THE ASTROPHYSICAL JOURNAL, 451:L83–L85, 1995 October 1

HOT-PLASMA EJECTIONS ASSOCIATED WITH COMPACT-LOOP SOLAR FLARES

K. SHIBATA,[1] S. MASUDA,[2] M. SHIMOJO,[3] H. HARA,[1] T. YOKOYAMA,[1] S. TSUNETA,[4] T. KOSUGI,[1] AND Y. OGAWARA[5]

Received 1995 May 25; accepted 1995 July 19

ABSTRACT

Masuda et al. found a hard X-ray source well above a soft X-ray loop in *impulsive compact-loop flares* near the limb. This indicates that main energy release is going on above the soft X-ray loop, and suggests magnetic reconnection occurring above the loop, similar to the classical model for *two ribbon flares*. If the reconnection hypothesis is correct, a hot plasma (or plasmoid) ejection is expected to be associated with these flares. Using the images taken by the soft X-ray telescope aboard *Yohkoh*, we searched for such plasma ejections in eight impulsive compact-loop flares near the limb, which are selected in an unbiased manner and include also the Masuda flare, 1992 January 13 flare. We found that *all these flares were associated with X-ray plasma ejections high above the soft X-ray loop* and the velocity of ejections is within the range of 50–400 km s^{-1}. This result gives further support for magnetic reconnection hypothesis of these impulsive compact-loop flares.

Subject headings: gamma rays: observations — MHD — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

One of the biggest discoveries by the soft X-ray telescope (SXT) (Tsuneta et al. 1991) aboard *Yohkoh* (Ogawara et al. 1991) is that of cusp-shaped loop structures in *long duration event* (LDE) *flares* (Tsuneta et al. 1992a) and *large-scale arcade loops associated with filament eruption* or *coronal mass ejections* (CME) (Tsuneta et al. 1992b; Hanaoka et al. 1994; McAllister et al. 1995; Hudson, Haisch, & Strong 1995). The observed loop configurations of the LDE flares and arcade loops are quite similar to the magnetic field configuration suggested by the classical *two-ribbon-flare model* (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976). This model, which is hereafter called the CSHKP model, predicts that magnetic fields are first opened up by global MHD instability associated with filament eruption to form vertical current sheet, and then magnetic field lines in the current sheet successively reconnect to form apparently growing flare loops. Hence this class of magnetic reconnection model (see, e.g., Forbes 1990 for a modern version; see also Moore & Roumeliotis 1992) is now being considered to be established, at least, phenomenologically for the LDE flares and similar large-scale arcade loops associated with filament eruption and CMEs.

There are, however, many *impulsive flares* which are not similar to the LDE flares. Impulsive flares are bright in hard X-rays and show the impulsive phase whose duration is short, whereas LDE flares are usually weak in hard X-rays and do not necessarily show the impulsive phase. The apparent shape of the impulsive flares in SXT images is a *compact-loop* or a *simple loop*, as already found by *Skylab*. This led some theoreticians to consider the loop flare models which assume energy release occurring inside the loop (Alfvén & Carlqvist 1967; Spicer 1977; Uchida & Shibata 1988). Apparent lack of cusp-shaped structure of impulsive flares in SXT images has been thought to be negative evidence against reconnection models such as the CSHKP model.

Recently, using the hard X-ray telescope (HXT) (Kosugi et al. 1991) aboard *Yohkoh*, Masuda et al. (1994) discovered that *in some of impulsive compact-loop flares occurring near the solar limb, a loop top hard X-ray* (HXR) *source appeared well above a soft X-ray* (SXR) *bright loop during the impulsive phase*. This indicates that the impulsive energy release did not occur within the soft X-ray loop but above the loop. This is a quite exciting discovery because bright soft X-ray loops were often considered to be evidence of "loop flares" in which energy release occurs within the loop, as discussed above. One possible physical mechanism to produce such loop top hard X-ray source is *magnetic reconnection* occurring above the loop; i.e., a high-speed jet is created through the reconnection and collides with the loop top, producing fast-mode MHD shock, superhot plasma, and/or high-energy electrons emitting hard X-rays. In this sense, the discovery of the loop-top HXR source may open a possibility to unify two distinct classes of flares, two-ribbon flares (or LDE flare) and compact-loop flares (or impulsive flare), by the single mechanism of magnetic reconnection (Shibata 1995).

