

X-RAY JETS AND X-RAY PLASMOIDS

K. Shibata

National Astronomical Observatory of Japan, Mitaka, Tokyo 181, Japan

ABSTRACT

The soft X-ray telescope (SXT) aboard *Yohkoh* has discovered *coronal X-ray jets* associated with small flares (microflares – subflares). It has also discovered *X-ray plasmoids* not only from large LDE flares but also from compact impulsive flares. X-ray jets are well collimated hot plasma ejections, while X-ray plasmoids are blob-like hot plasma ejections (sometimes seen as loop-like ejections in three dimensional view). Nevertheless, the velocity of both hot plasma ejections is similar, of order of a few 100 km/s on average. The observational characteristics of these newly discovered hot plasma ejections are reviewed, and a unified model based on magnetic reconnection mechanism is presented to account for these apparently different mass ejections.

Key words: jets; plasmoids; flares; reconnection; MHD.

1. INTRODUCTION

X-ray jets have been discovered by the soft X-ray telescope aboard *Yohkoh* as transitory X-ray enhancements with apparent collimated motion (Shibata et al. 1992, Strong et al. 1992, Shimojo et al. 1996, Shibata, Shimojo, and Yokoyama 1996, Hanaoka 1996). They are associated with microflares or subflares, which occurred in X-ray bright points (XBPs), emerging flux regions, or active regions (see Fig. 1 for a typical example).

The X-ray jets are important not only because they can be a prototype of astrophysical jets (e.g., Burgarella et al. 1993), but also because they may have a clue to solve coronal heating and acceleration of high speed solar wind since they are associated with small flares (microflares – subflares). Some of small scale structures observed in the solar wind may be related to these jets (Feldman et al. 1993, Hammond et al. 1995).

On the other hand, *Yohkoh* soft X-ray telescope has discovered another new ejection feature, *X-ray plasmoids* (or *X-ray plasma ejections*) (Shibata et al. 1995, Nitta 1996, Tsuneta 1997, Ohyama and Shibata 1997, 1998). X-ray plasmoids are blob-like hot plasma ejections, and sometimes seen as an erupting X-ray loop. They are ejected not only from LDE flares but also

from compact impulsive flares such as Masuda-type flares (Shibata et al. 1995) so that they can be evidence of magnetic reconnection occurring above soft X-ray loop, supporting the conjecture by Masuda et al. (1994). Although X-ray plasmoids are morphologically very different from X-ray jets, there are many common properties in both hot plasma ejections.

In this article, I will review observations of these newly discovered hot plasma ejections in the corona with emphasis upon the role of magnetic reconnection, and will present a unified model explaining both X-ray jets and X-ray plasmoids with a single physical mechanism, magnetic reconnection.

2. X-RAY JETS

2.1. TYPICAL EXAMPLE

Figure 1 shows a typical example of X-ray jets reported by Shibata et al. (1992). It was observed on 1991 November 12 between 0812 and 1315 UT and was associated with a small subflare. The length of the jet is about 2×10^5 km, and its apparent velocity is more than 100 km/s. It is also found that the northern side boundary of this jet moves slightly north between 1128 UT and 1136 UT at a translational velocity of 20 – 30 km/s. This kind of lateral motion is often referred to as “whip-like motion”.

The average temperature of the jet is $\sim 3 \times 10^6$ K, and the electron density at the midpoint of the jet is 4×10^8 cm⁻³. The total mass and kinetic energy of the jet are 2×10^{13} g and 10^{27} erg, respectively. The latter is an order of magnitude smaller than the total thermal energy ($\sim 3 \times 10^{28}$ erg) released in a small flare that occurred at the footpoint of the jet during the ejection of the jet.

