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Letter to the Editor

New observed evidence of magnetic reconnections in the impulsive phase of a flare

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Abstract. That a magnetic reconnection process occurs in a flare impulsive phase is reported in this letter, and together with the process an accompanying inflow is observed for the first time. The observations strongly suggest some forms of interaction between the two loop systems, and the process is also a strong suggestion of an inverse Y-type neutral line formation.

Key words: Radiation mechanisms: bremsstrahlung – Sun: corona – Sun: flares

1. Introduction

The stored magnetic energy in solar flares can be released to a very high degree – up to the 10^{31}–10^{32} ergs within 10^2–10^3 seconds. Theoretically, it is necessary to minimize the characteristic length scale ℓ, which is associated with changes in the magnetic field, because the τ_D is proportional to ℓ^2 so that we can compare the magnetic diffusion time τ_D with the time scale of the energy release. The magnetic configuration with two sets of oppositely directed fields in close proximity—so called neutral point (or current sheet) can make the ℓ as small as possible. The physical process of energy dissipation in such a configuration is called the magnetic reconnection. Finding an evidence of the reconnection and accompanied phenomena observationally keeps a challenging for solar physicists (e.g. Tsuneta, 1996, Shibata et al., 1992, Masuda et al., 1994).

I report in this letter an observed reconnection process. And the accompanied inflow is reported for-the-first-time. The reported reconnection process occurred between the two loops in an impulsive phase of a flare, which started at 04:09UT on June 4, 1992. The event was observed by the Soft X-ray Telescope (SXT, Tsuneta et al., 1991), Hard X-ray Spectrometer (HXS, Yoshimori et al., 1991) and Hard X-ray Telescope (HXT, Kosugi et al., 1991) boarded on Yohkoh (Ogawara et al., 1991). The active region producing the flare was AR7186 (N10E40 on the solar disk). The observations strongly suggest some forms of interaction between the two loop systems and the process itself also has strong evidence of an inverse Y-type neutral line formation.

2. A magnetic reconnection process observed in the soft X-ray

Fig. 1 shows the SXT images of the active region. The images reveal many loop-like structures. Among them, two loops A and B are prominent. The intersection of the two loops began to brighten at 04:04:09UT, and continued to increase its brightness till 04:07:21UT. During the period the whole loop B brightened and its footpoint brightness increased significantly, the footpoint of loop A brightened, too. Corresponding to these X-ray footpoints, we observed the chromospheric flare kernels, whose locations were at the west footpoints of loops A and B (Zhang, 2000). More interestingly, the north-eastern tip (i.e. the apex) of loop B was displacing in the direction of north-east in the mean time. The apex displacement indicates the loop's rising. A jet-like brightening, taking its root at the footpoint of loop B, ejects approximately eastward at 04:06:17UT but changed into a direction of northeast at 04:07:21UT. Finally, the jet had turned about $20 - 25°$ clockwise until 04:08:25UT. A similar chromospheric spray originates from one of the flare kernels (Zhang, 2000), which is relevant to the footpoint of loop B. Loop B disappeared during 04:07:21–04:08:25UT.

The brightening of the intersection indicates that the current sheet had been formed at the tangential boundary between the two loops and that the reconnection was in progress. Moreover, the loop B-rising must push against loop A (pointing to the neutral point). Therefore, the magnetic field lines near the neutral point were carried toward the current sheet and reconnected. In other words, the loop B-rising made the field lines inflow. Loop B rose north-eastwards about 1 pixel ($5''$) in the SXT image, i. e. $3.6 \times 10^6\mathrm{m}$ within an interval of 64 seconds. Thus, considering that the correction for the line-of-sight component is not made, the inflow speed of the field lines is estimated to be

