VERTICAL STRUCTURE OF HARD X-RAY SOURCES IN SOLAR FLARES

S. Masuda

National Astronomical Observatory, Mitaka, Tokyo 181, Japan *

Abstract

Hard X-ray images of unbiasedly sampled ten flares, which occurred near the solar limb and were observed with the Hard X-ray Telescope (HXT) aboard *Yohkoh* during the period from October, 1991 to September, 1993, are analyzed in detail to investigate the vertical structure of hard X-ray sources. From temporal, spectral, and structural behaviors derived from series of images, it is found that hard X-ray sources are classified into three types: "(double) footpoint source(s)", "loop-top impulsive source", and "loop-top gradual source". Characteristics of these components, as well as their interpretation, are discussed.

1. Introduction

Hard X-ray emission from solar flares provides us with the most direct information concerning where and how electrons are energized and confined, as well as where they lose energy due to collisions with ambient plasmas. Though the double-source structure frequently observed $\gtrsim$ 30 keV has been confirmed by Sakao (1994) as the fundamental structure, it may only represent the double footpoints in the chromosphere into which the energized electrons stream down and in which they lose energy. Thus it does not necessarily reveal the primary energy release site in solar flares. On the other hand, several authors (*e.g.*, Frost and Dennis 1971; Hudson 1978; Kane *et al.* 1979) have reported coronal hard X-ray sources for a limited number of behind-the-limb flares. If such a coronal source is observed simultaneously with the double footpoint sources in a single flare, it may help us to understand more clearly where electrons are energized. It is important to establish the three-dimensional structure of hard X-ray sources in order to derive the distribution of energetic electrons in flaring loops.

* current address : *Solar Terrestrial Environment Laboratory, Nagoya University, 3-13 Honohara, Toyokawa-shi, Aichi 442, Japan*