It is interesting to note that a void appeared at the footpoint of the jet after its ejection, suggesting the change of field connectivity through magnetic reconnection (Fig. 2). In fact, Kitt Peak magnetogram show that the void correspond to small positive polarity imbedded in the background negative polarity and thus can be the center of “anemone”. (Note that the sunspot umbra is usually seen dark in soft X-ray images.) Another interesting feature is that the width of the jet is nearly constant. This is probably related to the existence of opposite polarity at the

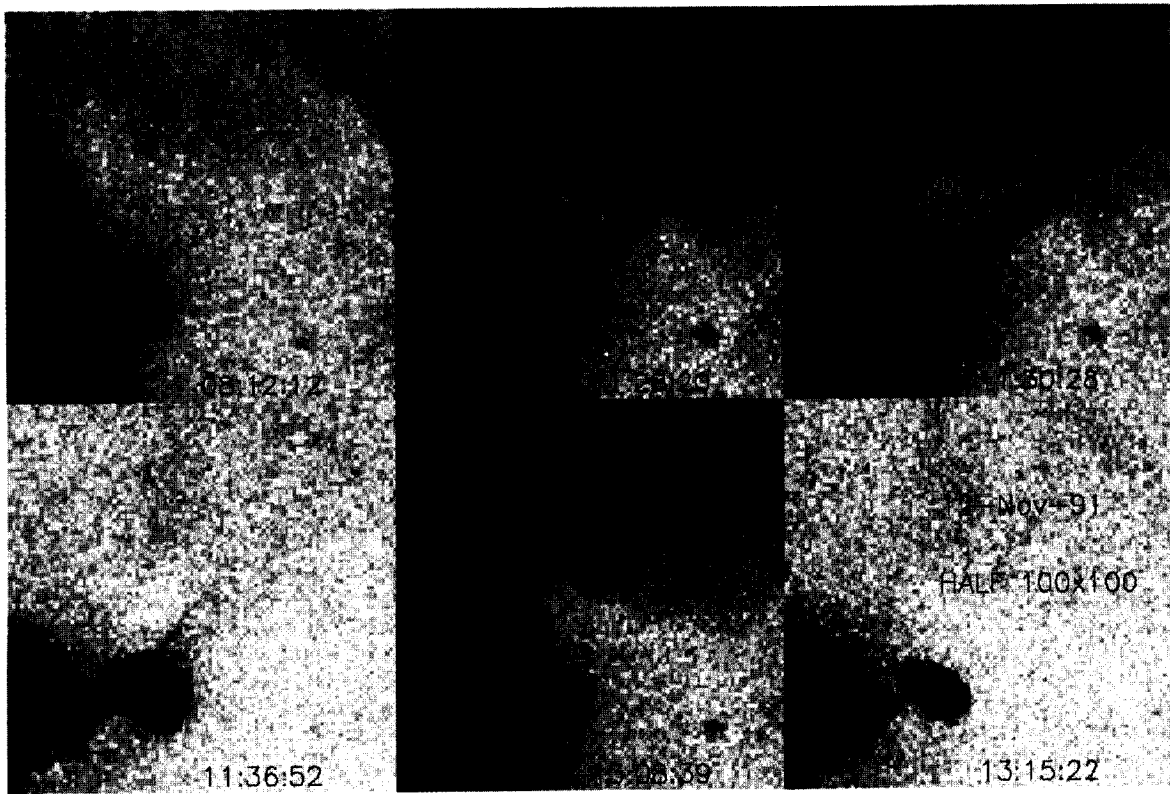


Figure 1. Typical example of X-ray jet observed by SXT on 1991 November 12, in active region NOAA 6918. The size of each image is $500'' \times 500''$. Note that these are negative images.

footpoint of the jet (see hypothetical field configuration in Fig. 2).

2.2. BASIC PROPERTIES

Shimojo et al. (1996) performed comprehensive analysis of 100 jets observed during the period from November 1991 to June 1992, and revealed the following statistical properties of X-ray jets: ¹ Most jets are associated with *small flares (microflares - subflares)* at their footpoints. The length of the jets is a few $10^4 - 4 \times 10^5$ km (average $\simeq 1.5 \times 10^5$ km), the apparent velocity is $10 - 1000$ km/s (average $\simeq 200$ km/s), and the lifetime ranges from a few minutes to more than a few hours. The number of jets decreases as the length, the velocity, or the lifetime increases (Fig. 3). The histograms (Fig. 3) are similar to those of flares and EUV explosive events (Cook and Brueckner 1991). Many jets ($\sim 68\%$) appear in or near to active regions (ARs). Among the jets ejected from bright-point like features in ARs, most ($\sim 86\%$) are observed to the *west* of the active region. The X-ray intensity distribution along an X-ray jet often shows an *exponential* decrease with distance from the footpoint (see Shimojo et al. 1998b).

¹Here, X-ray jets are defined as collimated X-ray mass ejections whose aspect ratio (length/width) is larger than 3.

