Hard X-Ray Sources and the Primary Energy-Release Site in Solar Flares

Satoshi Masuda
Solar-Terrestrial Environment Laboratory, Nagoya University, 3-13, Honohara, Toyokawa, Aichi 442
Takeo Kosugi, Hirohisa Hara, Taro Sakao, and Kazunari Shibata
National Astronomical Observatory, 2-21-1, Osawa, Mitaka, Tokyo 181
and
Saku Tsuneta
Institute of Astronomy, The University of Tokyo, 2-21-1, Osawa, Mitaka, Tokyo 181

(Received 1995 March 13; accepted 1995 August 1)

Abstract

Accurately coaligned hard and soft X-ray images, taken simultaneously with the Hard X-ray Telescope (HXT) and the Soft X-ray Telescope (SXT) aboard Yohkoh, of impulsive solar flares on 1992 January 13 (17:29 UT), 1992 October 4 (22:21 UT), and 1993 February 17 (10:35 UT), occurring near the limb, clearly reveal that, in addition to double-footpoint sources, a hard X-ray source exists well above the corresponding soft X-ray loop structure around the peak time of the impulsive phase. This hard X-ray source shows an intensity variation similar to double-footpoint sources and a spectrum that is relatively hard compared with that of loop-top gradual source which appeared later in the flare. We believe that this is the first clear evidence that magnetic reconnection, which is responsible for the primary flare energy release, is under progress above the soft X-ray flaring loop. Maybe this “loop-top” hard X-ray source represents the reconnection site itself or the site where the downward plasma stream, ejected from the reconnection point far above the hard X-ray source, collides with the underlying closed magnetic loop. The characteristics of this hard X-ray source are quantitatively discussed in the schemes of thermal (T $\gtrsim$ 10$^8$ K) and nonthermal interpretations of hard X-ray emission.

Key words: Sun: flares — Sun: magnetic field — Sun: X-rays

1. Introduction

The Yohkoh satellite (Ogawara et al. 1991), carrying two X-ray imagers as well as two types of spectral-analysis instruments, was launched into an orbit around the Earth by the Institute of Space and Astronautical Science (ISAS) on 1991 August 30. The two imagers, namely the Soft X-ray Telescope (SXT; Tsuneta et al. 1991) and the Hard X-ray Telescope (HXT; Kosugi et al. 1991), are so designed as to obtain flare images with high spatial and temporal resolution. The soft X-ray emission originates from hot and dense plasmas confined by magnetic fields; we thus expect that the coronal magnetic-field topology and its change during a flare can be revealed with SXT. On the other hand, hard X-rays are emitted via electron–ion Bremsstrahlung from energetic electrons produced in the impulsive phase of a flare. Thus, combined with SXT, HXT has the capability to locate the particle-acceleration site and/or the particle precipitation site in the (changing) magnetic-field morphology. In short, Yohkoh has a good set of imagers to examine the key problem of solar flares, i.e., the magnetic-field topology and the reconnection process which is possibly involved in it.

Since launch, Yohkoh/SXT has conducted many observations relevant to these problems. Among them, one of the most important is the finding of “propagating arcade formation” (Tsuneta et al. 1992a), in which a closed-loop arcade is formed progressively from one end to the other in an eruptive process. They show as an example one of the largest, occurring on 1991 November 12, near to the north pole when a polar crown filament disappears. The arcade formation began at $\sim$ 00:00 UT, propagated westwards ($v = 20$–40 km s$^{-1}$), and reached the west limb at $\sim$ 12:00 UT, when the process still in progress, as revealed by the increasing height and footpoint separation ($v = 2$–4 km s$^{-1}$). The arcade which reached the west limb showed a cusp shape which, together with the increasing height and footpoint separation, was suggestive that magnetic-field reconnection was still in progress.

These cases are not usually classified as flares, because their X-ray intensity was weak. Apart from such a nomenclature problem, Yohkoh/SXT also found a simi-
lar cusp-shaped structure in several long-duration flares (Tsuneta 1993, 1994). One of the best examples is shown in figure 1 [see Tsuneta et al. (1992b) for more detail]. Of crucial importance is that the cusp part, especially its outer boundary portion, has higher temperatures than the other portions inside the loop, and that the whole loop increases its height and footpoint separation with time. Again, this may be regarded as observing the evolving reconnection process; see Tsuneta (1993, 1994) for other evidence concerning this interpretation. It is noteworthy that the involved magnetic configuration is just what had been proposed theoretically (e.g., Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp, Pneuman 1976).

