1. Introduction

Hard X-ray (HXR) emission in solar flares has been studied for many years. According to recent observations, HXR emission can be seen from different parts of a flare: two footpoint (FP) sources, a looptop (LT, also called Masuda-type) source, and a coronal (above the X-point) source. The FP sources were firstly observed by HXIS aboard Solar Maximum Mission (SMM) (Hoyng et al. 1981a, b). In the early 1990s, Yohkoh/HXT discovered the LT source (Masuda 1994). In the late period of the flare evolution, HXR emission from the legs of the loop was evident, and a loop-like HXR structure appeared, especially at 25–50 keV, which is unusual, and has been rarely reported before. We consider this phenomenon to be observational evidence for chromospheric evaporation. To confirm this point, we calculated the height distribution of the energy deposition by an electron beam using different atmospheric models. The results suggest that, in order to engender the observed loop-like HXR emission in this flare, the coronal mass density and the electron-beam flux should be extremely high, which is a possible reason why loop-like HXR emission is rarely observed.

Key words: Sun: chromosphere — Sun: flares — Sun: X-rays, gamma rays

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As is well known, a theoretical solar-flare model predicts the process of chromospheric evaporation, which has been confirmed by many observations. During the impulsive phase of flares, energetic electrons collide with the dense plasma in the chromosphere, and lose their energy through bremsstrahlung. The huge energy release heats the chromospheric material rapidly, which causes an overpressure and engenders a plasma upflow along the loop. Most of the observational evidence of chromospheric evaporation is based on the blue-shifted components of soft X-ray emission lines produced by the upward-flowing plasma (Doschek et al. 1980; Feldman et al. 1980). Brosius and Phillips (2004) reported oppositely directed flows using the Coronal Diagnostic Spectrometer (CDS: Harrison et al. 1995) on board the Solar and Heliospheric Observatory (SOHO) during an HXR burst. Milligan et al. (2006a, b) combined RHESSI and CDS observations to study the process of chromospheric evaporation. They used RHESSI data to derive the energy of the driving electron beam. Liu et al. (2006) presented evidence of chromospheric evaporation in HXRs observed by RHESSI. They found that the emission centroids of the HXR sources moved from the FPs to the LT during the impulsive phase of the flare. Through detailed analyses, they suggested that such a result reflects continuous chromospheric evaporation. A similar gradual upward motion of HXR sources along flare loops was also reported by Sui, Holman, and Dennis (2006).

In most of the HXR observations, due to the limited dynamic range and sensibility of the instruments, we can only detect the HXR emission from the FPs or the LT. The emission from the FPs is interpreted in terms of thick-target bremsstrahlung (Brown et al. 1983), while the mechanism for the LT emission is still uncertain. Some authors think that the LT emission is caused by collisional bremsstrahlung from trapped electrons, while others consider the emission as being due to the high density or temperature at the LT (see Fletcher 1999 for a review). However, in the loop region between the FPs and the LT, the plasma is relatively tenuous. Collisions between the energetic electrons and the ambient ions are usually rare, and thus cannot yield HXR emission strong enough to be detected. This is the reason why we cannot find loop-like HXR emission in the majority of flares. Theoretically, if the flare loop becomes dense enough by some processes, say, chromospheric evaporation, and the instrument has a wide dynamic range, it is possible to detect loop-like HXR emission in the loop legs other than the FPs and LT. In fact, some recent observations
have indicated such a possibility. Veronig and Brown (2004) reported two solar flares observed by RHESSI in which the emission is mainly from the coronal loop. They explained this as being thick-target bremsstrahlung in the loops of flares. Liu et al. (2006) observed a transient emission from the loop legs in an intermediate energy band (12–18 keV) in a limb flare. In this paper, we present RHESSI HXR observations of the 2005 January 20 event, which clearly showed loop-like emission in 25–50 keV during some phases of the flare evolution. We consider this as being evidence of chromospheric evaporation, which makes the loop dense enough in producing visible HXR emission.