2.3. PHYSICAL CONDITIONS

Shimojo et al. (1996, 1998b) analyzed temperature and emission measure of some small jets. They found that the average temperature of jets is $\sim 3 - 7$ MK, which is comparable to that of microflares at the footpoints of the jets, and the average electron density is $0.7 - 4 \times 10^9$ cm^{-3} . The latter is somewhat larger than those derived for larger jets (Shibata et al. 1992, 1994b). The total thermal energy is $10^{26} - 10^{27}$ erg, which is about 1/10 of the total (released) thermal energy of the footpoint flare. The kinetic energy of jets is estimated to be $10^{25} - 10^{26}$ erg (see Table I).

2.4. MORPHOLOGICAL PROPERTIES: EVIDENCE OF MAGNETIC RECONNECTION

There are a lot of evidences of magnetic reconnection in jets (Shibata et al. 1994a,b, 1996):

(a) *Two Types of Interaction between Emerging Flux and Coronal Field*: Shibata et al. (1994a) found two types of the interaction (reconnection) between emerging flux and coronal field; the *anemone-jet* type and the *two-sided-loops/jets* type. The former occurs when emerging flux appears in coronal holes. In this case, a jet is ejected in a vertical direction. On the other hand, the latter occurs when emerging flux appears

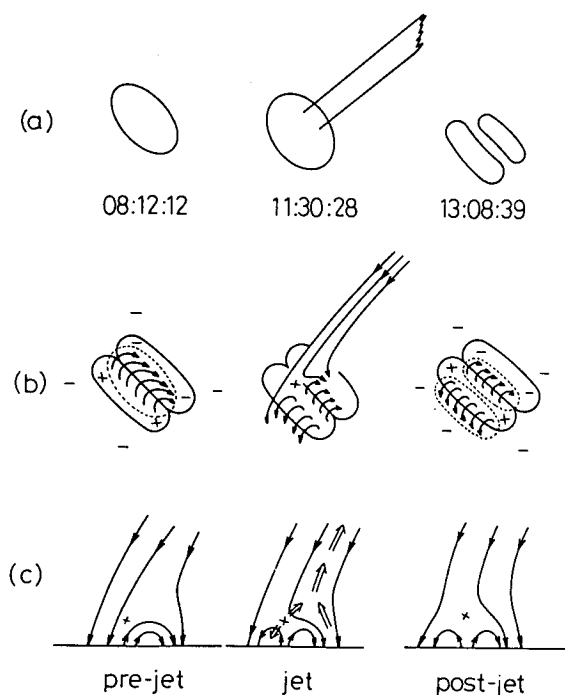


Figure 2. Schematic picture of the possible physical situation of the 1991 November 12 jet. (a) Cartoons of the SXT image of the active regions and jets for pre-jet, jet, and post-jet stages. (b) Magnetogram data and the bird's-eye view of the inferred magnetic field line configuration. (c) Side view of the magnetic reconnection occurring between the emergent flux and the pre-existing coronal field.

in quiet regions, and two loop brightenings (or jets) occur in the horizontal direction at both sides of the emerging flux.

(b) *Converging Shape of Jets:* Shimojo et al. (1996) found that the width of the jets often decreases with height (i.e., *converging shape*), which is similar to the shape of $H\alpha$ surges observed in emerging flux regions (Kurokawa and Kawai 1993) and EUV macrospicules (Karovska and Habbal 1994). This shape suggests that the cross-section of flux tube decreases with height, i.e., the field strength increases with height. Such situations arise if there is a neutral point near the footpoint of the jet as in the *anemone-jet* model in Fig. 4. This situation is expected also when the satellite spots appear in an opposite polarity region, and in fact such magnetic field properties have been confirmed by comparing NSO/Kitt Peak magnetogram with SXT images of many jets (Shimojo et al. 1996 and section 2.5).

(c) *A Gap Between Footpoint of Jet and Brightest Part of Footpoint Flare:* Though the footpoints of jets roughly correspond to small flares, close examination of the footpoints has revealed that often small flares (or loop brightenings) occur separately (by more than a few thousand km) from the exact footpoints of jets (Shimojo et al. 1996). This characteristic is also seen in tiny XBP jets. Such a gap is expected for magnetic reconnection mechanism, because the heated reconnected field lines are quickly ejected in opposite directions to form one bright loop and a separate jet in the other direction (Fig. 4).

