Yohkoh SXT/HXT Observations of a Two-Loop Interaction Solar Flare on 1992 December 9

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Abstract

Observations with the Soft X-ray and Hard X-ray Telescopes aboard Yohkoh of a simple solar flare on 1992 December 9 are discussed. The soft X-ray morphology suggests evidence of a loop-loop interaction mechanism: the images reveal two parallel magnetic loops prior to the flare, and their merging just before onset of the hard X-ray burst. This flare therefore provides a chance to examine the two-loop interaction model for solar flares. It is found (1) that the observed soft X-ray behavior of the two loops in the preflare phase well matches to the two-loop interaction model between strong and weak current loops and (2) that the observed time scale of the two-loop coalescence is almost equal to that estimated from explosive-reconnection theory. In the impulsive phase, it is found (3) that the loop-top portion near to the interaction region first brightens in the 14–23 keV hard X-rays and (4) that the 23–33 keV hard X-ray emission around the peak time originates dominantly from two compact sources at the two ends of the merging loops. These hard X-ray observations are explained by high-energy electrons that are produced in the two current loop interaction.

Key words: Particle acceleration — Sun: activity — Sun: flares — Sun: X-rays

1. Introduction

The two-loop interaction hypothesis for explaining solar-flare energy release has been repeatedly proposed by various authors (e.g., Gold, Hoyle 1960; Tajima et al. 1987; Sakai, de Jager 1991; Chargevshvili et al. 1993; Zhao et al. 1993). One of the most crucial tests of this hypothesis may be provided by simultaneous soft X-ray and hard X-ray imaging observations, because the former gives the magnetic loop configuration that may vividly show the two-loop interaction, while the latter observes the behavior of energetic electrons accelerated and confined in it.

Using the imaging capability of the Soft X-ray Telescope (SXT) (Tsuneta et al. 1991) aboard the Yohkoh satellite (Ogawara et al. 1992), we have for the first time observed vividly many phenomena, which lead us to support the idea of a loop-loop interaction. Hanoka (1994) analyzed SXT data of a flare occurring on 1992 July 15, and concluded that the flare occurred through the interaction of sheared coronal loops. Cheng and Acton (1994) presented two clear examples of active-region transient brightenings which seemed to result from interactions between loops: the observed images show a precise configurational change before and after the occurrence of a loop-loop interaction, which is one of the most confirmative processes of this hypothesis. Shimizu et al. (1994) studied the morphology of 142 active-region transient brightenings observed with the SXT, and suggested that the interaction of multiple loops is an important mechanism of these phenomena. Takahashi (1994) analyzed SXT images of the 1992 August 17 flare, and indicated that the loop-loop interaction triggered it.

As for transient brightenings, through an extensive morphological study of Shimizu et al. (1994), it has been confirmed that most of them are due to a magnetic interaction of multiple loops. However, it is not yet clear whether this mechanism can be a direct trigger of flares, which release a larger amount of energy compared to that of transient brightenings. In fact, the energy involved in a transient brightening is $10^{25} - 10^{29}$ erg, at or below the low end of the subflare energy range.

In this paper we present observations of a simple flare with the SXT and the Hard X-ray Telescope (HXT)
(Kosugi et al. 1991) aboard the Yohkoh satellite. This flare is remarkable in that two loops, which later merge into one, can clearly be seen in the preflare stage. This flare may thus provide a chance to examine the validity of the two-loop interaction model as the trigger of flares, and further to put a constraint upon how particles are accelerated in it.

We describe our observations and analyses in section 2. In section 3 we compare the observations to theory and present a brief interpretation.

2. Observations and Analyses

2.1. Overview

A GOES C2.7 class solar flare occurred on 1992 December 9 at ~10:40 UT near to the east limb (~E60) in the active region NOAA 7363. Figure 1a shows the GOES time profiles of the flare. The Yohkoh satellite observed this flare from the beginning until ~10:44 UT, when the satellite interrupted observations for the downlink of data to a ground station. The "flare mode" of the Yohkoh satellite was triggered at 10:42:47 UT and continued until the end of the observation. The hard X-ray time profiles in the HXT L- (14–23 keV) and M1- (23–33 keV) bands are shown in figure 1b. The M1-band data were available only when the satellite was in the flare mode.