2. Observations and Data Analysis

The flare under study is a GOES X7.1-class flare that occurred on 2005 January 20. This event was detected by many spacecrafts and ground-based solar observatories, and became one of the most-studied flares during solar cycle 23 (Krucker et al. 2005; Hurford et al. 2006; Simnett 2006). The SOHO spacecraft observed a very fast coronal mass ejection (Krucker et al. 2005; Hurford et al. 2006; Simnett 2006). The solar energetic particle event related to this flare was also very intense, and Ground Level Enhancements (GLE) were detected by a world-wide network of neutron and muon detectors (Plainaki et al. 2007).

RHESSI had an excellent coverage of this flare. Figure 1a shows the RHESSI light curves in different energy bands. The lightcurves were averaged over every 4 s. The flux in low energies (< 25 keV) rises gradually and peaks at ~06:48:27 UT. On the other hand, the flux at high energies (> 25 keV) has a pulse at ~06:46:00 UT. The sharp steps at ~06:42:00 and ~06:48:50 UT are due to attenuator/decimation state changes that can keep the detectors from being saturated at high counting rates (Lin et al. 2002; Smith et al. 2002). The former was caused by a moving Attenuator 1 (A1) to A3, and the latter was caused by moving Front Decimation 3 (FD3) to FD4. Because the attenuators mainly reduced the flux of low-energy photons, while having little effect on high-energy photons, the drops of the lightcurves at 6–12 and 12–25 keV are more evident than those at higher energy bands. Note that a correction was made automatically for the drops at ~06:48:50 UT when plotting the lightcurves, so that these drops are much less obvious than those at ~06:42:00 UT.

Figure 1b shows HXR images at 25–50, 50–100, and 100–300 keV (solid contours) overlaid on the magnetogram observed by SOHO/MDI. The magnetogram was taken at 05:46:02 UT, and the HXR images were integrated for the time interval of 06:46:09–06:46:17 UT. The dotted lines in the figure represent the magnetic neutral lines. This map clearly shows that the two compact HXR sources lie on the two sides of the magnetic neutral line. They are supposed to be the conjugate FP regions of the flare loop.

To compare with observations at other wavelengths, we overplot the RHESSI 6–12 keV and 25–50 keV images on the SOHO/EIT map in figure 1c, where the EIT 195 Å image was taken at 06:48:12 UT. The solid contours overlaid on the image show the 25–50 keV emission that is the same as in figure 1b. One can see that the two FPs are connected by a bright loop in the EIT 195 Å map. The emission from the LT can be seen in the low-energy band (6–12 keV), with an emission area much larger than that in the FPs in high-energy bands.

2.1. Pileup Effect

Before doing quantitative analyses, it is necessary to check if the pileup effect1 is crucial in this flare. There are several ways to do this. One simple way is to use the SSW routine hsi_correct_pileup to obtain the ratio of the pileup counts to the total counts. Figure 2 shows the pileup ratio during 06:43:00–06:48:00 UT. This period covers the main phase of the flare that is the focus of this study. It can be seen that the ratio is very small at the beginning (06:43:00 UT) and gradually rises with time. In most of the interval, the ratio is ≤ 25% (a moderate level), and does not reach 50% until the end. The dashed lines in figure 2 show the interval during which the loop-like HXR emission is visible (~ 06:46:00–06:47:10 UT). The pileup ratio is ~ 14% at 06:46:00 UT, while it rises to ~ 36% at 06:47:10 UT.

Another approach to check the pileup effect in HXR images involves confirming the possible pileup region through comparing the low-energy images with the high-energy ones (S. Krucker, private communication). We reconstructed HXR CLEAN images (Hurford et al. 2002) in two different energy bands, 12–25 keV and 25–50 keV. According to the count rate shown in figure 1, the photons at 12–25 keV have the highest count rate, implying that the pileup effect is most possible at 25–50 keV. In figure 3a, we show the 25–50 keV image at 06:47:04–06:47:08 UT as the background, and overlay the 12–25 keV image at the same time using black contours. It shows that the emission at the lower energy band is mainly from the southern leg (Leg2) and the LT. Therefore, the possible pileup region should be in these two regions and unlikely, at least not important, in the northern leg (Leg1) and the two FPs.

