeXII, FeXIV and CaXVII ions. Characteristic temperatures of the line formation are given.

3. LTS Observations with *RHESSI*

RHESSI is a rotating Fourier imager with nine detectors made of pure germanium crystals (Lin *et al.*, 2002). The detectors record the energy and arrival time for each detected X-ray photon. The satellite enables us to obtain images and spectra of solar X-ray sources with high angular (2.3 arcsec) and spectral (1 keV for imaging spectroscopy) resolution.

High quality *RHESSI* observations offer a good possibility to study the nature of LTSs (e.g. Jiang *et al.*, 2006; Vaananen and Pohjolainen, 2007; Caspi and Lin, 2010), and maybe find a piece of evidence that will help to

Table I: List of analysed flares. (1) - Event, (2) - *GOES* class, (3) - Heliographic coordinates

	(1)	(2)	(3)
1	SOL2002-08-03T19:07	X1.0	S15W81
2	SOL2002-10-25T17:47	M1.5	N36W09
3	SOL2003-08-25T02:55	C3.6	S11E41
4	SOL2003-11-11T16:15	C8.5	N00E89
5	SOL2004-01-05T03:47	M6.9	S05E57
6	SOL2005-01-20T07:01	X7.1	N18W74
7	SOL2005-08-22T01:34	M2.7	S10W52
8	SOL2005-11-29T17:10	C4.0	S14W45
9	SOL2007-01-25T07:15	C6.3	S07E90

tell what is the structure of the sources. Kołomański *et al.* (2011) analysed three long-duration flares. The authors used *RHESSI* imaging spectroscopy to obtain physical parameters of LTSs and to calculate the energy balance of the observed sources. One of the conclusions presented in the paper is that each LTS observed was smooth, without any internal structure despite the high angular resolution of *RHESSI*. No LTS was visible in images reconstructed for the four narrowest grids (angular resolution $2.3 - 12$ arcsec). Thus, a large, diffusive LTS cannot be explained as a superposition of smaller unresolved subsources unless the separations of the subsources are smaller than the angular resolution of the finest *RHESSI* grid.

For our analysis we selected nine flares well observed by *RHESSI*. We chose flares of significantly different power and duration. The flares are listed in Table I and are shown in Figure 5. For each flare we reconstructed images with a PIXON algorithm (Puetter and Yahil 1999, and references within) in 1 keV energy intervals. To obtain images as good as possible we used a method of grid selection described by Kołomański *et al.* (2011).

4. Analysis and Results

Our goal was to check whether LTSs observed by *RHESSI* follow the SAR relation from SXT. For this purpose we estimated geometrical parameters of the LTSs (altitude, projected area) similarly as in Preś and Kołomański