In order to summarize the Yohkoh observations, according to the time profile shown in figure 1, we divide a flare into three phases: the preflare phase (10:10–10:42 UT), the early-impulsive phase (10:42–10:43 UT), and the impulsive phase (10:43–10:44 UT). During the preflare phase, only SXT images are available, while in the early-impulsive phase flux was detected in the HXT L-band. The SXT, HXT-L, and HXT-M1 band data are all available in the impulsive phase. In the following we describe the development of flare soft and hard X-ray sources during these phases.

2.2. Preflare Evolution of Soft X-Ray Loops

During the preflare phase, the SXT monitored the evolution of the active region at a cadence of typically once every minute for each of the analysis filters (thin Al or thick Al filter). The last image taken during this phase was at 10:41:53 UT through a thin Al filter. These preflare images are presented in figure 2. The snapshots show the evolution of two soft X-ray loops, with the brightening of the right-hand loop (the right loop) (a to c), the brightening of the left-hand loop (the left loop) and the fading of the right loop (c to f), the movement of the left loop toward the right and brightening of the right loop (f to g), the start of the two loops' merging (g), and remarkable footpoint brightenings (h). This behavior of the two loops was also confirmed by subtracting the images (figure 2, 3rd row); the subtraction of a from c yields a white image of the right loop, which means that this loop increased in intensity. Similarly, a brightening of the left loop from c to f is shown by the white feature in images f – c, while the negative (black) color of the right loop in this image is interpreted as indicating a fading of this loop. In images g – f, the increase in

Fig. 1. (a) Time profiles of the GOES X-ray intensity on 1992 December 9. The shadows indicate the times when the SXT acquired the images of figure 2. The upper and lower lines indicate the full-sun soft X-ray flux through 1–8 Å and 0.5–4 Å, respectively. The solid lines are observations by the GOES-7 satellite and the dotted lines by the GOES-8 satellite. (b) The hard X-ray time profiles of the 1992 December 9 flare in the HXT L- (13.9–22.7 keV) and M1- (22.7–32.7 keV) energy bands. The temporal resolution is 2 s (L-band alone) and 0.5 s (L- and M1-bands) before and after 10:42:47 UT, respectively. No M1-band data are available before 10:42:47 UT. Labels A to D give the time intervals during which photon counts are accumulated for synthesizing snapshot images shown in figure 6.
From the snapshot at 10:37:33 UT when the two loops were clearly visible (figure 2f), we can see that the two loops were approximately parallel to each other and that the separation of the two loops was $\sim 7''$. In figure 3 we present a schematic drawing of the two loops' evolution seen in the images of figure 2. To examine the behavior of the two loops quantitatively, we selected five rectangular areas, each representing a position occupied by the two soft X-ray loops and their surroundings, as shown in figure 3, and evaluated the intensity variation of each area in the sequence of the SXT images. The size of each area was chosen to be $1 \times 2$ pixel (or $2''5 \times 5''0$). We refer to these five areas as areas 1 to 5, respectively. As can be seen in figure 3, areas 1 and 2 contain the left loop, whereas area 3 involve the valley portion between the loops. The position of the right loop is overlapped with areas 4 and 5. The intensity variations of these areas are shown in figure 4. The curves in figure 4 confirm the qualitative view of the two loops' evolution described above. From $\sim 10:10$ UT to $\sim 10:19$ UT all of the areas show fairly flat intensity variations. We thus think that the two faint loops stably exist during this period. From $\sim 10:19$ UT to $\sim 10:29$ UT (a to c) the intensity at the right loop as well as that at the center of the loops (which indicates merging of the two loops) is clear with white color; the black feature of the left loop may indicate its movement towards the right during this period.
intensity of areas 4 and 5 remarkably increased, which is interpreted as being a brightening of the right loop. The situation that only the right loop is visible in figure 2c may be due to a difference in the relative intensity between the two loops at this time. Note that, however, the intensity of areas 2 and 3 also increased from a to c, suggesting that the intensity of the left loop and the valley portion between the loops also started increasing from $\sim 10:19$ UT. This is explained by the brightening of the left loop, and the commencement of the interaction process between the loops. From $\sim 10:29$ UT to $\sim 10:37$ UT (c to f), the intensity of areas 4 and 5 decreased, which is remarkable for area 5. We thus think that the right loop faded during this period. The intensity of areas 1 and 2, especially that of area 2, continued to increase during the same time interval, which supports the left loop's continuous brightening. As a result, the two loops reached almost the same intensity at $\sim 10:37$ UT (f) (see figure 2f). From $\sim 10:37$ UT to $\sim 10:40$ UT (f to g) the intensities of areas 1 and 2, the latter less prominently, decreased. We interpret this as being a movement of the left loop toward the right during this period. The right loop recovered its intensity from $\sim 10:37$ UT (f), because the intensity of areas 4 and 5 started to increase from this time. Also, area 3 shows a remarkable increase in intensity from f to g, leading to the visible merging feature at this area in figure 2g. After contact of the two loops at $\sim 10:40$ UT (see figure 2g), the intensity of all the areas rapidly increased (g to h). From the intensity variation of area 3, we can see that the intensity of the valley portion between the loops monotonically increased since $\sim 10:19$ UT. This indicates that there was a continuous intensity enhancement at the region between the loops, which is most naturally explained by the effect of the interaction between the loops. Also, the approach of the two loops and the configurational change after the coalescence (the two loops seen until g merged into one at h) support the two-loop interaction hypothesis.