In order to quantitatively estimate the pileup effect in the HXR source regions, we assumed a model in which the number of pileup photons in the higher energy image scale with the photons in the lower energy image. To correct the pileup effect in the former, we first integrated the 25–50 keV image to obtain the total number of photons. From figure 2, we could obtain the ratio of pileup photons at the time corresponding to the image in figure 3a to be ~ 30%. We then calculated the total number of pileup photons, and distributed them to each pixel according to the 12–25 keV intensities. At last, we subtracted the estimated pileup photons from the 25–50 keV image. Thepileup-corrected CLEAN image is shown in figure 3b. The emission from the loop legs is weakened, but still visible (~ 40% of the maximum emission). In addition, we also used a longer integration time of 30 s (06:46:30–06:47:00 UT) and plot the pileup-corrected image in figure 3c. It shows a similar result to that in figure 3b, only that the emission from the legs is now ~ 30% of the maximum emission.

According to the above analysis, we can conclude that the pileup effect does not influence our results significantly, especially in the impulsive phase (~ 06:45:10–06:47:10 UT). The loop-like HXR emission does really exist. Note that after ~ 06:48:00 UT, the pileup effect cannot be ignored, and may

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1 The pileup effect is caused by two or more photons that arrive very closely in time. These photons are detected as one photon having their energies added (Smith et al. 2002).
The most interesting feature of this flare is the structure of HXR sources during the whole evolution. Except for two FP and one LT sources that are common in RHESSI flares, this flare shows a clear loop-like emission in some period of the evolution. This is an unusual phenomenon. Liu et al. (2006) reported a limb flare of 2003 November 13 that also showed HXR emission from the loop in the intermediate energy band (12–18 keV). However, they found that the emission from the legs of the loop was a transient phenomenon. The loop-like emission of the flare on 2005 January 20 lasted longer and was more stable.

We now examine the HXR images during the whole evolution. Figure 4 shows 16 RHESSI CLEAN images in 25–50 keV that cover the interval from 06:42:52 UT to 06:52:05 UT. The integration time is 10 s for all of the images. We can divide the

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2 In this period, the emission is mainly from the LT. We discuss this in subsection 2.2.
evolution into four phases. Phase I — ~06:42:52–06:45:35 UT (figures 4a–4d). The two FPs clearly appear, while the LT is invisible during this period. Phase II — ~06:45:37–06:46:17 UT (figures 4e–4g). In this phase, the LT source appears. It is faint at the beginning, but becomes brighter with time. The FPs are still bright and well-shaped. Phase III — ~06:46:19–06:47:17 UT (figures 4h–4i). The emission from the legs of the loop appears. The LT source dominates progressively, while the emission from the FPs decays with time, and has a moving tendency toward the LT. Phase IV — ~06:47:31–06:52:05 UT (figures 4m–4p). The emission from the LT is dominant in this phase. The legs of the loop merge into the LT and can no longer be distinguished. The FPs disappear. Note that the check of the pileup effect in subsection 2.1 has shown that this effect cannot be neglected after ~06:48:00 UT. We think that the emission from the LT shown in the images (the fourth row) is mostly from pileup photons.

In order to make a more quantitative interpretation of this flare, we derived spatially resolved HXR lightcurves for different sources, labeled in figure 3. To ensure a signal-to-noise ratio that is high enough, we selected an integration time of 8s. We collected images every 1s. This means that the time intervals for two consecutive images overlap by 7 s. We plot in figure 5 the lightcurves for different HXR sources, which have a pixel spacing of 1s, but an actual time resolution of 8s, i.e., the integration time of the images. The abrupt drops of the lightcurves at ~06:42:00 UT and ~06:48:50 UT are due to the attenuator/decimation movements, as mentioned above. Because we used the CLEAN method to obtain the spatially resolved lightcurves, correction for the Front Decimation is not available. Therefore, we can see much larger drops at ~06:48:50 UT in the lightcurves in figure 5 than those in figure 1.

We can clearly see that different sources undergo different evolution processes. The lightcurves of the two FPs are highly correlative, as expected. The fluxes of the FPs peak at ~06:46:00 UT, which is nearly 3 min earlier than the peak of the LT at ~06:49:00 UT. The lightcurves from the two legs of the loop are similar, and clearly show a plateau portion from ~06:47:00 UT to 06:49:00 UT. After 06:49:00 UT, all of the fluxes decrease, with the LT source dominating over the other sources, as shown in figure 4.