(d) *Change of Topology of Footpoint Active Region:* When the ARs at the footpoints of jets can be re-

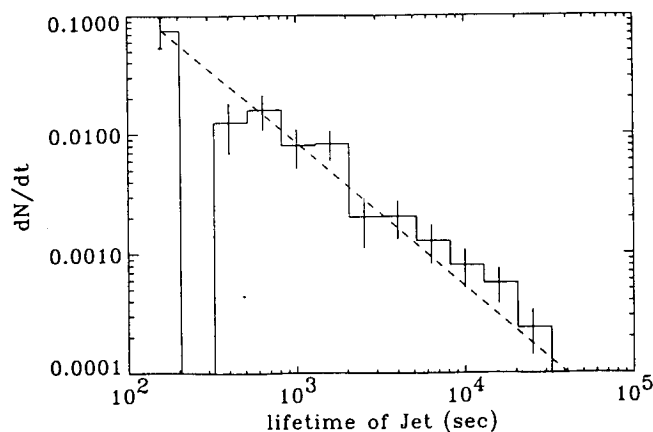
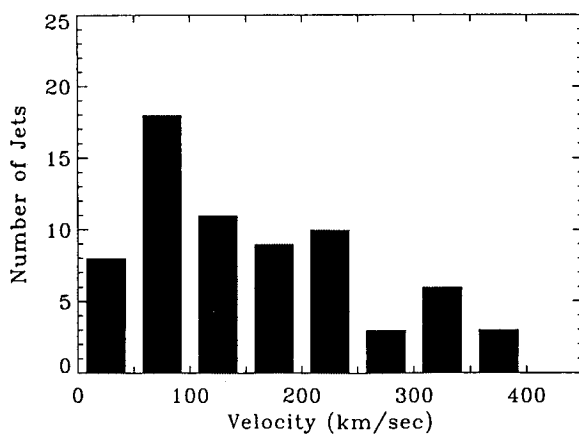
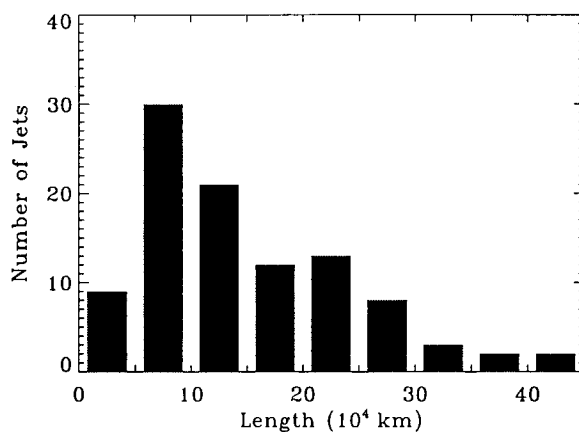


Figure 3. Histograms of velocity, length, and lifetime of X-ray jets (Shimojo et al. 1996).

solved well, their morphology changes substantially during the jets. For example, a loop system appeared during the 12 Nov. 1991 jet (Shibata et al. 1992 and section 2.1), while a loop system disappeared during the 11 Jan. 1992 jet (Shibata et al. 1994b).

(e) *Whip-like Motion of Jet:* In some cases, the jet moved perpendicularly to the jet axis at a few 10 km/s during the ejection of the jet, which has been referred to as *whip-like motion* of jet (section 2.1, Shibata et al. 1992, 1994b, Canfield et al. 1996). This might be an evidence of dynamical rearrangement of magnetic field configuration as a result of reconnection.

