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Hard X-ray emission at the footpoints of solar flares

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Abstract

We analyse X-ray flare observations made by the Soft X-ray Telescope and Hard X-ray Telescope on the *Yohkoh* satellite during period 1999–2001. For the strongest flares, when HXT imaging with high time cadence (0.5–1 s) is possible, clear changes in the asymmetry of the observed footpoints fluxes are revealed. We present four examples of flares which illustrate such asymmetrical time variations the best. Observed asymmetries are usually interpreted as due to a difference in magnetic field strength or field divergence at the footpoints, however this interpretation should lead to the existence of strong magnetic field oscillations or movements of the footpoints' locations in the presence of strong magnetic gradients. Our analysis indicates rather that either differences in the electron injection or electron distribution in each loop's leg is the source of the observed asymmetry variations. We discuss possible mechanisms which may be responsible for such effect.

Keywords: Chromosphere; Corona; Flares; Magnetic fields; Hard X-rays

1. Introduction

It is widely established from the *Yohkoh* Hard X-ray Telescope (HXT; Kosugi et al., 1991) observations that, during the impulsive phase of a solar flare, double (or multiple) hard X-ray sources often appear. They are usually located on either side of the magnetic neutral line, suggesting that they are magnetically connected, i.e., they are two footpoints of a single loop (Sakao, 1994). These sources often tend to show asymmetry in hard X-ray emission where the brighter source is usually located in a weaker photospheric magnetic field region and vice versa (Sakao et al., 1996). Double sources are interpreted as regions where non-thermal electrons precipitate after travelling along the magnetic loop legs (Aschwanden et al., 1999; Kundu et al., 1995; Li et al., 1997; Sakao, 1994). In such scenario, a weaker magnetic field allows more electrons to reach the chromosphere.

However, some flares do not fit the above scenario. Thus, of five flares analysed by Sakao (1994) for which magnetograms were available, one has a brighter footpoint located in the stronger photospheric magnetic field region. Asai et al. (2002) also reported an example of a flare for which the brighter footpoint was found in a stronger magnetic field. Recently, Goff et al. (2004) have found seven other double source events in which the brighter hard X-ray (HXR) footpoint is found in the region of stronger magnetic field.

Qiu et al. (2001) observed remarkable changes in the asymmetry of Hα footpoint emission during the impulsive phase of a flare on 2000 March 16. Their observation indicates also changes in HXR emission (see their Fig. 1) from two sites spatially coincident with the Hα kernel, though the authors do not discuss this behavior. Alexander and Metcalf (2002) found clear evidence for an energy-dependent HXR asymmetry in a flare on 2002 March 17. They also found that the asymmetry shows a transition from

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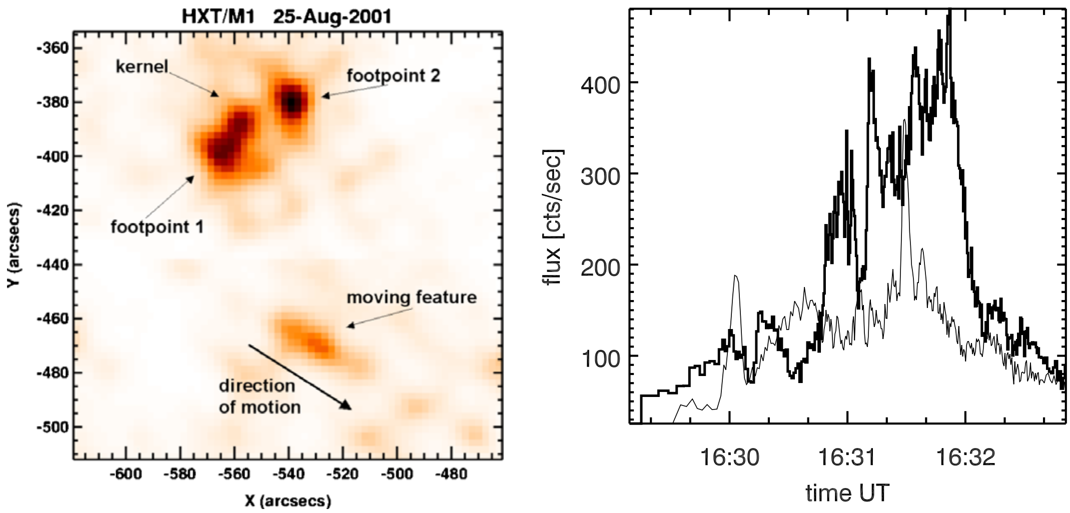

Fig. 1. Hard X-ray emission sources in M1 channel of *Yohkoh*/HXT on the 25 August 2001 flare (left panel). The light curves of the hard X-ray footpoint sources obtained (right panel). Strong quasi-periodic oscillations are seen. The thin line corresponds to the footpoint's 1 flux and thick to the footpoint 2.

the clear dominance of one footpoint to clear dominance of the other later during the flare impulsive phase. However, both these papers were based only on two and three images respectively.

