HARD X-RAY IMAGING OBSERVATIONS OF FOOTPOINT SOURCES IN IMPULSIVE SOLAR FLARES

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Abstract

Hard X-ray imaging observations of intense impulsive flares with the *Yohkoh Hard X-ray Telescope* have revealed that the hard X-ray emission in an energy range above 30 keV originates most frequently from double sources, suggesting that bulk of hard X-rays is emitted from footpoints of flaring magnetic loops. Temporal and spectral behaviors of the double sources are described and their physical implications discussed.

1. Introduction

Hard X-ray imaging observations of solar flares are expected to provide us with key clues to understand the origin of hard X-ray emission, acceleration and propagation of energetic electrons, and sites of particle acceleration with respect to flaring magnetic loops. In the early observations with *Hinotori* and *SMM*, several authors reported double-source structures in their hard X-ray images from a limited number of flares (see, *e.g.*, Hoyng *et al.* 1981). These observations suggest emission from footpoints of flaring loops, while others reported single-source structures (*e.g.*, Takakura *et al.* 1984). As for the origin of hard X-rays, Duijveman *et al.* (1982) claimed simultaneous brightening of hard X-ray double sources within $\sim$ 10 s, which may suggest that hard X-rays are emitted by accelerated electrons. However, due mainly to the low time resolution ($\sim$ 10 s) of hard X-ray telescopes aboard *Hinotori* and *SMM*, the origin of hard X-rays (thermal or non-thermal) has not yet been clarified (Dennis 1988). Also rather low energy ranges of these telescopes (typically below 20 keV), possibly contaminated by thermal

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emission of flares, prevent us from deriving firm conclusion on the characteristics of solar flare hard X-ray sources. The *Hard X-ray Telescope* (HXT; Kosugi *et al.* 1991) aboard *Yohkoh* (Ogawara *et al.* 1991) has advanced capability over its predecessors; in particular, it images solar flare hard X-ray sources in energy bands above 30 keV, in which no imaging observation had yet been carried out. Thus, HXT observations of hard X-ray sources in solar flares, especially sources in impulsive flares, in which a large amount of released energy is believed to be converted into particle acceleration, are expected to give us essential information on particle acceleration and subsequent hard X-ray emission. In section 2, we present a statistical study on hard X-ray source morphology in impulsive flares observed with HXT in the 33-53 keV band (M2 band). In section 3, we present case studies on characteristics of hard X-ray double sources observed in impulsive flares. Details of these studies are given by Sakao (1994).

2. A Statistical Study

Among flares observed with HXT between October 1991 and December 1992, a total of 28 was selected for a statistical study on a criterion that they have peak count rates in the M2 band of ≥ 30 cts/s/SC. There were 5 other flares which satisfied the count rate threshold, but they were excluded because they were either behind-the-limb events (so that emission from footpoints may be missing), long duration events with no impulsive behavior in the observed hard X-ray time profiles, or events with no background data available. We classified hard X-ray images of the 28 flares in the M2 band into three morphological classes, *i.e.*, single source, double sources, and multiple sources that consist of more than two discrete sources; all of the observed sources were patchy. We see that about 40 % (12 flares) of impulsive flares show double sources. The rest of the flares show either multiple- ($\sim$ 30 %; 8 flares) or single-source structure ($\sim$ 30 %; 8 flares).

The double sources are usually located on both sides of the magnetic neutral line. Moreover, they seem to be located on both ends of a long, thin structure which is seen in the L band (14-23 keV), possibly tracing a flaring magnetic loop. This suggests that the double-source structure, seen in an energy range above 30 keV, is not just a chance encounter of two distinct single sources, but it reflects fundamental process involved in the hard X-ray production: at least in impulsive flares, hard X-rays above 30 keV are emitted mainly from footpoints of flaring magnetic loops. As is shown below, intensity of hard X-ray emission from the footpoints is closely related to magnetic field strength (or field convergence) of the footpoints. The observed single-source structure can be explained if one of the footpoints of a flaring loop has such a strong magnetic field convergence that hard X-ray emission from the footpoint is too weak to be imaged by HXT. As an alternative explanation, if the flaring loop is so small, emissions from the two footpoints cannot be resolved by HXT, thus a single source would be observed. Multiple sources may be the ensemble of double sources.

