HARD X-RAY FOOTPOINT MOTION AND ACCELERATION MECHANISM

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ABSTRACT

An intense (X9.4/2B) flare, which occurred on 6 November 1997, was observed with the hard X-ray telescope on board *Yohkoh*. In the M2- (33 – 53 keV) and H-band (53 – 93 keV), This flare clearly show double footpoint sources during its impulsive phase. We have analyzed the locations and motions of these sources in detail. It is found that, at $\sim$ 11:53:06 UT, one of the footpoint sources in the M2-band moved to a new position earlier than the corresponding source in the H-band. The time-lag is about one second and the separation between the old and new positions is $\sim$ 5 arcsec. This happened between two major spikes in the time profile of hard X-ray intensity. This apparent motion might indicate that an epoch of energy release finished somewhere high in the corona and the next epoch started in another magnetic field system. This observation clearly shows that *higher* energy electrons precipitate into the footpoint region *later*. We try to interpret this particular phenomenon under the two assumptions, which are the direct precipitation model and the trap-and-precipitation model.

INTRODUCTION

The hard X-ray telescope (HXT; Kosugi *et al.* 1991) on board Yohkoh (Ogawara *et al.* 1991) has detected more than 3,000 solar flares during its operational period, from October 1991 to December 2001. For the first time, HXT achieved imaging observations of solar flares in the energy range above 30 keV. In that energy range, it is found that the double footpoint sources are dominant sources in the impulsive phase (Sakao 1994). These sources are created by precipitation of the high-energy electrons accelerated in the corona. Through a statistical study using tens of impulsive flares observed with HXT, general characteristics and tendencies on the footpoint sources were derived (Sakao *et al.* 1998). One of the important tendencies is that the *more intense* source out of two footpoint sources is located in the *weaker* magnetic field region. This is qualitatively interpreted as follows. Electrons are accelerated somewhere in the corona and go down to both footpoints along the magnetic field. Some of them are reflected by magnetic mirrors at the footpoints. This process works more effectively at the footpoint located in the stronger magnetic field region. Thus most of electrons precipitate into the footpoint located in the weaker magnetic field. In this process, some part of electrons might be trapped into the magnetic loop and they gradually precipitate into the two footpoints after their pitch angles are changed.

As described above, hard X-ray footpoint sources are emitted not only by electrons which directly precipitate from the acceleration site, but also by electrons which are reflected at one of footpoints and/or are once trapped in a magnetic loop. So hard X-ray footpoint sources have some information on the physical parameters of the trapping region and the pitch-angle distribution of accelerated electrons.

In this paper, we analyze hard X-ray footpoint sources with a very high time resolution (0.5 second) in order to understand rapid phenomena, on the order of the propagation from the acceleration site to the

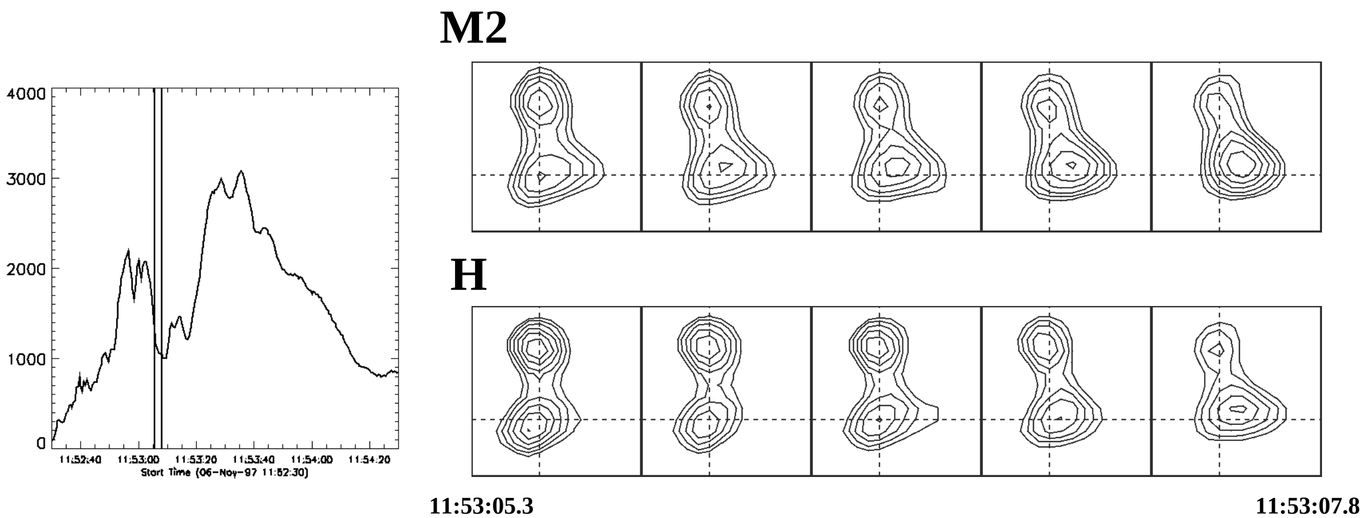

Fig. 1. Left: Hard X-ray time profile of the H-band (53 – 93 keV). The unit of the vertical axis is counts/sec/sub-collimator. The two vertical solid lines indicate the start and end time of the series of hard X-ray images shown in the right panels. Right: Time series of hard X-ray images. Upper and lower panels show hard X-ray images in the M2- and H-band, respectively. The photon accumulation time to synthesize an image is 0.5 second for each image. The field of view is $37'' \times 37''$. The contours indicate fixed values through the five images in each energy band. The contour levels are 12.5, 17.7, 25.0, 35.4, 50.0, and 70.7 % of the maximum intensity in each time series. The dashed lines indicate the original position of the southern source.

footpoints and the trapping time-scale in the corona.