We have found another example of a flare in which there is a marked asymmetry, with first one, then the other footpoint being dominant alternately several times during the impulsive phase (Siarkowski and Falewicz, 2004). In this paper, we briefly describe this event, reanalysing observations of Qiu et al. (2001), and present two other examples of flares in which the asymmetry changed markedly with time.

2. Observations

Hard X-ray images of the flare were obtained with the *Yohkoh*/HXT and reconstructed using the standard pixon reconstruction procedure (Metcalf et al., 1996). We used variable accumulation times assuming a threshold count rate of 200 counts in the M2 band (33–53 keV) giving a range of accumulation times from about 0.5–1.0 s during the flux maximum. The restored images are presented in Figs. 1 (left panel), 3, 5, and 7. The fluxes in the individual footpoints were obtained from the reconstructed images for three HXT channels: M1, M2, and H.

We defined flux asymmetry by $A = (F_2 - F_1)/(F_1 + F_2)$ where F_1 and F_2 are the fluxes at footpoints 1 and 2, respectively. For full symmetry $F_1 = F_2$, and $A = 0$; for perfect asymmetry $A = +1$ or -1.

The obtained values of asymmetries for analysed events are presented in Figs. 2, 4, 6, and 8. The vertical bars in these figures show the statistical errors of the fluxes and asymmetry. Errors of the fluxes were derived from the uncertainties provided by the pixon reconstruction algorithm (Metcalf et al., 1996). They represent the statistical errors only, and do not represent any systematic errors which might be caused by the reconstruction itself.

2.1. 25 August 2001

The first analysed flare (for more details see Siarkowski and Falewicz, 2004) occurred on 25 August 2001, with a GOES peak intensity of X5.3.

The *Yohkoh* satellite observed this flare from 16:18 UT, during four consecutive orbits up to about 22:00 UT. Fig. 1 shows an image obtained from the HXT/M1 channel (23–33 keV) flux integrated over the period 16:28–16:33 UT. Two main structures are evident: the first we interpret as a flare loop and the second as moving feature. Between 16:28 and 16:32 UT two bright footpoints were seen in the flare loop. After 16:32 UT a bright loop-top source developed.

The white-light emission of this flare has been analysed in detail by Metcalf et al. (2003).

Each footpoint source in Fig. 1 indicates fluctuations in both flux and position. Fig. 1 (right panel) presents the light curves for each footpoint as obtained for channel M1. The observed variations are very obvious as seen in a movie obtained from the reconstructed images. Fig. 2 presents four images from this movie obtained at channel M1 at 16:29:26, 16:30:03, 16:30:15, and 16:31:12 UT, respectively (upper panel) and the asymmetry for footpoints 1 and 2 (lower panel). Strong variations of asymmetry can be seen in the range from -0.3 to $+0.6$. Changes of the asymmetry are similar in all the channels but they are the strongest in the channel H.

Using the *SOHO*/MDI magnetogram we also estimated the footpoints' magnetic flux. During the entire event one of the footpoints indicates for a larger magnetic field than the other; the corresponding ratio was greater than 2. So motion of the loop footpoints in the presence of the magnetic field gradient cannot explain the observed strong asymmetry variations (Siarkowski and Falewicz, 2004).