It thus seems reasonable to consider the cusp-shaped magnetic-field structure, through which anti-parallel fields are reconnected with each other to form closed fields, as representing a basic process involved in flares. This conclusion, however, is premature and may be oversimplified. First, all of the flares which clearly show the cusp-shaped structure in soft X-rays are long-duration events without a strong impulsive behavior. Since a large proportion of the energy released in flares is usually borne by impulsively energized (or accelerated) electrons, it can be claimed that the cusp-shaped structure only represents a gradually progressing heating process, though that it may not necessarily be related to particle acceleration or primary energy release. Second, and more crucial, SXT images of normal impulsive flares usually show a bright single-loop or multiple-loop structure. This may be regarded as circumstantial evidence for the current-carrying single-loop model (e.g., Alfven, Carlqvist 1967) or the loop-loop coalescence model (e.g., Gold, Hoyle 1960; Tajima et al. 1987).

Accordingly, no definitive answer has yet been given concerning where the primary energy release site is located, or more specifically, where (and how) particles are accelerated or energized. Is it at the cusp-shaped reconnection point seen in long-duration soft X-ray events, inside a strongly sheared single magnetic loop, or at the contact point of the interacting multiple magnetic loops? We have endeavored to solve this problem by making synthetic analyses of hard and soft X-ray images for eight flares, taken simultaneously with HXT and SXT on board Yohkoh and well coaligned to each other.

In this paper we concentrate upon our discovery of a "loop-top" impulsive hard X-ray source which is located well above the apex of the corresponding soft X-ray flaring loop. Although a brief report of this discovery was made in a letter by Masuda et al. (1994), a full description is given for the first time in the present paper. The observations and analyses are discussed in section 2, followed by presentations of three examples in section 3, and interpretations and discussions in section 4.

2. Observations and Analyses

2.1. Instruments

HXT is an advanced hard X-ray imaging spectrometer for flare observations. It is a Fourier-synthesis type imager with 64 elements, each being a bigrigid modulation collimator and measuring a spatially modulated photon count. A set of 64 photon counts is converted into an image with the aid of image-synthesis procedures—usually based upon Maximum Entropy Method (MEM; e.g., Frieden 1972; Gull, Daniell 1978; Willingale 1981). The HXT has the following capability: i) simultaneous imaging in four energy bands, namely, the L-band (13.9–22.7 keV), M1-band (22.7–32.7 keV), M2-band (32.7–52.7 keV), and H-band (52.7–92.8 keV); ii) an angular resolution of ~5″ with a wide field of view covering the whole Sun; iii) a basic temporal resolution of 0.5 s; and iv) a high sensitivity with a total geometrical aperture of ~60 cm². For details concerning the instrument design, operation, and in-orbit performance of HXT, the reader is advised to refer to Kosugi et al. (1991, 1992) and Kosugi (1993, 1994). The HXT has been routinely operating under a well-calibrated condition (see Masuda 1994a) since 1991 October, and observed ~850 flares during the interval until the end of 1993 September.

On board the same satellite is SXT, which uses
grazing-incidence optics to form soft X-ray images of the Sun on a CCD detector. The angular resolution and pixel size of CCD are approximately the same, $\sim 2^\prime\prime5$. In addition to the mirror and CCD, the optical system includes a filter wheel assembly and a rotating shutter, both controlled by an on-board microprocessor, which realizes five different X-ray passbands with an adequate exposure time which depends on the solar activity. When a flare occurs, exposure cadence of up to one image per 0.5 s (the usual case is one image per 2 s) can be achieved by restricting the CCD region to be edited into the telemetry stream to a small region around the flare.

Hence, we now have the first opportunity to simultaneously observe solar flares in both hard and soft X-rays at high resolution. Note that HXT and SXT are complementary to each other in that the former observes non-thermal electrons and super-hot plasmas ($T > a few \times 10^7$ K), while the latter reveals the magnetic-field structure filled with thermal plasmas ($T > 10^6$ K).

### 2.2. Coalignment between HXT and SXT Images

To achieve our science goal, it is required that the HXT images be precisely overlaid on the corresponding SXT images which are taken simultaneously. Since the angular resolutions of the two imagers are $\sim 5$ and $\sim 2^\prime\prime5$, correspondingly, we need to establish a coalignment accuracy of better than $1^\prime$ for a detailed comparison between the two sets of images. This high accuracy was expected to be difficult to attain, even though the two imagers are attached to the two sides of a single optical bench, the center panel of the satellite.