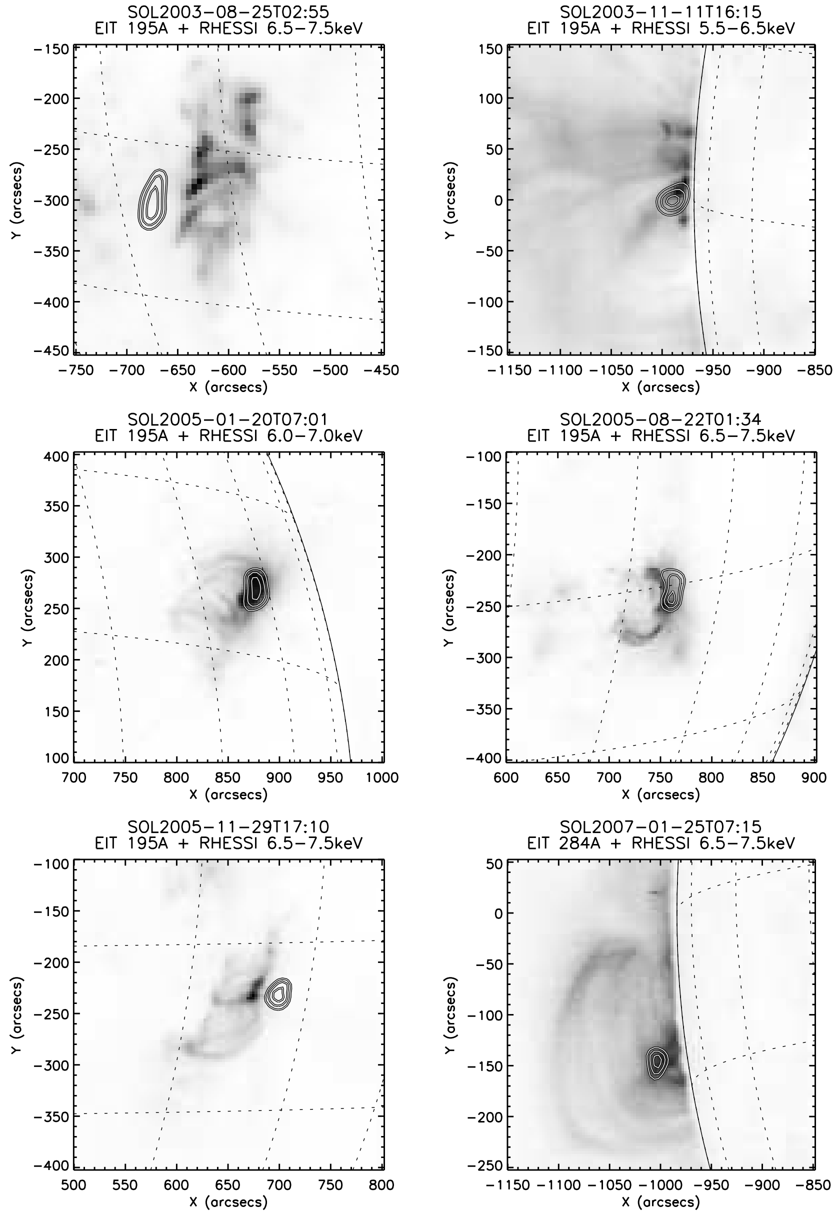

Figure 5: *RHESSI* images (contours) overlaid on *SoHO*/EIT images for 6 of 9 analysed flares. Images show the flares at their maximum phase. Contours have values 0.5, 0.7 and 0.9 relative to the maximum of brightness in a given *RHESSI* image. The solar limb and heliographical grid are shown. Each image has 300 × 300 arcsec field of view.