$$v_i \geq 56\mathrm{km/s}.$$

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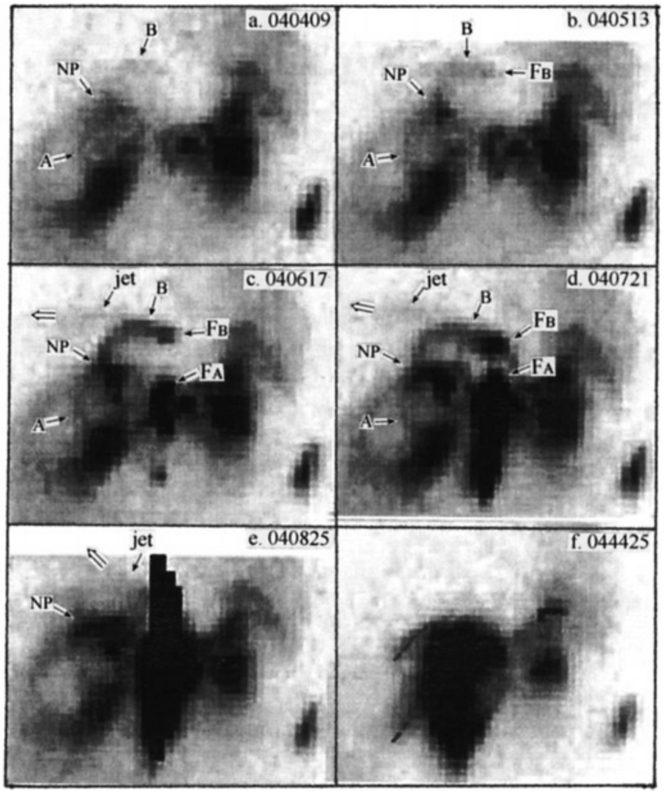

Fig. 1. The SXT images of AR7186. Number and time (hours, minutes and seconds) are in a up-right corner of each panel. Loops A and B are marked by "A" and "B", and feet of the loops are marked by "F_A" and "F_B". The "NP" (neutral point) is intersection of loops or current sheet, Arrow "$\Leftarrow$" points direction that jet, which rooted in F_B, ejected all along. The thorns in middle-up part at 040825UT were brightness saturated. Dashed curves at 044425UT indicate post-flare loops. Field of view (FOV) is $210.7'' \times 166.6''$. North is upward, and east is left. The contrast is negative.

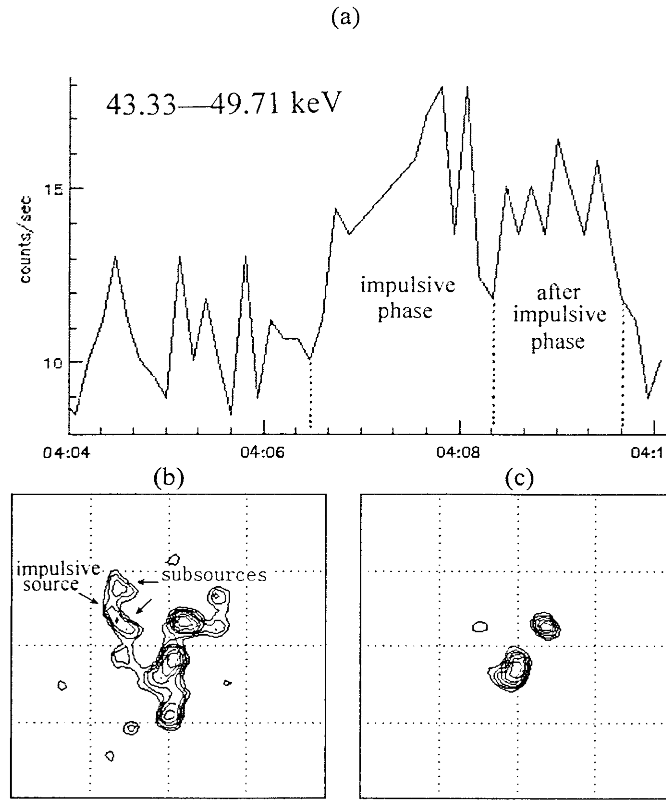

Fig. 2. a Hard X-ray photon time-profile for energy band of $43.33 - -49.71\mathrm{keV}$ recorded by the HXS. Three perpendicular dot-lines mark the times of 04:06:28.9, 04:08:20.9 and 04:09:20.0 UT, and separate time into segments inside and after the impulsive phase. **b** HXT contoured map is produced by integration over the time segment inside the impulsive phase. **c** HXT map integrated in the segment after the impulsive phase. Contours are 12.5, 17.7, 25.0, 35.4, 50.0, and 70.0% of peak brightness.