Both HXT and SXT are equipped for this purpose with their own aspect determination systems. Data taken from the two aspect systems have been accumulated for a long period since the launch, and have been carefully compared with each other, resulting in a confirmation of an orbital-phase dependent variation as well as a small long-term variation between the two outputs, both being on the order of a few arcsec. Using the data with these variations removed, we have fixed several parameters which describe the relation between the HXT and SXT coordinates within $\sim 1^\prime$ accuracy (see Masuda 1994a for details).

### 2.3. Spectral Analysis

Both HXT and SXT are capable of deriving spectral information. As for HXT, the gain of individual detectors and the photon energy discrimination levels have been kept constant since the beginning of routine observations in 1991 October (see Masuda 1994a). The energy response of the HXT instrument was estimated experimentally as well as theoretically by Inada-Koide (1994), where the effect of filters, the stopping power of the scintillation crystals, and the pulse-height response matrix are taken into account. Based upon this work, we made convenient tools to convert the measured photon counts in two adjacent energy bands into the incident photon spectral parameters. Here, we assume simple spectral shapes with only two parameters: a single power-law spectrum for the nonthermal model and an optically thin isothermal Bremsstrahlung spectrum.

Similarly, a pair of SXT images taken with two different X-ray analysis filters are used to derive via the filter ratio method the temperature and emission measure of a flaring plasma at individual pixel points. Pairs of the 11.6 $\mu$m Al filter and the 119 $\mu$m Be filter images were chosen as the best combination for the temperature analysis of solar flares. An isothermal plasma is assumed.
3. Finding of a “Loop-Top” Impulsive Source

During the course of our detailed analyses of eight solar flares occurring near the limb, and simultaneously observed with HXT and SXT, we found in three events that a hard X-ray source is located well above the apex of the corresponding soft X-ray flaring loop. This source appears in the impulsive phase, varies relatively rapidly, and is detectable not only in the lowest HXT energy band (14–23 keV), but also in higher energy bands. In two events out of the remaining five, although a similar “loop-top” impulsive source is found, it is at a location apparently embedded in the corresponding soft X-ray loop. One more flare also reveals a “loop-top” source, which is characterized by a quite soft spectrum, however. This may belong to a different type from the “loop-top” impulsive source; hard X-rays from this source can be understood as thermal emission from a ~ 40-MK plasma (super-hot thermal component). In the remaining two events, no “loop-top” source is found in the impulsive phase. It is to be remarked that the dominant hard X-ray emission in the impulsive phase originates from the double footpoint sources (Sakao 1994; Sakao et al. 1994) for the majority of flares analyzed, and that later in the gradual phase all of the eight flares reveal a “loop-top” source which is characterized by a steep spectrum (T < 40 MK) and a gradual variation (Masuda 1994a, 1994b).

Here, we concentrate on the “loop-top” impulsive source. Three representative cases are discussed below.

3.1. 1992 January 13 Flare at 17:29 UT

A GOES M2.0-class flare occurred near the west limb in the active region NOAA 6994 on 1992 January 13. Although no corresponding Hα ribbons were discernible
on the visible hemisphere, we guess from the Yohkoh SXT/HXT observations, which clearly show double footpoint sources in hard X-rays at the two ends of a soft X-ray flaring loop (figure 3) that the main part of this flare was not occulted, at least in X-rays, by the limb (A controversy still remains whether this flare occurs behind the limb; see Wang et al. 1995). The hard X-ray time profile obtained with HXT in the four energy bands is shown in figure 2. In the lowest energy band this flare shows two spikes whose peak times are approximately 17:28:30 and 17:29:30 UT. In the higher energy bands, however, it seems to be a single-spark event whose duration (FWHM) is about one minute.

In figure 3, we show hard X-ray images (contours) and soft X-ray images (gray scale). The HXT images (intensity maps) in the L-, M1-, and M2-bands (energy ranges 14–23–33–53 keV) are synthesized with MEM after accumulating photon counts for the interval 17:26:52–17:27:39 UT (rising phase), and shown on the right column from top to bottom, respectively. The four panels on the left and center column are an SXT image (intensity map) taken at 17:27:07 UT with the 11.6 μm Al filter, one more SXT image (intensity map) taken at 17:27:01 UT with the 119 μm Be filter, a temperature map derived from the two intensity maps, and an emission measure map. The field of view of each frame covers 32 × 32 SXT pixels, or 78′′4 × 78′′4. The solar limb position is shown by the solid line. For position references, two dashed lines are given in each panel. The accuracy of co-alignment is estimated to be within ~1′.