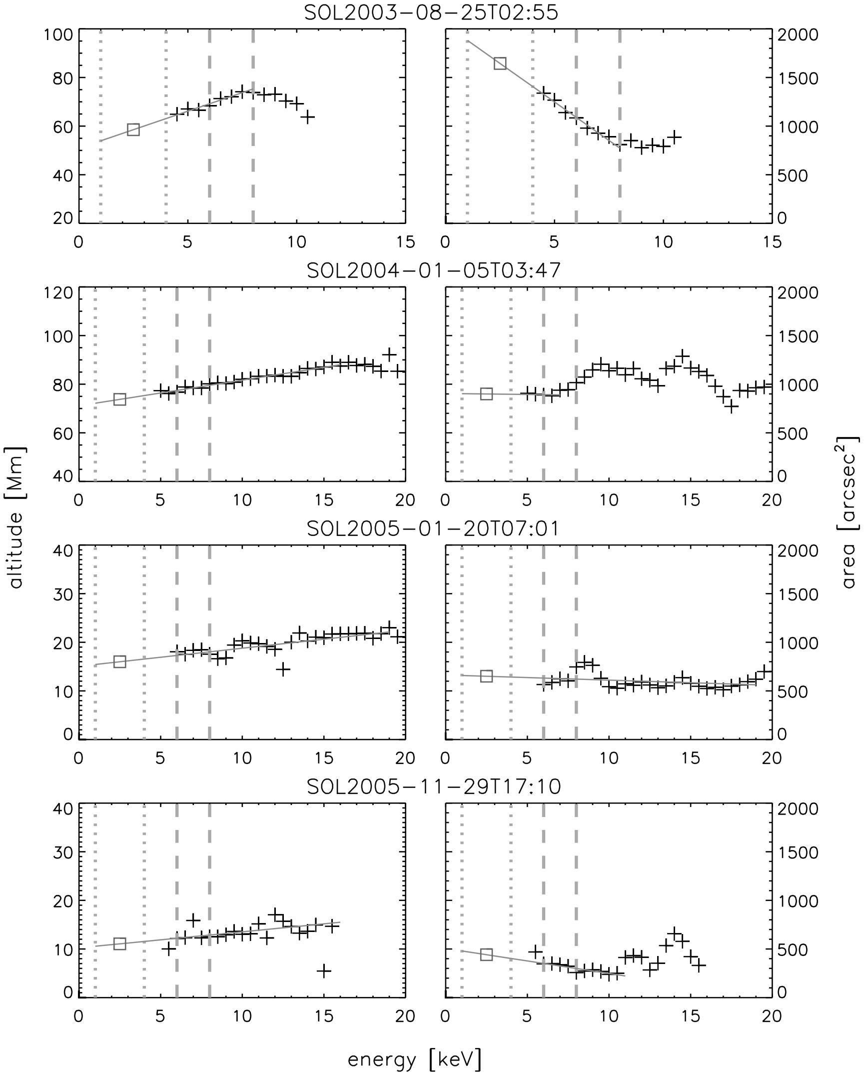

Figure 6: Relation between LTS altitude above the photosphere and energy (the left column) and between the projected LTS area and energy (the right column) obtained from *RHESSI* data. The relation is shown for 4 of 9 analysed flares. Altitude and area calculated for *RHESSI* energy range 5.5 − 8.5 keV (dashes vertical lines) were converted to SXT energy range 1 − 4 keV (dotted vertical lines). Linear fit to the relations were used to perform the conversion. The fit is shown by a grey line. LTS altitude and area for SXT range were calculated from extrapolation of the fit. Result of this extrapolation is shown by a grey square.

(2007). An LTS altitude was corrected for projection effect and an LTS projected area was defined by 50% intensity isoline relative to the brightest pixel in an image. Both parameters were estimated for the same time, as close as possible to the maximum of brightness of a flare (measured by GOES in the $1-8$ Å channel). To increase reliability and stability of the results each pair (altitude, area) was calculated as a mean value from five 1 keV wide *RHESSI* images in the energy range $5.5-8.5$ keV.

When comparing *RHESSI* results with SXT results we must keep in mind that these two instruments record radiation in slightly different energy ranges: $1-4$ keV for SXT and above 3 keV for *RHESSI*. Although the ranges overlap, in practice the reliability of RHESSI observations below 5 keV is low. Thus, we have to use a bit higher energy range $5.5-8.5$ keV. In such a case we must check how LTS altitude and size change with energy. The comparison of the results can be done only if altitude and size from *RHESSI* can be converted somehow to SXT energy range. For this purpose we decided to estimate altitude and area of a given source in energy range as wide as possible, i.e. in a range the source was visible (usually from ≈ 5 to ≤ 20 keV). Then we found the relation between energy and altitude or area and from extrapolation of the relation results for SXT range were estimated (see Figure 6).

The results of our study are shown in Figure 7 together with the previous results for SXT (Preś and Kołomański, 2007) and EIS (Preś and Kołomański, 2009). LTSs altitude and area (with error bars) from *RHESSI* observations are shown as estimated for the energy range $5.5-8.5$ keV. Arrows at each data point show a change in the parameters after extrapolation from the actual energy range to the SXT energy range. This change is not significant enough to alter the overall picture – the SAR relation is fulfilled by results obtained from different instruments.