If the reconnection hypothesis similar to the CSHKP model for two-ribbon flares or eruptive flares is correct in our impulsive compact loop flares, a plasma (or plasmoid) ejection is expected to occur in association with these impulsive flares (Fig. 1).[6] It should be noted here that in the case of the typical Masuda flare, the 1992 January 13 flare, the ground-based observations could not find any erupting feature in Hα (Wang et al. 1995). Hirayama (1991) claimed that even if there is no cool ($\sim 10^4$ K) mass ejection such as prominence eruption, hot ($>10^6$ K) plasma ejection can play a role similar to prominence eruption and induce reconnection and flares. Hence if the compact-loop flares are generated by the reconnection process similar to that in the two-ribbon flares (Fig. 1), we would expect hot-plasma ejections high above the reconnected loops seen as the soft X-ray (SXR) loops. The purpose of this Letter is to report on a result of the survey of such hot plasma (or plasmoid) ejections in impulsive compact-loop flares using *Yohkoh*/SXT data.

---

[1] National Astronomical Observatory, Mitaka, Tokyo 181, Japan; shibata@spot. mtk.nao.ac.jp.

[2] STE Laboratory, Nagoya University, Toyokawa, Aichi 442, Japan.

[3] Department of Physics, Tokai University, Kanagawa 259-12, Japan.

[4] Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181, Japan.

[5] Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229, Japan.

[6] Note that even if no plasmoid were present, this would not necessarily mean that reconnection is not occurring. In fact, there are other types of reconnection models (without plasmoid ejection) for flares (e.g., Priest 1982). However, in this Letter, we will demonstrate that even impulsive compact loop flares show evidence of plasmoid ejection, so that these flares may be physically similar to two-ribbon flares or eruptive flares.

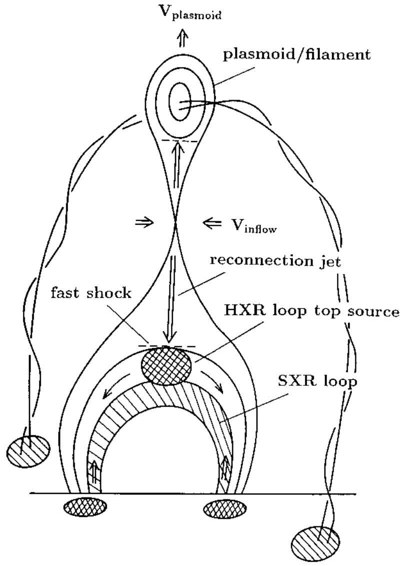

FIG. 1.—A reconnection—plasmoid ejection model for compact loop flares. Note that plasmas cofined by a closed field (in two-dimensions) or by a helically twisted flux tube (in three-dimension) are called *plasmoids*, as often used in magnetospheric community. In the classical picture of the two ribbon flares, the cool (~10^4 K) plasmas associated with the twisted flux tube is called *filament* or *prominence*. Hot (>10^6 K) plasma ejections are expected to be associated with the twisted tube or expanding loop high above the reconnected (SXR) loop. The cross-hatched region at the footpoints of the SXR loop shows the bright HXR/SXR double sources. The hatched region at the footpoints of the expanding (helical) loop penetrating the plasmoid shows predicted HXR/SXR distant sources.