2.3. Spectral Analysis

In order to confirm the emission property, we fit the HXR spectra for three different sources (FP1, Leg1, and LT) with a thermal component plus a power-law component. The spatial domains of the different sources are shown in figure 3c. The integration time of the spectra is 30s from 06:46:30 UT to 06:47:00 UT, during which the emission in the loop was clear. We chose 28 energy intervals from 3 keV to 114 keV, and used the CLEAN method to obtain the spatially resolved spectra. The result is shown in figure 6. For all three sources, the thermal and power-law components intersect at about 20 keV, above which the power-law components dominate. With this result, we conclude that the emission above 20 keV from the three sources is mainly of non-thermal origin. Also, we find that the spectral indices are different for the three sources. The FP1 source has the hardest spectrum with a power-law index of ~2.6. Along the loop, the spectrum has a tendency to become softer. For the Leg1 source, the power-law index is ~3.4. The LT source is the softest with a power-law index of ~4.1.
The emission measure ($EM$) of the thermal component is plotted in figure 7a. The $EM$ gradually rises with time in the whole process for all three HXR sources. Assuming a constant volume and using the relationship between the density and $EM$ ($n = \sqrt{EM/V}$), the density in the loop increases about 3 times during this period.

In figure 7b, we show the temperature variation of the FP1, Leg1, and LT. Considering the uncertainty of the temperature in the spectral fitting, the temperature change is not obvious during the flaring time. The temperature at FP1 is lower than that at Leg1 and LT. The temperature at LT is less than 30MK, which suggests that the LT emission is unlikely of thermal origin in this flare (Alexander & Metcalf 1997).

To investigate the non-thermal component variation during the flaring time, we further show the fitted flux evolution at 32 keV in figure 7c. Because the non-thermal emission dominates above $\sim 20$ keV, the flux at 32 keV can represent the variation of the non-thermal component. In the figure, the flux of the FP source peaks around $\sim 06:45:30$ UT, and then decreases with time. However, the fluxes of the Leg1 and LT sources gradually increase during the whole evolution. Notice that the non-thermal component in the Leg1 source keeps increasing after $\sim 06:46$ UT when that from the FP source starts to decrease. This means that the electron beam flux may decrease after $\sim 06:46$ UT, and therefore the increase of the non-thermal flux in the loop legs suggests an increase in the mass density there to enhance the efficiency of the thick-target bremsstrahlung.
Fig. 5. Lightcurves of different hard X-ray sources marked in figure 3. The rapid declines at ~06:48:50 UT were caused by moving FD3 to FD4 (see section 2). The CLEAN method results in step-like features there, rather than very sharp drops.

Fig. 6. Spectral fitting for different hard X-ray sources of the flare. The CLEAN method was used to deduce the spatially resolved spectra with an integration time of 30 s. The energy band in between the two vertical dotted lines was used for fitting. The solid line represents the original flux. The dotted and dashed lines represent the fitted thermal component and non-thermal component, respectively.
3. Discussions

We have studied the properties of RHESSI HXR images of the 2005 January 20 flare. With unprecedented spatial and temporal resolution, the RHESSI data show the HXR source structures in detail and the temporal evolution during the impulsive phase of the flare. The main finding of this study is clear loop-like HXR emission during some period of the flare evolution. We think that this is a consequence of strong chromospheric evaporation. According to the standard model of solar flares, in the impulsive phase, non-thermal electrons travel along the reconnected magnetic field lines from corona to the chromosphere and collide with the dense plasma. In this process, HXR emission can be produced through thick-target bremsstrahlung. At the same time, the released energy heats the chromospheric material and induces an upward mass motion along the loop. When the density in the loop is large enough, thick-target bremsstrahlung is possible within the loop legs, not only in the footpoints, as usual. If this is the case, we can see the HXR emission from the loop legs.

The general picture of the 2005 January 20 flare can be summarized as follows. Before the impulsive phase of the flare, the energy release process has begun, which can be seen from the lightcurves of the HXR sources. The similarity between the lightcurves of the LT and the FPs in the early phase of the flare suggests that the HXR emissions from these sources are probably caused by the same energetic electrons or, at least, related to the same energy release process of the flare. In the impulsive phase of the flare, the fluxes of the FPs rise rapidly, while the fluxes of the LT and the loop legs change little, which suggests that the density in the loop is small and insufficient to produce HXR emission although the evaporation has begun. With the loop density being increased, the LT becomes visible in HXRs. When the loop density is large enough, the whole loop can show HXR emission that is, of course, highly inhomogeneous. When the lightcurves of the legs show a plateau, the density in the loop should be in a quasi-stationary state.