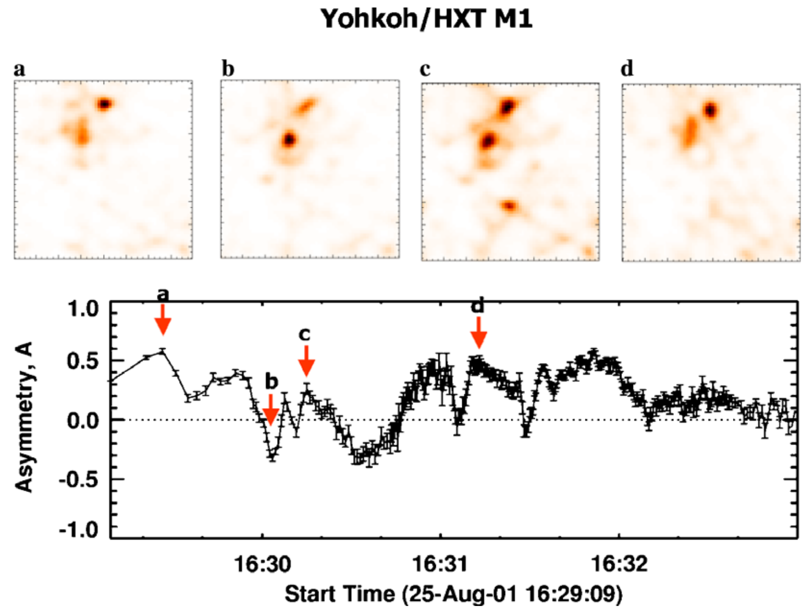

Fig. 2. Upper panel: images of the flare in HXT/M1 channel for the selected moments of time. Lower panel: time profiles of the footpoints' asymmetry for HXT channel M1. The arrows indicate the times of the images a, b, c, and d.

2.2. 20 August 1999

The second analysed flare occurred on 20 August 1999 in NOAA 8673 active region (S17 E81), with a GOES peak intensity of M9.8. The *Yohkoh* satellite observed this flare from about 22:30 UT to 23:20 UT. *Yohkoh*/HXT recorded strong emission in all of the four channels during the impulsive phase. For example, emission in the channel H (53–93 keV) reached a maximum flux as high as 788 counts/s/subcollimator at 23:06:10 UT. Fig. 3 shows images obtained from the M2 channel (33–53 keV) at 23:06:10 and 23:06:22 UT. Two structures, interpreted as two bright footpoints, were seen in the soft X-ray (SXR) flare loop.

Both footpoint sources in Fig. 3 show large fluctuations in the HXR fluxes. Time variations of this fluxes are shown in Fig. 4 (left panel). Strong time variations of the asymmetry can be seen in the range $A = -0.2/+0.4$ (see Fig. 4 – right panel). Changes of the asymmetry are similar in all the channels but they are the strongest in the channel M2.

2.3. 12 July 2000

The third analysed flare occurred on 12 July 2000 in the NOAA 9077 active region (N17 E27), with a GOES peak intensity of X1.9. The *Yohkoh* satellite observed this flare from about 09:55 UT, during one orbit up to about 10:55 UT. *Yohkoh*/HXT recorded strong emission in all of the four channels during the impulsive phase. For example, emission in the channel H (53–93 keV) reached a maximum flux as high as 181 counts/s/subcollimator at 10:31:20 UT.

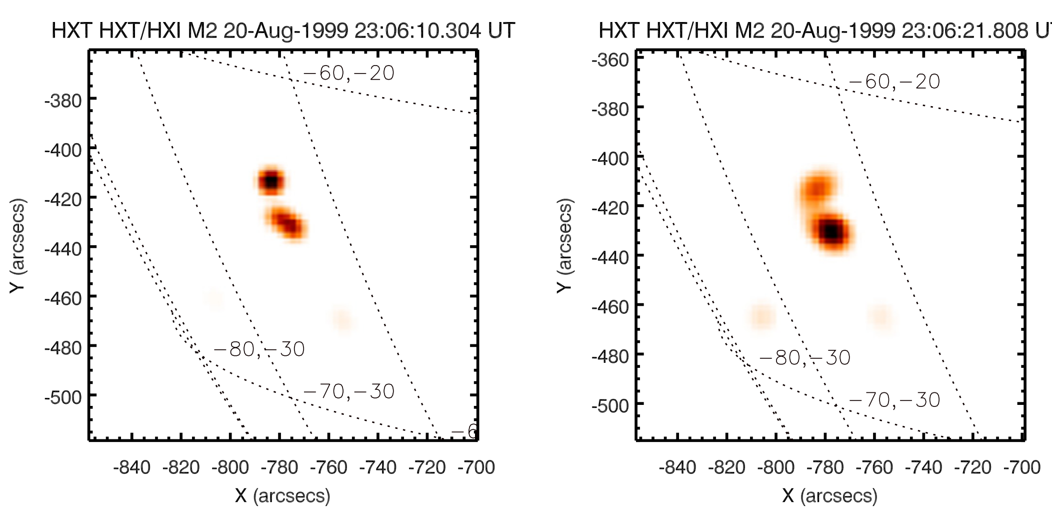

Fig. 3. Images of the emission in the HXT/M2 channel for the 20 August 1999 flare taken during the time when the asymmetry was strong.