OBSERVATIONS

A quite intense (X9.4/2B) flare occurred on 6 November 1997. The impulsive phase was well observed with HXT on board Yohkoh. Since a large flux of photons was detected, a series of hard X-ray images with the full time resolution of 0.5 second, can be derived, even in the highest energy band, the so-called H-band (53 – 93 keV). Four distinct sources are observed in M2- (33 –53 keV) and H-band in the impulsive phase (Sato *et al.*, 2000). The first and second most intense sources are located at the two ends of the soft X-ray flaring loop and they show a similar time behavior. These particular two sources are double footpoint sources. Their locations and motions are analyzed in detail.

At $\sim$ 11:53:06 UT, the southern footpoint source in the M2-band moved to a new position and one second later the corresponding source in the H-band followed it (right panels in Fig. 1). The separation between the old and new positions is $\sim$ 5 arcsec. Comparing the third panels in the series of images in fig. 1, it's easy to understand this small motion. In the M2-band image, the southern source has already moved to the new position though the southern source in the H-band is still at the same position. This happens during the valley period between two major spikes in the time profile of hard X-ray intensity (left panel in Fig. 1). So this apparent motion might indicate that a series of energy-release finished somewhere high in the corona and the next series of energy-release started at another magnetic field system. It is clearly shown in fig. 1 that the new source appears, not due to the fade of the old source, but the actual increase of the hard X-ray intensity at the new location.

INTERPRETATION AND DISCUSSION

First, the M2-band source moves to (or appears at) the new position and one second later the H-band source does. In this section, we try to interpret this particular phenomenon. To interpret it, we need some assumptions. Here we use two kinds of simple assumptions and discuss this observational result under each assumption. The first case is that high-energy electrons directly precipitate from the acceleration site to the footpoints. The other is that most of accelerated electrons are trapped once in a magnetic loop and then precipitate into the footpoints of the loop after their pitch angles are changed by collisions.

Direct Precipitation

Assuming that hard X-rays at the new position are emitted by direct precipitation of electrons accelerated high in the corona, the plausible interpretation is only that the higher energy electrons are accelerated about one second after the lower energy electrons are accelerated. The delay in the higher-energy range was reported previously (Bai *et al.* 1983). However, this is inconsistent with the analysis as described below.

According to the time-of-flight analyses using CGRO/BATSE data, it is found that there are two components in hard X-ray time profiles (Ashwanden *et al.* 1996*a*, 1996*b*, 1996*c*). In the high-frequency component, 'spike component', a time-delay is observed for the lower energy electrons. The interpretation is that this component is emitted by the direct precipitation of accelerated electrons from the acceleration site. Assuming that all electrons are accelerated at the same time at the same location, the distance between the acceleration site and the hard X-ray emitting region, probably footpoints of the flare loop, can be derived.

In our case, the higher energy band shows a significant time delay. Either our assumption, 'this source is created by the direct precipitation', or their assumption, 'all energy of electrons are accelerated at the same time' is apparently not correct.

Trapping and Precipitation

Next we consider the case that most of accelerated electrons are trapped in the magnetic loops and gradually precipitate into the footpoint region.

According to TOF analyses again, in the low-frequency part of the time profile, the high-energy emissions are significantly delayed compared with the lower-energy emission (Aschwanden *et al.* 1996*a*). They consider this as the effect of trapping in the loop. In this case, the time-lag is due to the difference of the collisonal deflection time in different energy of electrons (Aschwanden *et al.* 1996*a*).

Under the same assumption as their TOF analyses, in order to explain the observational time-lag between the M2- and H-bands, a high density, 2×10^{11} cm^3, is required for the trapping region. From the observations with the soft X-ray telescope (Tsuneta *et al.* 1991) on board Yohkoh, we can derive the information on density, supposing the thickness of the loop along the line of sight. According to the simultaneous observations of SXT, the maximum density of the loop is $\sim 1 \times 10^{12}$ and the density around the outer edge of the loop is $\sim 3 \times 10^{11}$. If the electrons are trapped in the outer edge of the loop, the time-lag in the hard X-ray observations is well explained. However, this interpretation raises a question. Precipitation of accelerated electrons causes chromospheric evaporation which by hypothesis causes the soft X-ray flaring loop. If this scenario is correct, why are most of accelerated electrons trapped in such a high density loop before they precipitate into footpoints of the loop? We have no answer to this question.

SUMMARY

We observed a unique motion of a hard X-ray footpoint source. The M2-band (33 – 53 keV) source moved to a new position and one second later the H-band (53 – 93 keV) source moved to the same position. There are two interpretations to explain this.
(1) Assuming that this source is caused by the direct precipitation of electrons from the acceleration site, the interpretation is that it takes a longer time ($\sim$ 1 second) to accelerate higher-energy electrons.
(2) Assuming that most of accelerated electrons are trapped in the magnetic loop and then gradually precipitate into the footpoints, the interpretation is that they are trapped in a high-density ($\sim 2 \times 10^{11}$ cm^{-3}) loop.

Neither possibility can be rejected only from these observations. We need another instrument which has a capability to observe trapped electrons with a good spatial resolution like Frequency-Agile Solar Radio telescope (Bastian *et al.* 1998).

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