This figure clearly reveals the following components:

- Soft X-ray flaring loop: A single loop-like structure seen in the SXT intensity maps. We see three bright patches, one at the loop apex, and the other two at the footpoints, although the northern footpoint is relatively weak. The intensity variation along the loop, however, is relatively small, say less than a factor of 5. The intensity variation along as well as across the loop is mainly due to a variation in the emission measure, not due to a variation in the temperature. The HXT L-band source seems to trace this soft X-ray loop.

- High-temperature region overlying the soft X-ray loop: Temperatures are derived to be ~20 MK from SXT. The intensity is relatively weak due to a small emission measure.

- Double footpoint sources in hard X-rays: Intense sources are located at the two ends (footpoints) of the soft X-ray loop. The double-source structure is clearly seen in the energy range above the M1-band, i.e., above ~20 keV. This double-source structure was first found for several flares with SMM/HXIS by Hoyng et al. (1981) and Duijveman et al. (1982) as well as with Hinotori/Solar X-ray Telescope by Takakura et al. (1984). Recently, using Yohkoh/HXT, Sakao et al. (1994) made a detailed study on this point, and confirmed (i) that the double-source structure is one of the basic, common properties of impulsive hard X-ray emission (≥30 keV) and (ii) that hard X-rays are emitted near the footpoints by accelerated electrons streaming down along the loop toward both ends.

- "Loop-top" hard X-ray source: A hard X-ray source is located well above the apex of the soft X-ray flaring loop; its centroid position is significantly higher than the latter by more than ~10′ and located at slightly higher altitudes in images taken in higher energy bands. This source occupies only a small portion of the high-temperature region overlying the soft X-ray loop. It is noteworthy that, well after the hard X-ray source fades out, say after 17:35 UT, the location becomes the home of the strongest soft X-ray kernel (not shown in the figure).

Now let us examine the properties of the "loop-top" hard X-ray source. The temporal behavior of this source is compared in figure 4 with those of the two footpoint sources. The integrated intensities are estimated from synthesized images for the two boxed areas, i.e., one for the "loop-top" source and another for the double footpoint sources. Data points are not given at a constant interval, because relatively long integration times are re-
required for obtaining reliable MEM images when the total intensity is weak. It is concluded from the ~10-s time-resolution data shown in figure 4 for the M1-band that this source varies almost simultaneously with the double-footpoint sources. It is not clear, however, whether the “loop-top” source exhibits rapid fluctuations with time scales of less than a few seconds, which are lacking in this event, even in the high time-resolution plot without imaging (cf. figure 2).

Hard X-ray spectral information for each source can be derived from the intensity ratios between two adjacent HXT energy bands. From the MEM images shown in figure 3, the X-ray count-rates attributable to the “loop-top” source are estimated to be 33, 33, and 14 ct s$^{-1}$ in the L-, M1-, and M2-bands, respectively. Hence, the intensity ratios are 1.0 between the L- and M1-bands, and 0.42 between the M1- and M2-bands. If we assume a single power-law spectrum, these ratios correspond to photon spectral indices of 2.6 and 4.1, respectively. This means that the single power-law assumption fails and that the spectrum steepens towards higher energies. It is noteworthy that these spectral indices are not so different from those obtained for the footpoint sources, i.e., < 2.0 and 4.0.

Another possible interpretation of the intensity ratios is that the hard X-ray emission originates from a thermal plasma. Assuming an isothermal plasma, we find from the M1/L ratio, as the most plausible temperature and emission measure, 200 MK and $5 \times 10^{43}$ cm$^{-3}$, and from the M2/M1 ratio 130 MK and $9 \times 10^{43}$ cm$^{-3}$.

3.2. 1992 October 4 Flare at 22:21 UT

A GOES M2.4-class flare occurred near the west limb in the active region NOAA 7293 on 1992 October 4. According to the Solar-Geophysical Data, the corresponding Hα flare was located at S05W90 and had an importance of SN. This flare is a multiple-spike event, as can be seen in the HXT time profile of figure 5. The data gap between 22:24 UT and 22:30 UT is due to a data downlink to a ground station.