5. Conclusions

Two possibilities concerning the nature of loop top sources are considered at the present time:

- LTSs are relatively large, diffuse but coherent regions, physically different from the rest of a hosting loop and from 'post-flare loops'. If this is true sections of LTS are not physically separated because a similar temporal evolution of the section and smooth change of physical

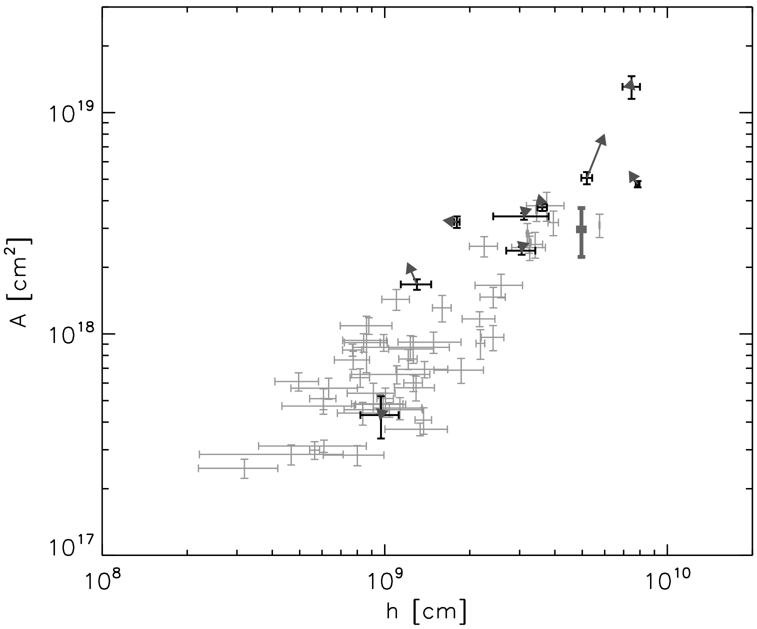

Figure 7: Relation between the projected LTS area (A) and its altitude above the photosphere (h) for the time of the maximum of a flare as seen by SXT (thin grey, from Preś and Kołomański (2007)), EIS (thick grey, form Preś and Kołomański (2009)) and *RHESSI* (black, this paper). Arrows at each *RHESSI* data point show a change in the parameters after extrapolation from the actual energy range to the SXT energy range.

parameters is observed. Moreover, energy and plasma outflows from the source should be suppressed (e.g. Jiang *et al.*, 2006; Kołomański *et al.*, 2011). A small-scale internal structure cannot be excluded (e.g. Jakimiec *et al.*, 1998). In this case the main problem to solve is how such LTSs form.

- LTSs diffuse appearance is 'formed' by instrumental imperfection (too low angular, thermal and temporal resolutions). Superposition of multitude of separate filamentary tops of loops made by magnetic reconnection creates an illusion of large, diffuse source (Warren, 2000; Longcope *et al.*,2010). If this is true the main problem to solve is how a region that consists of multiple isolated elements can produce a gradual and smooth change of physical parameters.

In this paper we try to find a new piece of evidence that would help us to tell which possibility is true. We decided to check if the size-altitude relation (SAR) found for LTSs based on *Yohkoh*/SXT data is valid also for LTSs observed by *RHESSI*. If not, it would mean that diffuse appearance LTSs is not real.

Nine flares of significantly different power and duration were selected for our analysis. In each flare one distinct LTS was observed. An altitude and a projected area of each LTS was determined from 1 keV wide images in the energy range $5.5 - 8.5$ keV. However, the results from *RHESSI* are for a slightly different energy range than the results from SXT ($1 - 4$ keV). Thus, we found the following relations: altitude vs. energy and area vs. energy for the *RHESSI* results and then from extrapolation of the relations we calculated altitude and area for the SXT energy range. The original and converted results do not differ much from each other (Figure 7). Both sets of results seem to follow the SAR relation found earlier by Preś and Kołomański (2007) form SXT observations.

Does it mean that LTSs are diffuse structures? Our result seem to support this possibility. If the diffuse appearance of the sources was only an instrumental effect their projected area should be different when seen with instruments of different angular, thermal and temporal resolutions. And in such a case the SAR relation would not be similar for results from different instruments. Of course, the result presented in this paper is not the final evidence. To find this evidence a further study on the nature of LTSs is needed. The study that will use data from more and more advanced solar telescopes (e.g. AIA on-board *SDO*) and numerical simulations. At the moment one is sure that a correct model of solar flares cannot be built without understanding the properties and nature of LTSs.

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