Figure 2, as well as figure 4, shows the result of thin Al filter data. Using thick Al filter data we obtained similar images and curves. Thus, the observed intensity variation was due to a change in the density, not due to that of the temperature. The temperature of the two soft X-ray loops during the preflare stage was estimated to be $\sim 5 \times 10^6$ K. Here, we used the filter ratio method (Hara 1992).

2.3. Hard X-Ray Image in the Early-Impulsive Phase

From $\sim 10:42$ UT, the hard X-ray flux started increasing (figure 1b), although the flare mode of the satellite was not triggered until 10:42:47 UT thus only the L-band data are available in the early-impulsive phase. We synthesized the HXT L-band image using data of 10:41:51–10:42:45 UT (figure 6A). The loop top portion is the brightest in the image, in contrast to the footpoint brightening seen in the later image (figure 6B). Hence hard X-rays in the early-impulsive phase may be interpreted to be emitted from the coalescence region of the two loops.

2.4. Impulsive Phase Behavior

Figure 5 shows SXT and HXT images taken during the impulsive phase, around the peak time of the hard X-ray flux. During the impulsive phase, SXT images were obtained from $\sim 10:43$ UT to $\sim 10:44$ UT, once about every 8 s for each of various filters. All of these images show a single-loop structure, as presented in figure 5a, suggesting a strong energy release from the coalesced loop. The HXT L-band image at this time (figure 5b) is elongated like a loop structure, which resembles the SXT image (figure 5a), with an intensity enhancement at the northern and loop-top parts of the loop. In the HXT M1-band, the hard X-ray emission originates dominantly from two compact sources, separated from each other by $\sim 20''$ or $\sim 15000$ km (figure 5c). No HXT higher band images
were synthesized because of poor photon-counting statistics. To confirm that the two sources seen in the HXT M1-band represent the two ends of a magnetic loop, we compare the image with a magnetogram taken at the Okayama Observatory in figure 5c. It is found that the two sources are located at the opposite sides of a magnetic neutral line. Hence, it is not unreasonable if we take the sources as being the two footpoints of a magnetic loop (or loops).