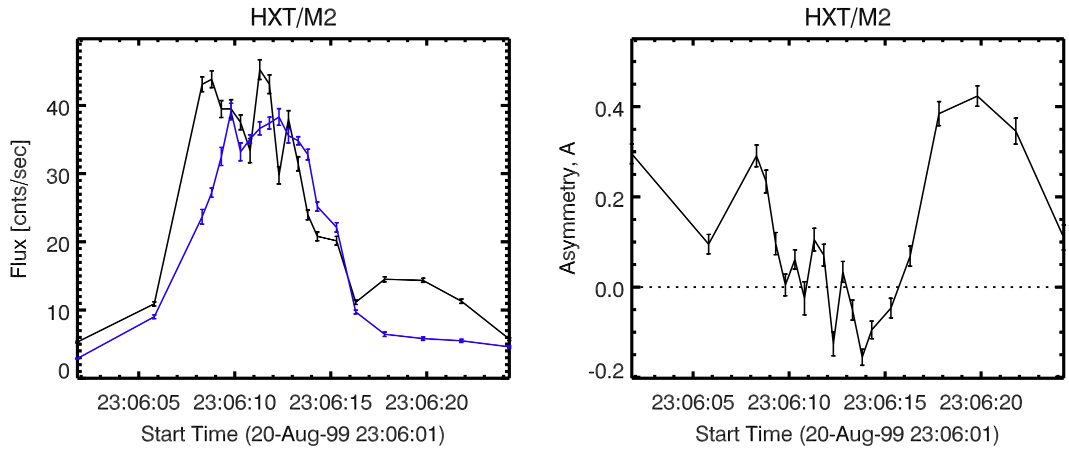

Fig. 4. Light curves of hard X-ray footpoint sources obtained in the M2 channel of HXT for the 20 August 1999 flare (left panel). Strong quasi-periodic oscillations are seen. Right panel shows the time profile of the footpoints' asymmetry for HXT channel M2.

Fig. 5 shows images obtained from the M2 channel (33–53 keV) at 10:31:24 and 10:31:42 UT when the asymmetry was strongest. Two structures, interpreted as two bright footpoints, are seen. The loop top is evident in soft X-ray emission. Both footpoint sources in Fig. 5 indicate clear fluctuations in HXR fluxes. Time variations of this fluxes are shown in Fig. 6. Strong time variations of the asymmetry can be seen in the range $A = \pm 0.25$ (see Fig. 6 – right panel). Changes of the asymmetry are similar in all the channels but they are the strongest in the channel M2.

2.4. 16 March 2000

The fourth analysed flare occurred on 16 March 2000 in NOAA 8906 active region (S17 W34), with a GOES peak intensity of C9.0. The *Yohkoh* satellite observed this flare from about 18:00 UT to 19:00 UT. *Yohkoh*/HXT recorded emission in all of the four channels during the impulsive phase. For example, emission in the channel H (53–93 keV) reached a maximum flux as high as 12 counts/s/subcollimator at 18:35:12 UT. This flare was also analysed by Qiu et al. (2001). The authors investigated a strong changes in the asymmetry of Hα footpoint emission, but not discussed asymmetry behavior in the HXR emission.

Fig. 7 shows two images obtained from the M1 channel (23–33 keV) for two times: 18:35:02 UT and 18:35:59 UT (when the asymmetry was strongest). Two structures, interpreted as two bright footpoints, are seen. Both footpoint sources presented in Fig. 7 indicated clear fluctuations in HXR fluxes as shown in Fig. 8. Strong time variations of the asymmetry can be seen in the range $A = -0.16/+0.09$ (see Fig. 8 – right panel). Changes of the asymmetry are similar in three channels (L, M1, and M2) but they are the strongest in the channel M1.

3. Discussion and conclusions

We have analysed four flares for which clear asymmetry footpoint variations are observed with good time cadence. The present analysis allows us to draw the following conclusions.