3. The reconstruction of field lines observed in the hard X-rays

HXS recorded the hard X-ray photon time profiles of the flare. The energy range of the HXS is from $32.67\mathrm{keV}$ to $56.67\mathrm{keV}$. The hard X-ray emission continues from 04:04UT until 04:10UT and it has an obvious increase from 04:06:28.9UT to 04:08:20.9UT (impulsive phase) in an energy range of $43.33 - -49.71\mathrm{keV}$ (Fig. 2a). In other words, these HXS observations are a non-thermal emission since observations above $40 - -50\mathrm{keV}$ are purely due to thick target bremsstrahlung emission by non-thermal electrons.

HXT recorded the temporal hard X-ray emission only at L-band ($14 - -23\mathrm{keV}$), and M1–H band data in HXT were not recorded because the flare mode was not triggered. The obvious increase of L-band hard X-ray emission was from 04:07UT to 04:08:20UT, that is, the observations from SXT/HXS/HXT gave the evidence that the impulsive phase of the flare was before 04:08:20 UT. Although the HXT L-channel has both thermal and non-thermal contributions, the comparison of the HXT and HXS light curves indicates that much of the increased radiation is non-thermal. Therefore, although only L-band emission data are available, very interesting features can be found from integrating the L-band maps (Figs. 2b-c). Figs. 2b and 2c contoured maps integrated respectively inside and after the impulsive phase. Thus, the features presented only in the impulsive phase can be deduced by a comparison of the maps. The remarkable difference between them is a looplike hard X-ray source occurred only in the northeast part of Fig. 2b but not in Fig. 2c, so the hard X-ray loop is an impulsive source. The contours of 25% of the source are separated as two "sub-sources" which correspond to the double feet of the loop-like sources and locate somewhere on the legs of either A or B (Fig. 3).

Besides, the contours of 12.5% and 17.7% are shaped like a loop, which takes the north leg of loop A and the south leg of loop B as its own legs. This means that the HXT looplike source is a new loop reconstructed due to the reconnection. Moreover, the existence of the sub-sources suggests that the non-thermal electrons with a very high energy and corresponding long mean free paths impinge from the current sheet along loops A and B down halfway on their legs. Finally, the shape and the position-

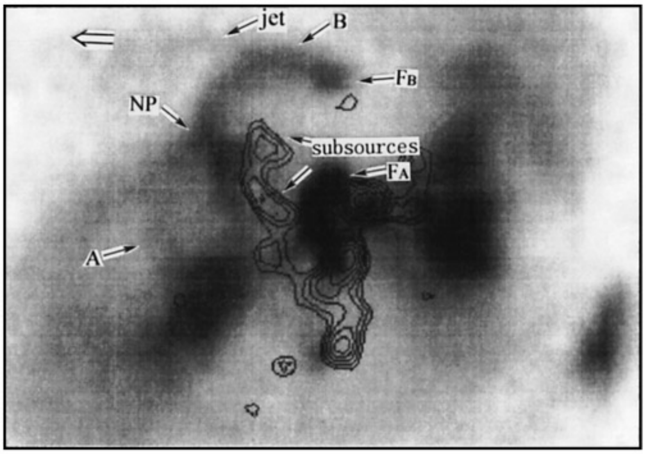

Fig. 3. The SXT image (04:06:17) (gray scale) co-aligned with HXT map (contoured) of the impulsive phase. The loop like HXR source (marked by "impulsive source") suggests that the north leg of loop A was connected with the south leg of loop B to become a new loop due to reconnection. Two sub-sources at feet of the new loop formed since non-thermal electrons impinged from current sheet (neutral point).