2. THE 1992 JANUARY 13 FLARE

Using soft X-ray (0.25–2 keV) images taken with the soft X-ray telescope (SXT) aboard *Yohkoh*, we searched for hot-plasma ejections in the 1992 January 13 flare, typical example of impulsive compact-loop flares showing the hard X-ray (HXR) source high above the SXR loop (Masuda 1994; Masuda et al. 1994, 1995). Figure 2 (Plate L11) shows soft X-ray images of this flare. A compact loop seen in the short-exposure images is the same as the SXR loop discussed by Masuda et al. (1994), above which a loop-top HXR source was seen during the impulsive phase at 17:27–17:29 UT (see Fig. 1 of Masuda et al. 1994). A careful examination of the long-exposure images revealed at least two very faint erupting features high (4×10^4–8×10^4 km) above the SXR loop. They are indicated by the arrows A and B in Figure 2; the ejection A seems to be looplike, and the ejection B looks more like a jet. The velocity of these ejections is ~100–150 km s^{-1}. The onset of both ejections are nearly simultaneous with the impulsive phase, shown by the HXR light curve (33–53 keV) in Figure 3. Note that the ejections cannot be seen in the short-exposure images because their SXR intensity is comparable to or less than the noise level of the short-exposure images. It is also seen that a small SXR bright point (C in Fig. 2) appeared 2×10^4 km south of the SXR bright loop. This may correspond to one of the footpoints of the large-scale erupting feature.

To see the evolution of the faint structures in more detail, we show in Figure 4 (Plate L12) the time-lapse difference picture of SXT images shown in Figure 2. We can see an approximately loop-shaped region propagating outward. This corresponds to the ejection A in Figure 2. The direction of propagation is not just to the west but slightly inclined to northwest. Interestingly, this seems to be consistent with the direction of the loop-top HXR source.

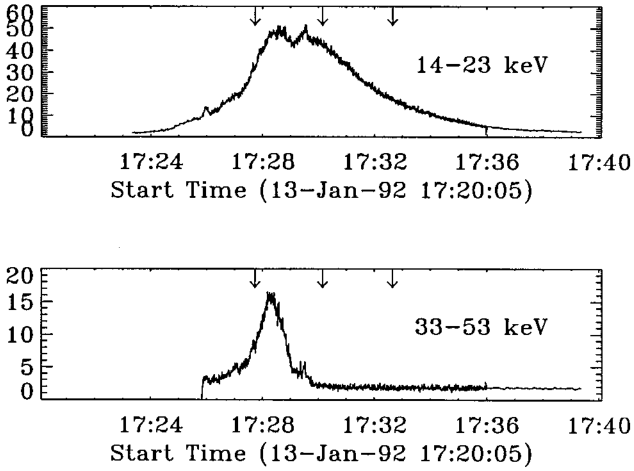

FIG. 3.—The HXR (33–53 keV) light curves of the 1992 January 13 flare. The arrows indicate the time of SXT images (long-exposure images) shown Fig. 2.

3. SURVEY OF HOT PLASMA EJECTIONS IN IMPULSIVE COMPACT-LOOP FLARES NEAR THE LIMB

Is such hot-plasma ejection common in compact-loop flares? To check this, we searched for hot-plasma ejections in eight compact-loop flares listed in Table 1. These flares are selected by Masuda (1994) from the events that were observed with the hard X-ray telescope (HXT) (Kosugi et al. 1991) during the period between 1991 October and 1993 September. Here the following two selection criteria are applied: (1) The peak count rate in the HXT M2 band (33–53 keV) exceeds 10 counts s^{-1} per subcollimator. (2) The heliocentric longitude exceeds 80°. Limb events were selected to examine the vertical structure of impulsive flares. Note that these flares represent an unbiased set. Masuda (1994) found that three events (1992 January 13, 1992 October 4, and 1993 February 17; see Table 1) show the loop-top HXR (23–53 keV) source well above (5″–10″) the SXR loop; three (1991 December 2, 1992 February 6, and 1992 February 17) are marginally above or on the top of the loop (<5″), and the remaining two (1992 April 1, 1992 November 5) show no clear impulsive HXR loop-top source.