3. Case Studies

Out of the 28 flares mentioned above, seven flares, which show the distinct double-source structure at the peak of hard X-ray emission, were selected for detailed studies. These flares are listed in table 1. Characteristics of the double sources are studied from viewpoints of: (1) temporal correlation in hard X-ray flux between the double sources, (2) locations of the double sources with respect to the corresponding photospheric magnetic field, and (3) hard X-ray spectra of the double sources structure.

Results of temporal/spectral behavior of the double sources are summarized in table 1 (see also figures 1 and 2). In the table, the following quantities are given: (a) Difference in flux from the double sources in the M2 band, in the form of flux ratio $R_{\mathrm{A/B}} = S_{\mathrm{A}}/S_{\mathrm{B}}$, where S_{A} and S_{B} are hard X-ray fluxes from the double sources A and B ($S_{\mathrm{A}} \gtrsim S_{\mathrm{B}}$). (b) Relative time lag

$\Delta\tau$ of hard X- ray fluxes between the double sources derived by the cross correlation analysis (together with 1σ level). Here $\Delta\tau > 0$ means that emission from source A lags emission from source B. (c) Photon indices γ_A and γ_B assuming power-law photon spectra. (d) Strength of longitudinal photospheric magnetic field B_A and B_B in which the double sources A and B are located.

From this table, the following can be pointed out (see Sakao (1994) for more details): (1) Simultaneity of hard X–ray fluxes from the double sources holds for the majority of the flares (6 out of 7), with no time lag (*i.e.*, $\Delta\tau = 0.0$) within the statistical uncertainty. (2) The brighter footpoint tends to have a harder spectrum than the darker ($S_A > S_B \rightarrow \gamma_A < \gamma_B$ and vice versa) in five out of 7 events. (3) All the double sources are located on both sides of the magnetic neutral line (for the 5 events for which magnetograms are available). Also, the brighter footpoint tends to be located in a weaker photospheric magnetic field region ($S_A > S_B \rightarrow |B_A| < |B_B|$ and vice versa), regardless of the magnetic polarity (in four out of the 5 flares).

Table 1. Summary result of temporal/spectral behavior of the double sources.

Flare	GOES	$R_{A/B}$	$\Delta\tau^{(c)}$ (s)	γ_A	γ_B	B_A (G)	B_B (G)
91/11/15	X1.5	~ 1.5	0.0 ± 0.1	2	2.5	$\sim +100$	~ -400
91/12/03	X2.2	~ 1.3	0.0 ± 0.2	3	3.5	~ -80	$\sim +300$
92/02/07	M3.7	~ 1.5	$0.0^{+1.0}_{-0.7}$	$2.5^{(e)}$	$3^{(e)}$	~ -30	$\sim +200$
91/12/16	M2.7	$\sim 0.8^{(a)}$	0.0 ± 0.2	3.4	3.8	$\sim +300$	~ -700
92/09/10	M3.2	~ 1.3	0.0 ± 0.3	2.3	2.3	—	—
91/11/10	M2.2	$\sim 1.0^{(b)}$	$0.2^{+0.3}_{-0.5}$	3.0	3.3	—	—
91/11/02	M9.1	~ 1.5	$\sim -1.5^{(d)}$	3–4	3–4	$\sim +400$	~ -100

(a) $R_{A/B} \sim 1.0$ in the H band. (b) $R_{A/B} \sim 1.2$ in the H band.
(c) $\Delta\tau > 0$ indicates that emission from source A lags that from source B.
(d) Derived from the difference in peak times between the emissions from the double sources.
(e) Derived from M2/M1 bands count data pair while H/M2 bands are used for the other flares.

4. Summary and Discussion

4.1. Fundamental structure of hard X-ray sources

Out of 28 impulsive flares observed with HXT from 1 October, 1991 to 31 December, 1992, about 40 % showed double-source structure at the peak of hard X-ray emission in the M2 band. The others showed either multiple-source or single-source structure, which may be ensemble of pairs, or one of a pair, of double sources, respectively. When double sources are seen, they are located on both sides of the magnetic neutral line. This suggests that the double sources are not formed by just a simple chance encounter of two single sources, but that they are magnetically conjugate with each other, *i.e.*, hard X-rays ($\gtrsim 30$ keV) are emitted from the two footpoints of a single loop, which is one of the fundamental characteristics in solar flare hard X-ray emission.