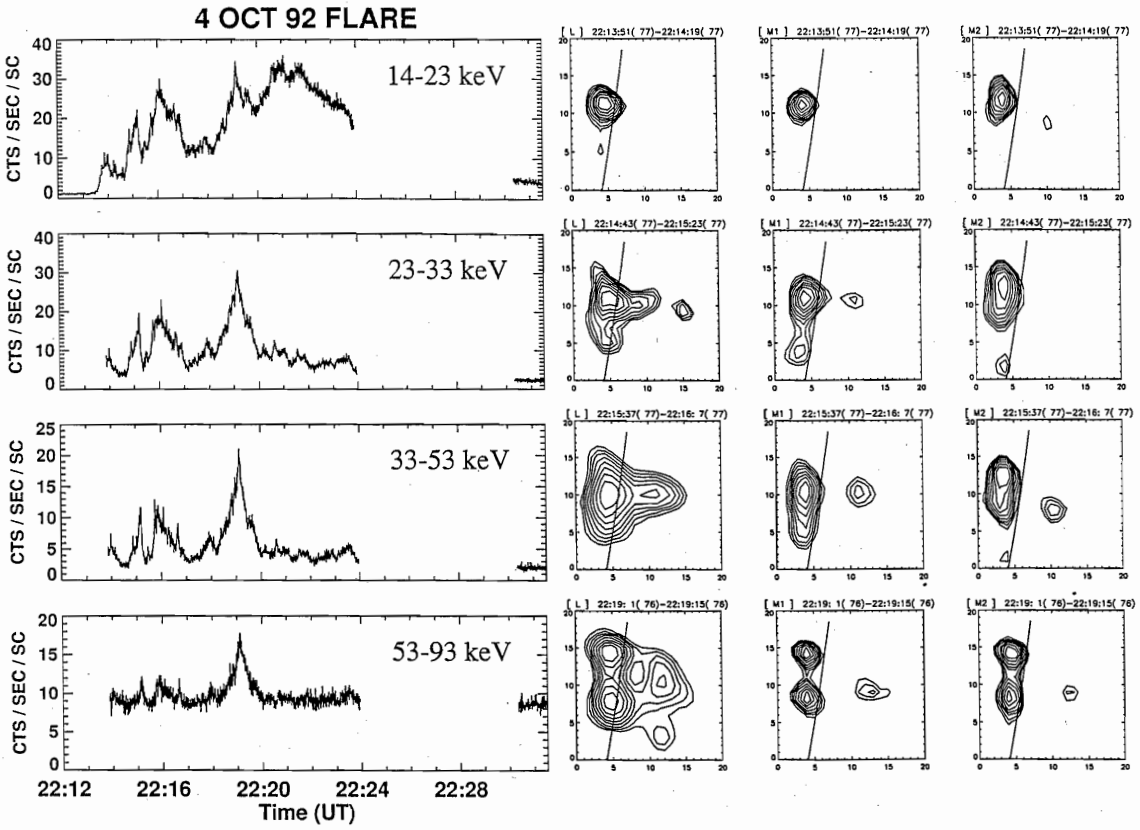

Fig. 1. HXT time profile (left) and images (right) of the 4 October, 1992 flare. Each frame covers 49 × 49 arcsec. Contour levels are 70.7, 50.0, 35.4, 25.0, 17.7, 12.5, 8.8 and 6.3% of the peak intensity for each map.

2. Observation and Data Selection

The Hard X-ray Telescope (HXT; Kosugi *et al.* 1991) on board *Yohkoh* is a hard X-ray imager with high sensitivity and a wide field of view covering the whole Sun. The angular resolution is $\sim$ 5 arcsec. The HXT covers the 13.9 to 92.8 keV energy range in four energy bands, *i.e.*, the L-, M1-, M2-, and H-bands (13.9 – 22.7 – 32.7 – 52.7 – 92.8 keV). The basic temporal resolution is 0.5 s. With these capabilities, HXT detected more than 850 flares during the period from October, 1991 to September, 1993. Out of more than 850 events, ten flares that satisfy the following two criteria were chosen to examine the vertical structure of hard X-ray sources: i) peak count rate in the M2-band exceeding 10 cts/s/SC, and ii) heliocentric longitude exceeding 80°. Criterion i) is to guarantee that at least one image is available up to the M2-band and ii) is set to choose near-the-limb flares.

3. The 4 October, 1992 Flare

Because of the brevity of this paper, we will discuss in detail only one example, a GOES M2.4-class flare occurring on 4 October, 1992 at S05W90. As shown in figure 1 (left), four spikes are seen in the energy range in and above the M1-band. In the L-band these spikes are superimposed on a gradually-varying component. The L-band hard X-ray intensity still

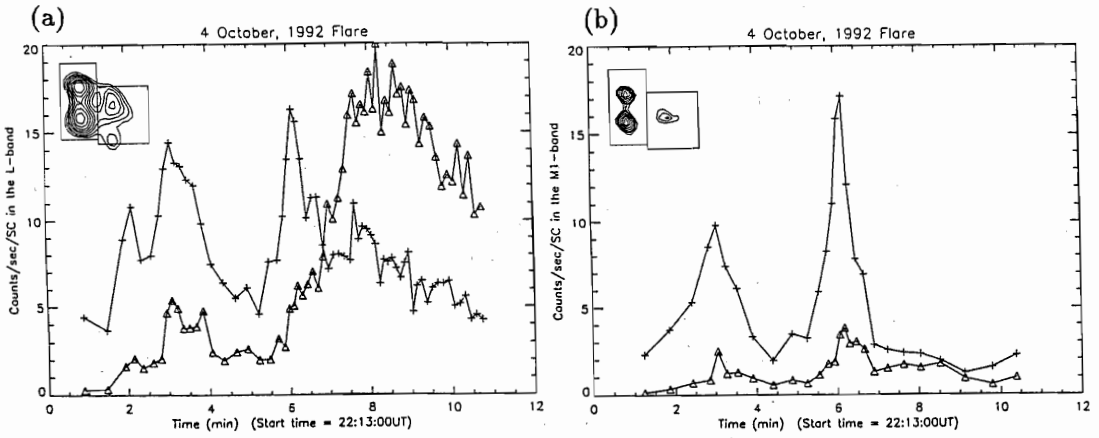

Fig. 2. Comparison of time histories between footpoint and loop-top sources for the 4 October, 1992 flare. (a) Time profiles in the L-band for the footpoint (+) and loop-top sources (△). (b) Same as (a) but for M1-band.

increases after the peak of the fourth spike and reaches its maximum with ~ 2 minutes later.