We surveyed SXR ejection features in these flares and found that *all these flares were accompanied by faint X-ray plasma ejections*. It was found that: (1) The range of velocity of the ejections is 50–400 km s^{-1}. Interestingly, flares with HXR

TABLE 1

SUMMARY OF EIGHT COMPACT-LOOP LIMB FLARES

Date	Peak Time (UT)	GOES Class	Height of HXR Source above SXR Loop	Ejection	Velocity of Ejection (km s^{-1})
1991 Dec 2	0455	M4	<5″	Yes	50–150
1992 Jan 13.....	1729	M2	5″–10″	Yes	100–150
1992 Feb 6......	0325	M8	At apex	Yes	30–70
1992 Feb 17	1542	M2	<5″	Yes	50–150
1992 Apr 1......	1014	M2	No loop top	Yes	130–170
1992 Oct 4......	2221	M2	5″–10″	Yes	300–370
1992 Nov 5	0620	M2	No loop top	Yes	100–150
1993 Feb 17	1036	M6	5″–10″	Yes	100–150

sources well above (5″–10″) the loop top show systematically higher ejection velocities (Table 1). (2) The size of the ejections is typically $(4–10) \times 10^4$ km. (3) The SXR intensity of the ejections is 10^{-4}–10^{-2} of the peak SXR intensity in the bright SXR loop. The low SXR contrast of such ejections against a bright active region background probably explains why these events have not always been seen in equivalent flares on the disk. Note that this is the first systematic survey of X-ray ejecta in association with flares. In Hα, Smith & Ramsey (1964) reported that 23 out of 71 flares, which are larger than importance 2, showed clear association with filament eruptions (or disappearances). The percentage of association of flares with X-ray ejecta is higher than that with optical filament eruptions (or disappearances), although the number of samples in our case is smaller than that of optical flares.

It is also interesting to note that the height of the SXR loops and the distance between the two footpoints in these flares increase with time, as expected from reconnection hypothesis. We further noted that the shape of the SXR loops in decay phase (~30 minutes later) looks more similar to a cusp than a circular shape.

4. DISCUSSION

These observations give further support for the magnetic reconnection hypothesis (Fig. 1). In our view, the erupting feature corresponds to the plasmoid (or a large-scale helically twisted loop), and the magnetic reconnection is triggered by the eruption of it. The magnetic reconnection theory (e.g., Priest 1982) predicts two oppositely directed high-speed jets at Alfvén speed [$V_A \simeq 3000(B/100 \text{ G})(n_e/10^{10} \text{ cm}^{-3})^{-1/2}$ km s^{-1}, where B is the magnetic flux density and n_e is the electron density] from the reconnecting point. A jetlike feature (ejection B) found in 1992 January 13 flare (Fig. 2) may correspond to the upward jet, although the velocity of the observed "jet" (~100–150 km s^{-1}) is much smaller than the theoretically expected velocity ($V_{\text{jet}} \sim V_A \sim 3000$ km s^{-1}). (The same puzzle applies also to the observed velocity of "plasmoid".) The downward jet collides with the top of the SXR loop, producing superhot (a few 100 MK) plasmas and/or high-energy electrons at the loop top, as observed in the HXR images. The superhot and/or high-energy electrons stream down the loop, resulting in two HXR/SXR bright sources at the footpoints. The HXR loop-top source is not bright in SXR because the evaporation flow has not yet reached the point where the jet collides with the loop top and hence the electron density (and so the emission measure) is low. We would also expect similar physical process above the reconnection point (see Fig. 1); an upward-directed jet collides with the erupting loop, producing superhot region at the colliding point and the HXR/SXR bright points at the footpoints of the erupting loop. Indeed, we find an SXR bright point during the impulsive phase somewhat far from the SXR loop. This bright point may correspond to a footpoint of the erupting loop. It would be interesting to search for such distant impulsive bright points also in HXR images.

We found SXR erupting features in all eight limb impulsive flares, whereas the number of flares with HXR sources well above (5″–10″) the loop top is only three. Why is that? Whether the HXR loop top source can be seen well above the SXR loop top may depend on the speed of the reconnection; i.e., if the reconnection is fast, the newly reconnected loop can be quickly transferred above the already reconnected loop before the evaporation flow reaches the top of the newly reconnected loop. On the other hand, if the reconnection is slow, the evaporation flow fills the newly reconnected loop, making bright SXR loop soon, and the colliding point of the jet with the loop is close to (or on) the top of the SXR loop. Hence the height of the HXR source above the SXR loop depends on the speed of reconnection. We can measure the speed of reconnection from the apparent rise velocity of the SXR loop (postflare loop). According to our preliminary measurement, we indeed found that the apparent rise velocity of the SXR loop in three limb flares with HXR sources well above (5″–10″) the loop top in impulsive/gradual phase is 12–17 km s^{-1}, much larger than that (0–10 km s^{-1}) in other impulsive flares, consistent with the prediction from the reconnection hypothesis.