Hard X-ray images of this flare around the peak time of the most intense spike at ~22:19 UT are compared in figure 6 with the SXT images. This figure has the same organization as figure 3. The hard X-ray images are synthesized from the photon count accumulated for 14 seconds, from 22:19:01 UT to 22:19:15 UT. Two SXT images, one with the 119 µm Be filter and the other with the 11.6 µm Al filter, were taken at 22:18:55 UT and 22:18:57 UT, respectively. Though soft X-ray images were taken with the same filters between 22:19:01 UT and 22:19:15 UT, they were taken with one more filter, a so-called neutral density filter. When we make a quantitative analysis, for example temperature and emission measure analysis, images taken with the neutral density filter are not suitable.

This flare differs from the 1992 January 13 event in that no clear soft X-ray loop structure is seen. Rather the soft X-ray source looks like a single patch. Nonetheless, we can recognize the existence of a loop from the combined SXT and HXT images. The soft X-ray bright patch, possibly corresponding to the apex part of the loop, is located at a projected height of ~1 $\times 10^4$ km above the limb at around 22:19 UT, and gradually increases its height throughout the whole duration of the flare ($v \approx 10$ km s$^{-1}$).

Again, in this flare, we find a “loop-top” hard X-ray source above the soft X-ray brightest region. Although the relative intensity of this “loop-top” source is weak compared with the double-footpoint sources, it can be perceived even in the M2-band. The source is compact in the M1- and M2-bands, but when seen at the same position in the L-band it is much larger.

In order to further investigate the above results, we
examined the temporal behavior separately for both the footpoint and the loop-top sources in detail by using the same method as that in figure 4. Figure 7 gives a summary in which X-ray fluxes in the L-band, integrated over the two boxed regions as shown at the upper-left corner in this figure, one corresponding to the footpoint source and the other corresponding to the loop-top source are plotted against time. It is evident that the footpoint source dominates in the impulsive phase (22:14–22:20 UT), while the loop-top source becomes dominant in the gradual phase (after 22:20 UT). The loop-top source, however, does exist in the impulsive phase, and shows a similar variation to the footpoint source throughout the impulsive phase, which is most clearly seen at 22:15 UT and 22:16 UT.

Figure 8 shows a similar time plot for the M1-band. Selected regions are the same as those for the L-band. Since the X-ray intensity in the M1-band is weaker than in the L-band, the time resolution of this plot is lower, so as to increase the counting statistics for each image. Hence, some rapidly varying components may be missing in this figure. Nonetheless, this figure again 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 also confirmed from a time plot in the M2-band (not shown), but with a poorer time resolution. No meaningful result has been obtained for the H-band, because the available time resolution is too poor.

The hard X-ray spectrum of this source is again quite similar to that of the 1992 January 13 event. When a single power-law shape is assumed, we obtain spectral indices of $\sim 1.3$ and $5.2$ from the M1/L and M2/M1 ratios, respectively. If we adopt a thermal spectrum shape, we
Fig. 7. Comparison of time histories between footpoint and loop-top sources for the 1992 October 4 flare. The sub-panel at the upper left corner shows the regions in which intensity is integrated. The sizes of the footpoint (the left box) and loop-top (the right box) regions are $10''7 \times 41''7$ and $27''0 \times 29''7$, respectively. The main panel shows the time profiles in the L-band for the footpoint (+) and loop-top sources ($\Delta$).

Fig. 8. Same as figure 7 for the M1-band.

find from the M1/L ratio a temperature of $\gtrsim 250$ MK and an emission measure of $\lesssim 1 \times 10^{44}$ cm$^{-3}$. On the other hand, the M2/M1 ratio leads us to a temperature of $\sim 100$ MK and an emission measure of $\sim 8 \times 10^{44}$ cm$^{-3}$.

3.3. 1993 February 17 Flare at 10:35 UT

The third event occurred around the west limb on 1993 February 17. This is the most intense flare among the three events in the soft X-ray (GOES M5.8 class) and hard X-ray (peak counts in the HXT L-band is greater than 200 ct s$^{-1}$ SC$^{-1}$; see figure 9) regions. According to the Solar-Geophysical Data, the corresponding Hx flare is located at S07W87 in the active region NOAA 7420. The duration is about 15 min and 3 min in the L-band and the M2-band, respectively (figure 9).