In figure 6 we show the morphological evolution of the hard X-ray source in the HXT L-band images. Note that this flare is so weak that a relatively long accumulation of photon counts is necessary for synthesizing images. Even though some spurious features do exist in the synthesized images, due to the low signal-to-noise ratio, we can derive the following: (i) The L-band source is elongated throughout the flare, suggestive of tracing the magnetic loop(s). (ii) Still, we can see a configurational evolution in the images. In the early-impulsive phase (figure 6A), the brightest region tends to be located at the central portion, and extends southward, probably corresponding to the coalescence region shown in figure 3 by a hatch. At the first peak of the impulsive phase (figure 6B), the brightest region shifts northwards, and at the second peak the whole loop is equally bright (figure 6C). The loop top then becomes brightest in the later impulsive phase, or at the very beginning of the gradual phase (figure 6D). This loop-top source might be the emission from high-temperature ($>10^7$ K) material evaporated from the footpoints and confined in the magnetic loop.

Using data taken with the SXT during the impulsive phase, we calculated the energetics of the flaring loop as follows. By adopting the filter ratio method to the data obtained through the thin Al and Be filters, we derived the temperature of the flaring loop to be $T \sim 8 \times 10^6$ K, which was almost constant during the impulsive phase. From the filter-response characteristics (Hara 1992), the emission measure can then be computed to be $EM \sim 10^{48}$ cm$^{-3}$, which increased monotonically by a factor of 2 during the impulsive phase. We also derived $T$ and $EM$ values using GOES data (figure 1a) to check the values obtained from the SXT data, and confirmed that they are in good agreement. Assuming the volume of the loop to be $V \sim 3 \times 10^{27}$ cm$^3$ based upon the SXT images and the filling factor to be unity, the electron density of the loop turns out to be $n_e \sim 2 \times 10^{10}$ cm$^{-3}$; hence, the thermal-energy content of the loop, $E_{th} = 3n_e k T V$ (where $k$ is the Boltzmann constant), is $2 \times 10^{29}$ erg. On the other hand, the magnetic energy released through the two-loop interaction process was derived to be $E_{mag} \sim B_0^2 V/(8\pi) \sim B_z^2 V/(8\pi)$, where $B_0$ and $B_z$ are the poloidal (azimuthal) and toroidal components of the magnetic field, respectively. This is because, according to Tajima (1982), the threshold for an explosive reconnection of two loops is given as $B_0 \sim B_z$, and the process occurs when $B_0 \geq B_z$. Using the fact that the line-of-sight (longitudinal) component of the magnetic field at the footpoints of the loop was observed to be $B_\parallel \sim 100$ G with the Okayama magnetogram and esti-
mating $B_x \sim B_\parallel$, we could thus calculate $E_{\text{mag}} = 1 \times 10^{30}$ erg. The result obtained here, $E_{\text{th}} \sim 0.1 \times E_{\text{mag}}$, means that the magnetic-field energy contained in the relevant loop was sufficient to power the flare.

3. Interpretation

The SXT images in the preflare phase of the 1992 December 9 flare provided clear evidence of a two-loop interaction. We can see that the two loops are parallel to each other at $\sim 10:37$ UT (figure 2f), which coalesce a few minutes later. Thus, according to the classification scheme proposed by Sakai and Koide (1992), this is a two-loop interaction of the I-type associated with a partial reconnection. Both of the two loops were originally faint, but then increased in soft X-ray intensity one by one until reaching almost equal brightness. They then partially collided, and soon thereafter completely merged into one. Although the two loops had been discernible for more than 20 min, since they partially collided with each other it took about 2 min for the hard X-ray burst to be detected.