Finally, we suggest that the hot plasma ejections found in this paper might be miniature versions of the much larger scale CME events. In fact, our hot plasma ejections are sometimes seen as expanding loops (see Fig. 4) topologically similar to CMEs (Hundhausen 1993). If these events are similar, the physics of the impulsive compact-loop flares would be essentially the same as that of CMEs, and hence we can say, against Gosling (1993) but in agreement with Hudson et al. (1995), that impulsive compact-loop flares (and LDE flares as well) would be important for understanding CMEs and solar-terrestrial relations.

The authors would like to thank R. C. Canfield, H. S. Hudson, N. Nitta, A. McAllister, and K. T. Strong for useful comments, and T. Hirayama for stimulating discussions. The *Yohkoh* satellite is a Japanese national project, launched and operated by ISAS, and involving many domestic institutions, with multilateral international collaboration with the US and UK.

REFERENCES

Alfvén, H., & Carlqvist, P. 1967, Sol. Phys., 1, 220

Carmichael, H. 1964, in Proc. AAS-NASA Symp. on the Physics of Solar Flares, ed. W. N. Hess (Washington, NASA), NASA-SP 50, 451

Forbes, T. G. 1990, J. Geophys. Res., 95, 11919

Gosling, J. T. 1993, J. Geophys. Res., 98, 18937

Hanaoka, Y., et al. 1994, PASJ, 46, 205

Hirayama, T. 1974, Sol. Phys., 34, 323

———. 1991, in Lecture Note in Physics, No. 387, Flare Physics in Solar Activity Maximum 22, ed. Y. Uchida et al. (New York: Springer), 197.

Hudson, H. S., Haisch, B., & Strong, K. T. 1995, J. Geophys. Res., 100, 3473

Hundhausen, A. J. 1993, J. Geophys. Res., 98, 13177

Kopp, R. A., & Pneuman, G. W. 1976, Sol. Phys., 50, 85

Kosugi, T., et al. 1991, Sol. Phys., 136, 17

Masuda, S. 1994, Ph.D. thesis, Univ. of Tokyo

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

Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., & Ogawara, Y. 1994, Nature, 371, 495

McAllister, A., Dryer, M., McIntosh, P., Singer, H., & Weiss, L. 1995, ESA SP-373, 315

Moore, R. L., & Roumeliotis, G. 1992, in Lecture Note in Physics, No. 399, Eruptive Solar Flares, ed. Z. Svestka, B. V. Jackson, & M. E. Machado (New York: Springer), 69

Ogawara, Y., et al. 1991, Sol. Phys., 136, 1

Priest, E. R. 1982, Solar Magnetohydrodynamics (Dordrecht: Reidel), 344

Shibata, K. 1995, Adv. Space Res., 17, (4/5)9

Smith, S. F., & Ramsey, H. E. 1964, Z. Astrophys., 60, 1

Spicer, D. 1977, Sol. Phys., 53,305

Sturrock, P. A. 1966, Nature, 211, 695

Tsuneta, S., et al. 1991, Sol. Phys., 136, 37

Tsuneta, S., Hara, H., Shimizu, T., Acton, L. W., Strong, K. T., Hudson, H. S., & Ogawara, Y. 1992a, PASJ, 44, L63

Tsuneta, S., Takahashi, T., Acton, L., Bruner, M. E., Harvey, K. L., & Ogawara, Y. 1992b, PASJ, 44, L211

Uchida, Y., & Shibata, K. 1988, Sol. Phys., 116, 291

Wang, H., Gary, D. E., Zirin, H., Kosugi, T., Schwartz, R. A., & Linford, G. 1994, ApJL, submitted