Liu et al. (2006) found a flare showing HXR emission from the flare loop using RHESSI data, and noticed a movement of the centroid of the HXR sources from the FPs to the LT. They regarded this as evidence of chromospheric evaporation because the increased density of the loop shortens the penetration depth of the electron beam. In our study, we did not detect clear source motions in the 2005 January 20 flare during most of the evolution. However, the loop-like HXR emission in the loop legs during some period of the flare evolution suggests an increased density in the loop, and therefore verifies the existence of chromospheric evaporation in another way.

Finally, we need to answer the question why the loop-like HXR emission reported here is a rare phenomena in observations. We believe that, theoretically, the HXR emission in the loop legs should be a common phenomenon. However, in most cases, such emission is too faint to be resolved by the current HXR detectors and/or image-reconstruction methods. The 2005 January 20 event should be among the very few events with some extreme conditions. To test this point, we made some quantitative analyse concerning this event. We first integrated the 25–50 keV photons in the loop legs and the footpoints, respectively, and found that the former is ~10% of the latter. Under the scenario that the HXR photons are from bremsstrahlung of non-thermal beam electrons when they precipitate downwards, we can say that, approximately, the beam electrons need to deposit ~10% of the total energy in the coronal part in order to produce the HXR emission in the loop legs. We then calculated the height distribution of the energy deposition by beam electrons in different atmospheric models using a method proposed by Emslie (1978). The electron beam is assumed to have a power-law form with a low-energy cutoff of 25 keV and a spectral index of 4. For the quiet-Sun model VAL3C (Vernazza et al. 1981), the coronal column mass density is about 6.2 × 10⁻⁶ g cm⁻², yielding a very small fraction (<1%) of energy deposition in the corona. On the other hand, to deposit ~10% of the energy in the corona, the coronal mass density should be as high as ~7.3 × 10⁻⁷ g cm⁻², which is 3 orders of magnitude higher than the quiet-Sun value, and almost twice the value predicted by the strong-flare model F2 (Machado et al. 1980). The radiative hydrodynamic models calculated by Allred et al. (2005) show that for an electron beam with a flux of 10¹⁰ erg cm⁻² s⁻¹, the coronal mass density can be increased by 2–3 orders of magnitude relative to the preflare value. This implies that for the 2005 January 20 flare, the electron beam flux should be larger than 10¹ⁱ erg cm⁻² s⁻¹.

This fraction is obtained in the case after the correction for the pileup effect mentioned in subsection 2.1.
We now make an estimation of the electron beam flux in this flare. Under the assumption that the non-thermal emission in the loop legs is produced via the thick-target bremsstrahlung by electrons with a single power-law distribution and a low-energy cutoff of 20 keV, we derived the total electron beam flux in the flare. We then approximately distributed the total electron beam flux into each pixel in proportion to the photon flux, as was done in Chen and Ding (2005). Using this method, we obtained the maximum electron beam flux in Leg1 to be \( \frac{1.6 \times 10^{11}}{\text{erg cm}^{-2} \text{s}^{-1}} \). This value is roughly comparable to the desired value mentioned above. For the high coronal mass density required to generate loop-like emission, one possible interpretation is gentle chromospheric evaporation before the impulsive phase of the flare. We find that the FP and LT sources at 25–50 keV appear at an early phase (\(~06:39:10\) UT), which is nearly 7 min before the flare peak. The LT source at 12–25 keV can be identified even earlier (\(~06:33:10\) UT). This fact suggests that pre-heating and gentle chromospheric evaporation can exist for quite a long time before the flare, which make the coronal mass density considerably high before the impulsive phase of the flare.

Therefore, we can conclude that only under some extreme conditions, i.e., a very high coronal mass density and a very strong electron beam, can we detect loop-like HXR emission. Of course, with the development of HXR detectors and image-analysis methods in the future, we can expect to see increasing numbers of such events with loop-like HXR emission.

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References

Masuda, S., Kosugi, T., Hara, H., Sakao, T., Shibata, K., & Tsuneta, S. 1995, PASJ, 47, 677