We examine here the above observations with a magnetic energy-release model due to a two-current-loop interaction. For this purpose, we divide the observations during the preflare phase into two stages, i.e., before and after 10:40:49 UT, when the SXT image showed the partial collision of the two loops (figure 2g). We refer to each of them as stage 1 and stage 2, respectively. During stage 1 the two loops are not yet coalesced. However, a quantitative analysis suggests that the densities of the two loops and their surroundings (especially the valley portion between the two loops) were increasing, and that the two loops were approaching each other. We thus consider that the interaction gradually occurs during this stage. At 10:40:49 UT the two loops partially collided, and then in stage 2 the merging process rapidly progressed.

To investigate the mechanism during stage 1, Fushiki and Sakai (1994) recently performed a 3-D MHD simulation. Their work focused on the earlier stage of the two-loop interaction, in contrast to some previous studies which examined the physical conditions after the two-loop reconnection (e.g., Sakai, Ohsawa 1987). They initially assumed two force-free current loops, one of them having a current two-times stronger than the other, and investigated the collision process of the two loops. Interestingly, during the approach of the two current loops, the plasma density in a weak current loop increases. This matches the observed behavior of the left loop from $\sim 10:29$ UT to $\sim 10:37$ UT (figures 2, 3 c to f), in that it gradually increased the plasma density and became bright in soft X-rays. However, we cannot explain with this model why the right loop had faded away during this period.

In stage 2, a partial reconnection was observed in the SXT image at 10:40:49 UT (figure 2g), which took place for about 2 min prior to the onset of a hard X-ray burst (cf. figure 1b). The quickness of the coalescence process starting from this time can be understood if the timescale of this phenomenon is determined by the Alfvén transit time, $\tau_A$, in the interacting loops. Assuming that the magnetic field along the interacting loops is $\sim 100$ G and the number density of ions in the interacting region to be $\sim 10^{10}$ cm$^{-3}$, the Alfvén velocity, $v_A$, is $\sim 2 \times 10^8$ cm s$^{-1}$. Hence, $\tau_A = 2r/v_A \sim 4$ s, where $r$ is the radius of the loop (after coalescence), which we assumed to be 4000
km based on the SXT images. Our observations show that the coalescence process continued for less than two minutes, or only 30 $\tau_A$. We thus conclude that this process can be explained by the explosive-reconnection model (Sakai, Ohsawa 1987), not by the steady-driven reconnection model (e.g., Petschek 1964). The soft X-ray images after 10:40:49 UT (figure 2g) show a single loop (figure 5a), suggestive that the two loops have coalesced or merged into one.

The HXT image during the early phase of the hard X-ray emission (figure 6A) suggests that hard X-rays are first emitted from the interaction region. Most probably, electrons are energized here, and then stream down along the magnetic loop(s) into the footpoints, resulting in hard X-ray emission from the entire loop (in the L-band) or from the double footpoint sources (in the M1-band) during the impulsive phase (figures 5b, c). Unfortunately the spatial resolution of the HXT ($\sim 5''$) is not sufficiently high to conclude whether the hard X-rays are emitted from a single footpoint or two pairs of footpoints, which may be crucial for considering whether the two loops have completely merged into one loop or not. Later, in the gradual phase, energy impulsively released flows downwards into the footpoints, and “evaporates” a dense, chromospheric material up to the corona. It creates a hot plasma near to the loop top, which is seen as a bright source in the HXT L-band image (figure 6D). We can also see this chromospheric evaporation in the sequence of SXT images taken during the impulsive phase.

In the SXT images taken during the preflare phase, we observed a brightening of the right loop (figure 2a to c) and then its fading (figure 2c to f). This phenomenon is regarded as being an example of transient brightenings studied by Shimizu et al. (1994). We also observed soft X-ray footpoint brightening in the SXT image taken at 10:41:53 UT (figure 2h), which took place for about one minute prior to the hard X-ray burst. It is interesting in this aspect that Hudson et al. (1994) reported, using SXT data, impulsive, thermal, soft X-ray emission at the footpoints of magnetic loops during solar flares. They concluded that the impulsive soft X-ray emission comes from material heated by precipitating electrons at loop footpoints and evaporating from the deeper atmosphere into the flaring flux tube, which may also apply to our case.

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