4.2. Characteristics of hard X-ray footpoint sources

Case studies of the double sources seen in the seven intense impulsive flares revealed the followings: (a) In most cases (6 out of 7), hard X-rays are simultaneously emitted from the double sources within a fraction of a second, strongly suggesting that they are emitted near the footpoints by accelerated electrons streaming down along the loop towards both ends. (b) For flares in which magnetic field data are available, 4 out of 5 showed that the brighter footpoint is located in the weaker magnetic field region. This suggests that the brighter footpoint has larger electron precipitation due to weaker magnetic field convergence than the darker footpoint, hence is brighter in hard X-rays. (c) The brighter footpoint tends to have a harder energy spectrum than the darker footpoint (5 out of 7). The points (b) and (c) can be understood as follows: Electrons precipitating to the darker footpoint are reflected back to the corona due to the stronger magnetic field convergence. They emit X-rays higher than those precipitating to the brighter footpoint. In this case, emission from the darker footpoint will be a mixture of thick- and thin-target emission due to lower plasma density of X-ray emitting region, while X-rays from the brighter footpoint are emitted by purely thick-target interaction. The observed difference in γ of ~ 0.5 may be consistent with this explanation (note that the same electron spectrum produces a harder X-ray spectrum in the thick-target case than in the thin-target case, and that the spectral index differs by 2).

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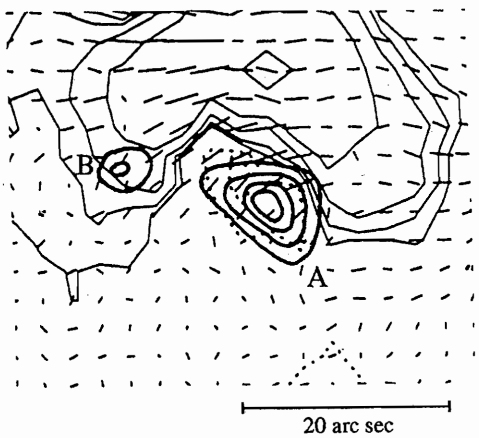

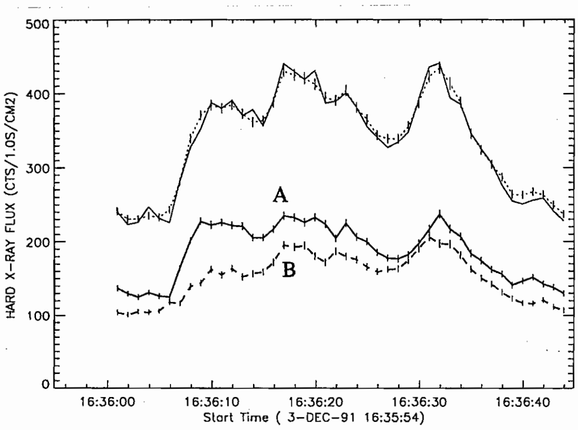

Fig. 1. Overlay of H band (53-93 keV) hard X-ray sources of the 3 December, 1991 flare at 16:36:17 UT (thick solid contours) with a vector magnetogram taken at MSO from 21:35:15 UT to 22:28:35 UT. Thin solid contours represent positive polarity while dashed contours negative polarity. The contour levels for the longitudinal magnetic field strength are $\pm$ 50, 100, 200, 400, 800, 1600, and 3200 G for positive (+) and negative (−) polarity, respectively. Short straight lines indicate transverse magnetic field strength.

Fig. 2. Time variation of hard X-ray flux from the double sources of the 3 December, 1991 flare from 16:36:00 UT to 16:36:44 UT in the M2 band in every 1 s. Thin solid line denotes spatially-integrated incident flux. Thick solid line and dashed line denote fluxes from sources A and B in figure 1, respectively. Dotted line is the sum of source A and B fluxes. Error bars in the figure indicate 1σ level.