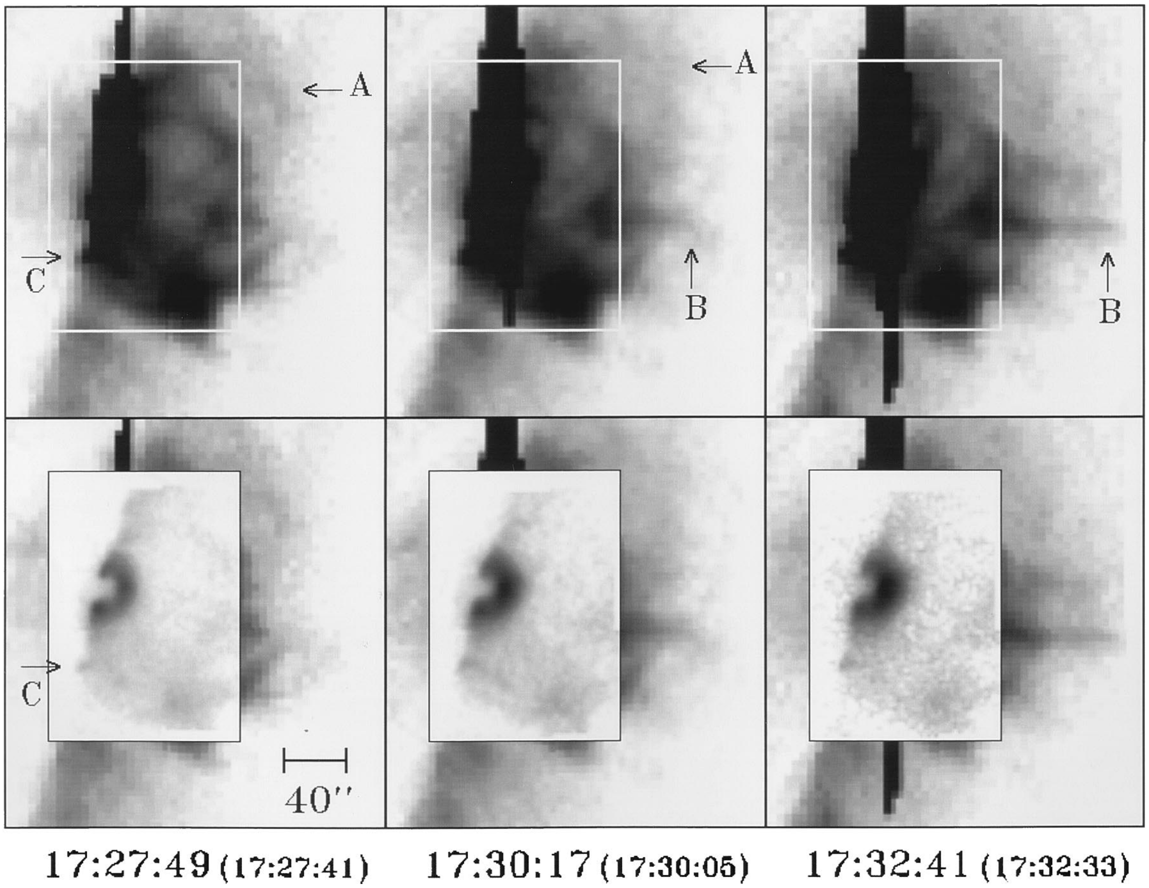

FIG. 2.—Soft X-ray (negative) images of the 1992 January 13 flare. The upper panels show long-exposure images at 5″ spatial resolution, and the bottom panels show short-exposure images at 2″.5 resolution (at nearly the same time) composited on the long-exposure images. The time in the brackets denotes the exact time when the short-exposure images are taken. 40″ correspond to ~29,000 km.

SHIBATA et al. (see 451, L84)