Figure 10 shows hard X-ray images (contours) and soft X-ray images taken with the 119 $\mu$m Be filter and the other with the 11.6 $\mu$m Al filter. The configuration is the same as the previous two figures (figures 3 and 6). The hard X-ray image is synthesized with an accumulation between 10:36:16 and 10:36:26 UT and the soft X-ray images were taken at 10:36:24 UT (Be filter) and 10:36:26 UT (Al filter), respectively.

In the soft X-ray image, at least three different loops, two lower lying loops and a large diffuse loop, can be seen. The southern one of two small loops is the brightest loop both in the impulsive phase and in the gradual phase in soft X-rays. It increases in both height and footpoint.
Fig. 10. Hard X-ray image (contours) and the soft X-ray image (gray scale) for the 1993 February 17 flare. The hard X-ray image is synthesized after accumulating photon counts for the interval 10:36:16–10:36:26 UT. The soft X-ray images are taken with the 119 μm Be filter at 10:36:24 UT and with the 11.6 μm Al filter at 10:36:26 UT. The contour levels are 7.0, 50.0, 35.4, 25.0, 17.7, 12.5, and 8.8% of the peak intensity. These images cover 32 × 32 SXT pixels (78″ × 78″).

separation with time. The northern one is more compact than the southern one. Its relative intensity decreases with time. The large loop is located above the small two loops. This loop is clearly seen in the early impulsive phase, but not so clearly in the later phase.

In the M2-band of hard X-rays, two sources exist at low altitude. These correspond to the two small loops in soft X-rays. In the early phase, these hard X-ray sources have almost the same intensity. However, the southern one becomes dominant in the later phase. In addition to these hard X-ray sources, three sources can be seen in the M2-band image. Two sources out of the three are located above the two small soft X-ray loops; the other is located at a higher altitude, which corresponds to the larger soft X-ray loop.

We first discuss the northern loop and hard X-ray source. As described before, this part consists of three components: a soft X-ray loop, a hard X-ray source located at the lower part of the soft X-ray loop, and another hard X-ray source located well above the soft X-ray loop. Although this flare has a very complex structure, this part has almost a similar configuration to that of the previous two events, i.e., this part consist of a soft X-ray flaring loop, a hard X-ray footpoint source, and a hard X-ray loop-top source located above the soft X-ray loop. The hard X-ray spectrum of this source is almost similar to the previous two events. When a single power-law shape is assumed we obtain spectral indices of 3.6 and 6.1 from the M1/L and M2/M1 ratios, respectively. If we adopt a thermal-spectrum shape, we find from the M1/L ratio a temperature of ~ 108 MK and an emission measure of ~ 1 × 10^{45} cm^{-3}. On the other hand, the M2/M1 ratio leads to a temperature of ~ 74 MK and an emission measure of ~ 4 × 10^{45} cm^{-3}. The time behavior...
of the loop-top and footpoint sources are shown in figure 11. The time profiles of the two sources are also almost similar in this flare.

The southern part has the same configuration, a soft X-ray loop and two types of hard X-ray sources. The source, which is located above the soft X-ray loop, has a little soft spectrum, ($\gamma = 6.3$ and 7.4 from the M1/L and M2/M1 ratios, respectively). In the case of a thermal assumption, the M1/L ratio corresponds to an isothermal plasma whose temperature and emission measure are 47 MK and $2 \times 10^{46}$ cm$^{-3}$, respectively. The M2/M1 ratio corresponds to an isothermal plasma whose temperature and emission measure are 56 MK and $8 \times 10^{45}$ cm$^{-3}$, respectively.

4. Interpretation and Conclusions

The observations described in the previous section are summarized as follows:

- In addition to double-footpoint sources, a hard X-ray source which exhibits an impulsive time variation exists well above the apex of the corresponding soft X-ray flaring loop. This “loop-top” impulsive source is less intense than the dominant double-footpoint sources by a factor of $\sim 5$ at X-ray energies $\gtrsim 25$ keV.

- The “loop-top” impulsive source is relatively compact and occupies a small portion of the high-temperature region seen in soft X-rays. In the case of the 1992 January 13 flare, the source seems to be located at slightly higher altitudes at higher X-ray energies.

- The hard X-ray emission from this source shows a broken power-law spectrum with the break energy in the M1-band energy range (23–33 keV); it can also be interpreted as thermal emission originating from a plasma whose temperature and emission measure are typically $\sim 200$ MK and $\sim 1 \times 10^{44}$ cm$^{-3}$, respectively.