Usually, the brighter emission of the footpoint is related with the weaker magnetic field convergence (e.g., Sakao, 1994), i.e., in stronger magnetic field more electrons are

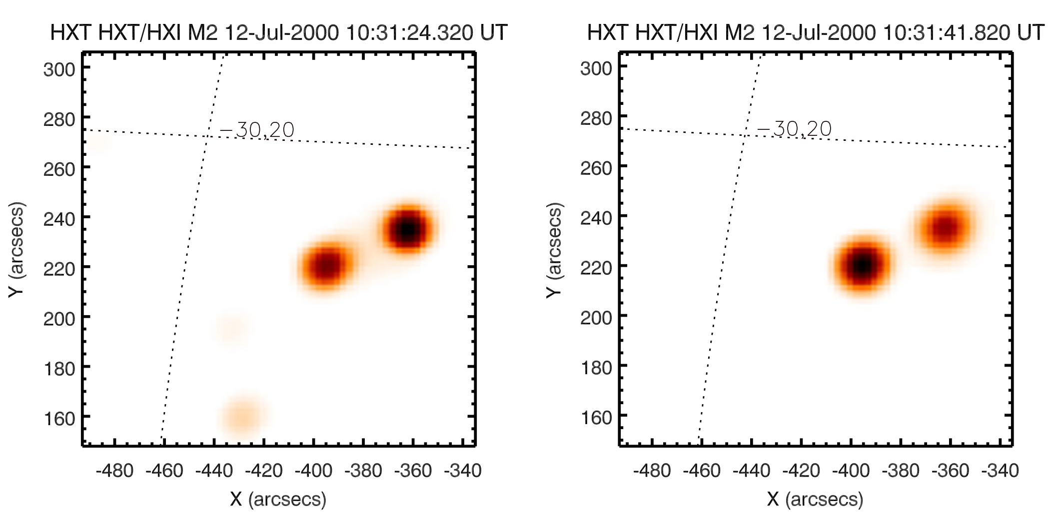

Fig. 5. Images of the emission in the HXT/M2 channel for the 12 July 2000 flare taken during the time when the asymmetry was strong.

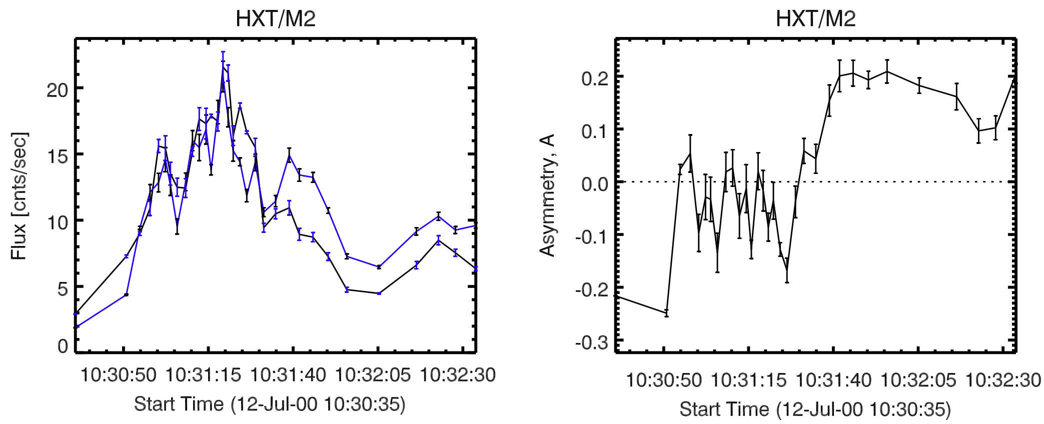

Fig. 6. Light curves of hard X-ray footpoint sources obtained in the M2 channel of HXT for the 12 July 2000 flare (left panel). Strong quasi-periodic oscillations are seen. Right panel shows the time profile of the footpoints' asymmetry for HXT channel M2.