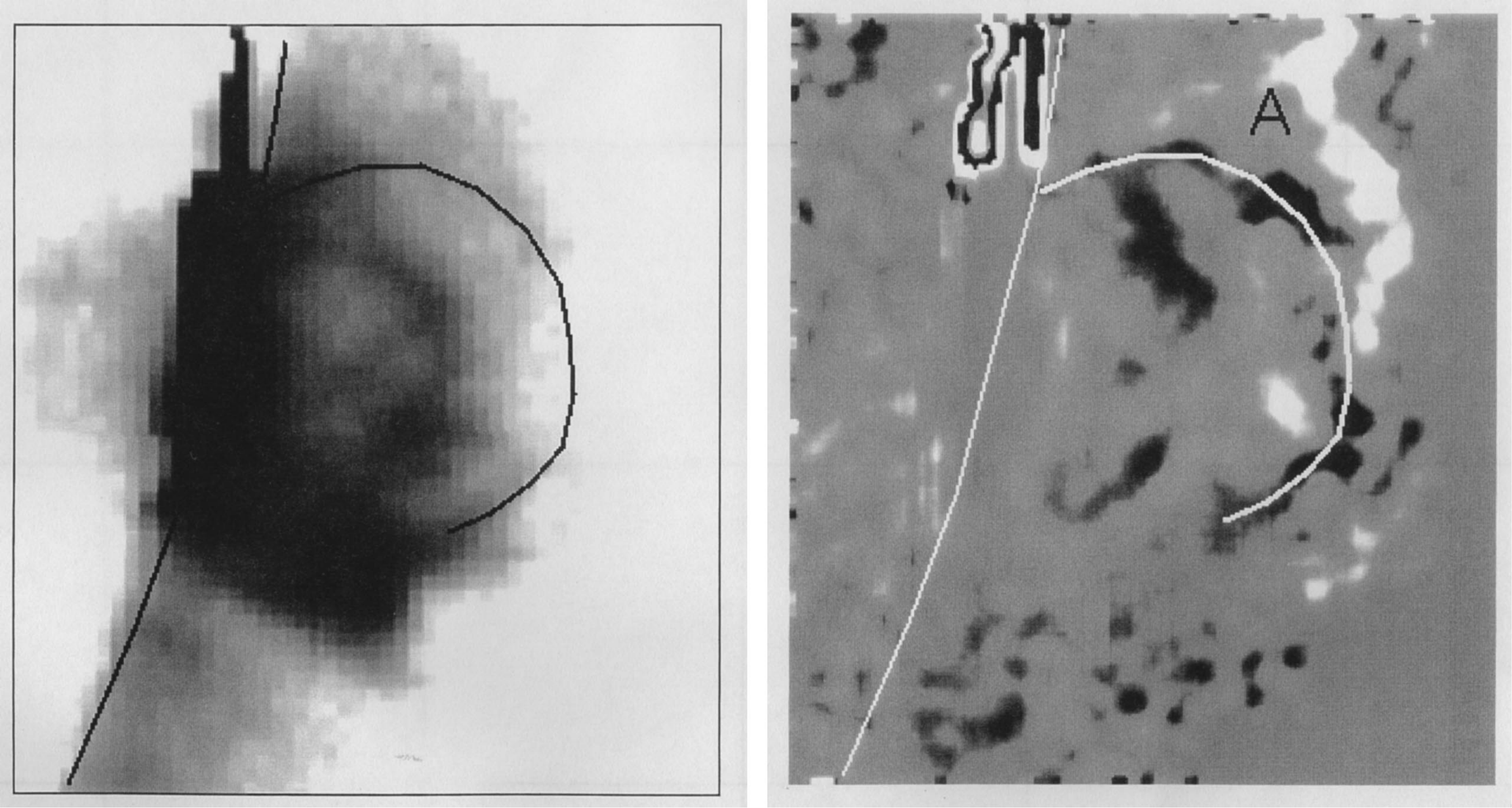

FIG. 4*a*

FIG. 4*b*

FIG. 4.—(*a*) The SXR (negative) image of the 1992 January 13 flare observed by *Yohkoh*/SXT in half-resolution mode at 17:27:49. (*b*) The time-lapse difference picture of the same flare between 17:29:03 and 17:27:49 UT [in (*a*)]. Black corresponds to a decrease in intensity between frames, while white corresponds to an increase. Hence, if a loop is moving outward (higher) it will appear white on the leading edge and dark on the trailing edge. The curve A overlaid on the loop-shaped dark region is thus the trailing edge of an expanding loop, which is the same as the erupting feature (A) in Fig. 2, and the outer white region is the leading edge of the expanding loop. The oblique line shows the solar limb.

SHIBATA et al. (see 451, L84)