This discovery of a “loop-top” impulsive hard X-ray source is of crucial importance for understanding the primary energy release mechanism of solar flares. First, it at least informs us that something quite important is going on outside the bright soft X-ray loop. Note that this statement holds independently of whether the individual interpretations given later are appropriate or not. Second, this something is directly related to the particle acceleration taking place in the impulsive phase. Recently, Sakao (1994) and Sakao et al. (1994) have confirmed from a detailed study of the correlation between the double-footpoint sources that no time lags greater than a few tenths of a second are found in the intensity variation at the two footpoint kernels. He concluded that energetic electrons are produced near the apex of a loop connecting the double-footpoint sources. Taking into an account this conclusion by Sakao, it is most likely that we observe the particle acceleration site as the “loop-top” impulsive source. Finally, the coaligned soft and hard X-ray images make it possible to speculate about a coronal magnetic field topology with a current sheet in which the reconnection is under progress.

The magnetic-field topology that we derived from our observations (figure 12) is morphologically similar to a series of models proposed by Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp and Pneuman (1976). In the following, for simplicity we neglect minor differences among their models, and call the unified one the CSHKP model. The important ingredients of the CSHKP model are elongated anti-parallel magnetic fields above the arcade of closed loops, current sheet (or neutral sheet) formation between them, and the reconnection of anti-parallel magnetic fields. The anti-parallel magnetic fields are supposed to be created in association with a prominence (or dark filament) eruption, and the rising X-type (or Y-type) reconnection point explains the observed increasing separation of the Hα flare ribbons and the increasing height of the post-flare loops with time.

From the viewpoint of reconnection theory (e.g., Petschek 1964), one more important ingredient of the CSHKP model is the reconnection outflow, or jet. Recently, based upon a theoretical consideration as well as numerical simulations, Ugai (1987) pointed out that the
outflow from the reconnection point will impinge upon the underlying closed loop and form a shock, resulting in the creation of a high-temperature region just above the closed loop. It is also plausible that electrons become energized or accelerated through the shock.

We now examine our observations more quantitatively based upon these considerations. First, for simplicity, we suppose that the "loop-top" hard X-ray source is of thermal origin. Then, from the emission measure $\sim 1 \times 10^{44} \text{ cm}^{-3}$, together with the observed area $\sim 1 \times 10^{18} \text{ cm}^2$ and the assumed line-of-sight thickness $\sim 1 \times 10^9 \text{ cm}$, we find the density $\sim 3 \times 10^8 \text{ cm}^{-3}$, the total number of electrons (or ions) $\sim 3 \times 10^{35}$, and the thermal energy content $\sim 3 \times 10^{26} \text{ erg}$ for the hard X-ray emitting 200-MK plasma. Similarly, from SXT observations we obtain a density of $\sim 2 \times 10^{10} \text{ cm}^{-3}$ for the 20-MK plasma at the location of the "loop-top" hard X-ray source. (Note that the much smaller emission measure of the 200-MK component as compared with that of the 20-MK plasma explains why the "loop-top" impulsive source lacks a clear counterpart in SXT images.) The 200-MK plasma can be created as a result of shock if the reconnection outflow velocity exceeds $\sim 3000 \text{ km s}^{-1}$. This velocity is not surprisingly large; an Alfvén velocity of 3000 km s$^{-1}$ only requires a magnetic field intensity of 200 G, even when the density is equal to $2 \times 10^{10} \text{ cm}^{-3}$. (The density, $2 \times 10^{10} \text{ cm}^{-3}$, is estimated at the location of the loop-top hard X-ray source. Since the reconnection point is located above it, the density could be small. Then the required intensity of the magnetic field becomes smaller than 200G.) Thus, the scenario to create the 200-MK plasma from the reconnection outflow is not unreasonable, or at least not inconsistent with the present observations.

We next will try to evaluate how efficiently electrons are accelerated. The electron ($> 20 \text{ keV}$) injection rate to the double-footpoint sources is evaluated by adopting the thick-target model (Brown 1971; Hudson et al. 1978) to be $\sim 2 \times 10^{35} \text{ s}^{-1}$, $\sim 1 \times 10^{35} \text{ s}^{-1}$, and $\sim 2 \times 10^{36} \text{ s}^{-1}$ for the 1992 January 13 event, the 1992 October 4 event, and the 1993 February 17 event, respectively. Correspondingly, the energy deposition rate due to energetic electrons is $\sim 1 \times 10^{28} \text{ erg s}^{-1}$, $\sim 4 \times 10^{27} \text{ erg s}^{-1}$, and $9 \times 10^{28} \text{ erg s}^{-1}$, respectively. These injection rates suggest a relatively large efficiency of electron acceleration; if we suppose that the precipitating electrons originate from the "loop-top" source, the rates demand to consume almost all electrons ($> 20 \text{ keV}$) in the 200-MK plasma in a second or so. Thus, it seems appropriate to consider that the nonthermal, precipitating electrons originate from the reconnection flow in parallel with the creation of the 200-MK plasma.