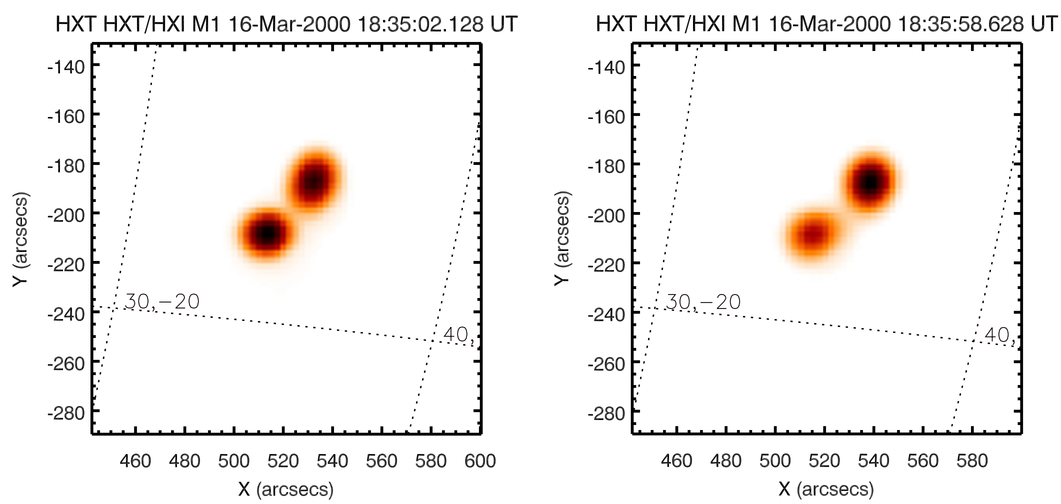

Fig. 7. Images of the emission in the HXT/M1 channel taken for the 16 March 2000 flare during the time when the asymmetry was strong.

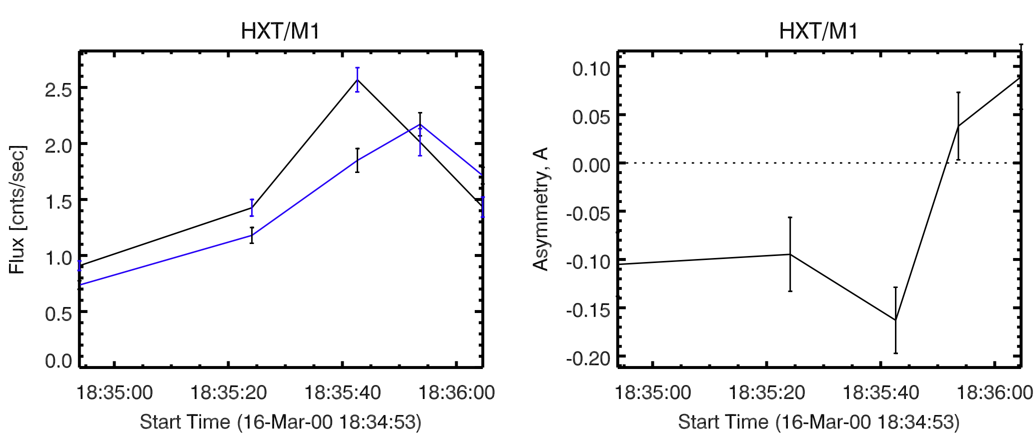

Fig. 8. Light curves of hard X-ray footpoint sources obtained in the M1 channel of HXT for the 16 March 2000 flare (left panel). Right panel presents the time profile of the footpoints' asymmetry for HXT channel M1.

reflected in the magnetic mirror back into the top of the loop. However, there are many examples of flares that do not fit with the above interpretation (Asai et al., 2002; Goff et al., 2004; Sakao, 1994). Additionally, there are also examples of flares for which time variations of the asymmetry are observed (this paper, Siarkowski and Falewicz, 2004). Observed time variation of asymmetry may be interpreted as differences in the injection conditions and/or the electron distribution in each loop's leg. A plausible candidate for an asymmetric source of energy release may be turbulent kernel located near the top of the flaring loop. In such a kernel, electrons moving along the loop legs (and emitting HXR at footpoints) are produced at small-scale reconnection sites, independently in both legs of the loop (Jakimiec et al., 1998). The observed changes in asymmetry can tell us about the time or spatial scale or the number of these elementary processes. A possible way in which this mechanism may occur is a configuration in which the magnetic field containing the flaring plasma is stressed. This process could continue to occur as long as the magnetic pressure in the region of MHD turbulence is higher than plasma pressure. In this state, electrons are still accelerated in the stressed, turbulent plasma until its pressure reaches the magnetic pressure, when plasma ejection would occur. This process can be repeated in a quasi-periodic manner producing local maxima in the hard X-ray emission and microwaves, until the magnetic energy is exhausted. This is generally in good agreement with observations (Aschwanden and Güdel, 1992; Kundu et al., 1994).

Another possibility which can explain time variations of asymmetry are oscillations of the whole flare loops system. Such oscillations can lead to time changes of the convergence of the magnetic field lines highly in the loop independently on the magnetic field strength in their footpoints. Finally, theoretical simulations of the particle trajectories in a reconnecting region in a 3-D magnetic field topology (Zharkova and Gordovsky, 2004) indicate strong asymmetric accelerations. Depending on the ratio of the magnetic field components, different proportions of electrons and protons can be injected into the different legs of the reconnecting loops.

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