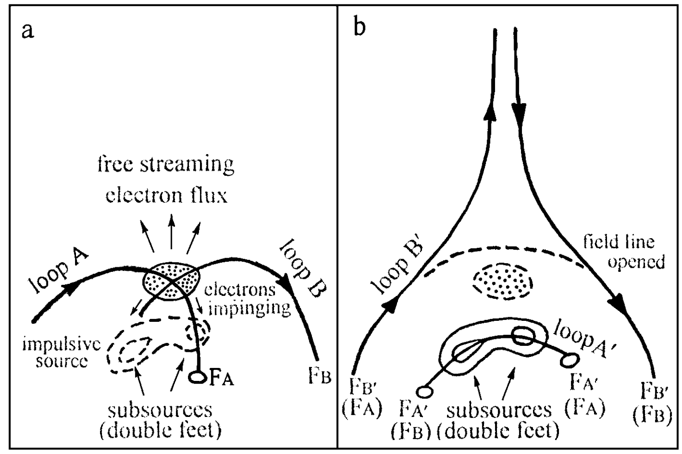

Fig. 4a and b. The schematic flare model of magnetic field line reconnection and of inverse Y-type neutral line development. **a** Current sheet (dot-area) is formed at the intersection of loops A and B, loop B-rising pushes against loop A, as a result, the magnetic field lines around the sheet enter into the sheet and reconnect. The illustrated loop-like hard X-ray source (marked by "impulsive source") with two sub-sources implies the reconstructed loop A' and non-thermal electrons impinging from the sheet toward double feet. **b** Loops A and B are reconstructed as new loops A' and B', the latter opening afterward. Heated chromospheric and lower coronal materials are evaporated along loop A' to form soft X-ray loops (post flare loops). The reconstructed loops (A' and B') and the reconnected loops (A and B) have common feet.

ship of the HXT loop-like source with loops A and B fully prove that the reconnection between loops A and B is a reality.

4. Analysis and implications

The reconnection started at 04:04:09UT (Fig. 1a), and the impulsive source gave the evidence of the reconstruction between loop A and loop B before 04:08:20.9UT (Fig. 2b), so we know that the loop-loop reconnection lasted for about 4 minutes.

In addition, the X-ray jet took its root at the footpoint of loop B, so its ejecting direction must be affected by the magnetic tension of the loop. The tension force acts to shorten the curved magnetic field lines. In other words, the larger the radius of curvature is, the smaller the tension force becomes. The rising of loop B indicates that the magnetic field lines are stretched longer, so the radius of curvature becomes larger. Therefore, the direction change of the jet during the B-rising (04:06:17–04:07:21 UT) implies that the tension acting on the jet decreased. The fact that the jet continued to change its direction during 04:07:21–04:08:25 UT suggests the tension decrease continually. This means that the field lines of loop B' were further dragged out or even broken. In other words, loop B' probably suffers from a change, that is, from a closed loop to an open one.

The schematic model of magnetic field lines reconnection is showed in Fig. 4 by summing up the observations. The current sheet formed at the intersection of loops A and B, the inflow (with velocity $v_i \geq 56\mathrm{km/s}$) made magnetic field lines around the sheet annihilate rapidly and reconnect. As a result, the south leg of loop B was connected with the north leg of loop A to construct a new loop A', whose existence is proved by the impulsive source (Figs. 2b, 3, and 4a). In addition, the south leg of loop A was connected with the north leg of loop B to form another new loop B' (showed as the dashed curve in Fig. 4b). The temperature of the plasma within the current sheet might be in excess of 10^8K since the Ohm dissipation, so bremsstrahlung was produced. The free-streamed thermal electrons flowed from the sheet down the legs of loops A and B (or of loop A') to cause non-thermal hard X-ray double feet (the sub-sources in Fig. 4a), the behavior of the thermal electrons is similar to one mentioned in the "dissipative thermal model" (Emslie and Rust, 1979). Meanwhile, the free-streamed thermal electrons flowed upward to hit higher loop B', then the closed field lines of loop B' became open, inverse Y-type neutral line configuration so developed (Fig. 4b).

This reconnection model resolves a paradox: That hard X-ray double (foot) sources are located at the footpoints of relevant soft X-ray loop. Yohkoh observations have proved that current sheet was above soft X- ray flare loop (Masuda et al., 1994) and impulsive hard X-ray double sources were non-thermal nature (Sakao et al., 1992). A question which has been raised is that the hard X-ray double sources would not be a position coincident with the footpoints of the soft X-ray loop and would be located at a position offset (Tsuneta, 1995). We see from the observations discussed above, the hard X-ray double sources, i.e. impulsive subsources, locate at the half legs of loop A', or the north leg of loop A and the south leg of loop B. Moreover, the soft X-ray loop (coronal postflare loop) occurs because the heated materials evaporate from the lower layers along the reconstructed loop A' (or a series of loops), so it has feet of $F_{A'}$(s). Therefore, the model (Fig. 4b) allows the electrons to travel along the soft

X-ray loops, and so the hard X-ray feet and soft X-ray feet are coincident.

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