From the above discussion, one may raise the question as to why the intermediate part along the electron passage between the "loop-top" source and the double footpoint sources does not brighten when the precipitation rate is so high. This is a difficult question to give a definitive answer. One possibility is that the density of energetic electrons ($> 20 \text{ keV}$), estimated by dividing the electron injection rate by the cross-sectional area and the electron velocity, is of the order on $10^7 \text{ cm}^{-3}$, and that the ambient plasma density is less than $10^{10} \text{ cm}^{-3}$, thus making the product smaller, and, hence, the brightness darker in the intermediate part than in the "loop-top" source, where the product is approximately $10^{17}$. In this case we need to postulate that the energetic electrons do not pass through the soft X-ray loop, which shows a much higher density. Probably, the loop may become dense as the result of chromospheric evaporation. This possibility, although not inconsistent with the observa-
tions, lacks supportive evidence. Thus, the problem still remains unsolved.

So far, we have discussed our scenario based on the assumption that the “loop-top” hard X-ray source is well explained by thermal emission from an isothermal plasma whose temperature is 200 MK. This assumption, however, has no definitive observational base. Rather, as implicitly mentioned previously, it is likely that the 200-MK plasma component coexists with the much denser 20-MK plasma in the same volume. If this is the case, the density of the 200-MK component can be drastically reduced, because the X-ray emissivity is proportional to the electron-ion collision frequency, and the ion density in this case includes not only the 200-MK component, but also the 20-MK plasma. Even so, since the downstream energetic electrons have a density of $10^7 \text{cm}^{-3}$ (as previously mentioned), and since the ambient plasma density changes only slightly along the electron path, this reduction factor cannot be so large in order to not have loop-shaped hard X-ray brightening along the electron path. It is to be noted that the situation we discuss here is similar to that discussed in terms of the nonthermal thin-target model (e.g., Brown 1975) which involves the ambient cool plasma plus nonthermal tail electrons. Maybe we can construct a nonthermal model for the “loop-top” impulsive source which does not contradict with the observations.

Two minor items should be mentioned here. The high-temperature region seen in soft X-rays is much larger than the “loop-top” hard X-ray source. A possible interpretation is that the reconnection outflow is not sharply beamed, and its outskirts have a slower velocity. Then, only a weak shock is formed and no strong energization occurs there. The soft X-ray flaring loop may represent previously reconnected magnetic fields filled with material evaporated from the dense chromosphere. Maybe the evaporation is caused not only by energetic electron precipitation, but also by heat conduction. In any case, it is a byproduct of the primary energy release.

We have presented the first clear observational evidence that the magnetic reconnection, which is responsible for the primary energy release including the impulsive particle acceleration, is under progress above the soft X-ray flaring loop. We believe that this basic important point has been established by this work.

We thank H. S. Hudson and L. W. Acton for help in polishing the manuscript and express our hearty gratitude to all members of the Yohkoh team for their dedicated efforts to the operation. Also, the staff members of NASA's Deep Space Network stations are acknowledged for their support to Yohkoh. This research is partially supported by the Scientific Research Fund of the Japanese Ministry of Education, Science and Culture under Grant No. 07740186.

References
Alfvén H., Carlqvist P. 1967, Solar Phys. 1, 220
Brown J.C. 1971, Solar Phys. 18, 489
Gold T., Hoyle F. 1960, MNRAS 120, 89
Gull S.F., Daniell G.J. 1978, Nature 272, 686
Hirayama T. 1974, Solar Phys. 34, 323
Hudson H.S., Canfield R.C., Kane S.R. 1978, Solar Phys. 60, 137
Inda-Koide M. 1994, PhD thesis, The University of Tokyo
Masuda S. 1994a, PhD Thesis, The University of Tokyo
Masuda S., Kosugi T., Hara H., Tsuneta S., Ogawara Y. 1994, Nature 371, 495
Sturrock P.A. 1966, Nature 211, 695