Figure 1 (right) shows hard X-ray images taken with HXT in the L-, M1-, and M2-bands (from left to right) in time series (from top to bottom). The time series correspond to the initial spike (~22:14 UT; hereafter spike P0) and the three prominent spikes (~ 22:15, ~ 22:16, and ~ 22:19 UT; hereafter spikes P1, P2, and P3, respectively).

At spike P0, images in the L-, M1-, and M2-bands show almost the same structure, a single compact hard X-ray source. This source may represent one of the footpoint pair or an unresolved pair itself. At spike P1, we perceive a horizontal expansion of the compact source in the three energy-band images as well as an upward expansion in the L-band image. These apparent expansions continue until spike P3, when the double-source structure becomes most clearly seen at a low altitude ("(double) footpoint source(s)"). In addition, another source becomes visible at spikes P2 and P3 at a location high in the corona ("loop-top source"). It is noteworthy that the footpoint source is dominant throughout the impulsive spikes from P0 through P3. The double sources at P3 are not located at the same place as those at the previous spikes. It seems that the flare energy is released not in a single loop repeatedly but progressively in overlying higher loops with time. Other points to be mentioned are that the loop-top source at P2 and P3 are located well above the corresponding soft X-ray flaring loop structure (Masuda 1994), and that it becomes slightly weaker in relative intensity to the footpoint source in higher X-ray energies, *i.e.*, its spectrum is slightly softer than the footpoint source.

Time histories of X-ray fluxes, separately for the footpoint source and the loop-top source, are shown in figure 2. In the L-band (figure 2(a)), the footpoint source dominates in the impulsive phase (22:14 – 22:20 UT) while that the loop-top source becomes dominant in the gradual phase (after 22:20 UT). The loop-top source, however, does exists in the impulsive phase and shows a similar variation to the footpoint source throughout the impulsive phase, which is most clearly seen at spikes P1 and P2.

The impulsive nature of the loop-top source is more clearly seen in the M1-band (figure 2(b)). Although the time resolution of this plot is lower due to weaker X-ray intensity, this figure more vividly shows that the loop-top source varies impulsively as the footpoint source. On the other hand, the gradual intensity increase of the loop-top source in the M1-band is not

so clearly seen as in the L-band. The impulsive behavior of the loop-top source is confirmed also from the time plot in the M2-band (not shown), but with a poorer time resolution.

4. Summary and Conclusion

From similar analyses of ten near-the-limb flares, we find that, in the impulsive phase, hard X-ray sources are located not only at a pair of footpoints of a flaring loop but also at or near the top of the loop. Later in the gradual phase, a loop-top source dominates whose characteristics differ from the loop-top source in the impulsive phase. Thus there is no doubt that three different hard X-ray components, namely "(double) footpoint source(s)", "loop-top impulsive source", and "loop-top gradual source", coexist even in a single solar flare. The characteristics of these three components are the following.

(Double) Footpoint Source(s): Sources of this type usually dominate over the hard X-ray emission in the impulsive phase, especially in $\gtrsim$30 keV. They tend to appear in pairs at the two ends (or footpoints) of a soft X-ray flaring loop; the double-source footpoint structure is seen in seven events out of the ten. The impulsive variation and hard spectrum are explained as originating from non-thermal electrons accelerated around the top of the loop and precipitating down along the loop into the chromosphere.

Loop-top Impulsive Source: Sources of this type appear in six events out of the ten. The source is relatively compact and is located well above the apex of the corresponding soft X-ray flaring loop (three events out of the six), or at or near the apex (the remaining three events). The temporal and spectral characteristics of the source are similar to those of the footpoint source, so that this source is intimately related to the footpoint source. Maybe the loop-top impulsive source represents the primary energy release site of solar flares.

Loop-top Gradual Source: Sources of this type appear at the apex portion of the corresponding soft X-ray flaring loop as a single source in all of the ten. This loop-top source is slightly diffuse and sometimes seems to trace the loop seen in soft X-rays. Although the source begins to brighten in the impulsive phase, it is most clearly in the gradual phase and seen below 30 keV . This source may represent the creation of high-temperature plasma.

The results obtained from this work casts strong constraints on the flare theory. Any flare model is required to explain the relation between the loop-top impulsive source and the footpoint source. The location of the loop-top impulsive source above the corresponding soft X-ray loop suggests the crucial importance of hard X-ray imaging observations to investigate the primary energy release mechanism in solar flares. Further studies will be made in the near future.

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