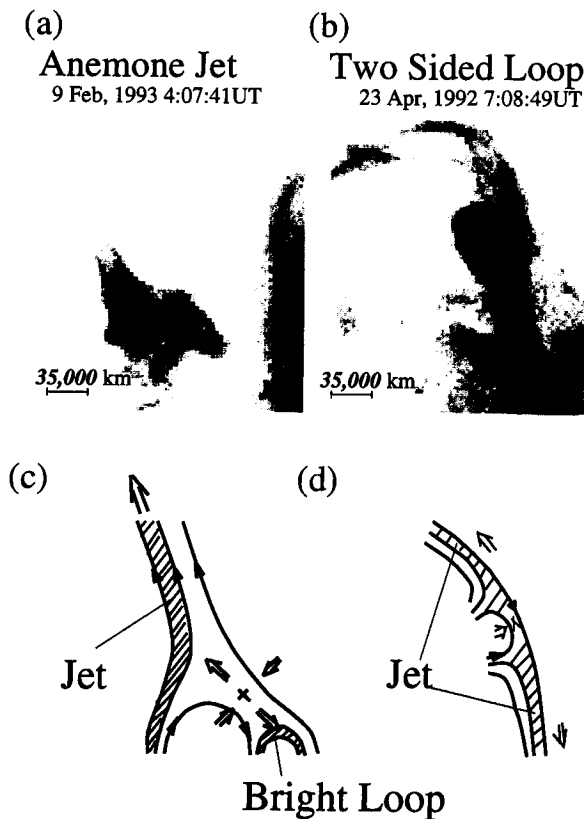


Figure 4. SXT images of two types of interaction of emerging flux with overlying coronal magnetic fields. (a) *Anemone-Jet* type observed on 9 Feb. 1993. (b) *Two-sided-loop* type observed on 23 Apr. 1992. Schematic illustration of (c) *Anemone-Jet* type and (d) *Two-sided-loop* type. (from Yokoyama and Shibata 1995a,b).

2.5. MAGNETIC FIELD PROPERTIES

Shimojo, Shibata, and Harvey (1998a) co-aligned SXT images with NSO/Kitt Peak magnetograms, and examined magnetic field properties of the footpoint of jets. They found that 8 % of studied jets occurred at a single pole, 12 % at a bipole, 24 % in a mixed polarity and 48 % in a satellite polarity. If the satellite polarity region is the same as the mixed polarity region, 72 % of jets occurred at the (general) mixed polarity region. This gives direct evidence of the presence of neutral points (or current sheets) near the footpoint of jets.

They also investigated the magnetic evolution of jet-producing area in some active regions, and found that X-ray jets favored regions of evolving magnetic flux (increasing or decreasing).

2.6. RELATION TO OTHER PHENOMENA

H α Surges: Often H α surges are associated with X-ray jets (e.g., Shibata et al. 1992, Canfield et al. 1996), though there are also negative cases (e.g., Schmieder et al. 1995). From observations of H α surges associated with X-ray jets, Canfield et al. (1996) found several new evidence of reconnection; *moving blue shift*

and *converging footpoints*. These surges spin around their axis, as modeled by Shibata and Uchida (1986, see Fig. 5).

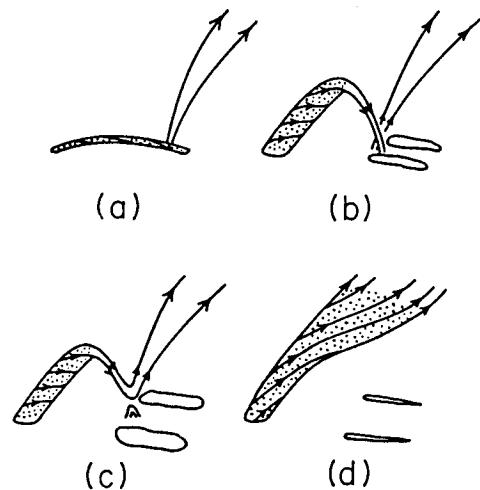


Figure 5. Schematic picture of formation of spinning magnetic twist jet as a result reconnection between twisted flux tube and untwisted flux tube (Shibata and Uchida 1986).

Type III bursts: Kundu et al. (1995) found that a Type III burst was associated with an X-ray jet (see also Auras et al. 1995, Raulin et al. 1996). This implies the existence of high energy electrons in these small flares and jets, and supports the view that the generation mechanism of X-ray jets and microflares may be physically similar to that for larger flares.

microflares: Shibata (1996b) studied the relation between microflares (transient brightenings; Shimizu et al. 1992) and jets in an emerging flux region NOAA 7176, and found more than 20 jets occurred in the 5 days after the birth of the region. All jets were associated with microflares, whereas the fraction of microflares associated with jets was about 60 percent. Since the probability of detection of jets is not 100 percent because of the limited time cadence of *Yohkoh* observations, this would suggest that more microflares may be associated with jets.

nanoflares: Koutchmy et al. (1997) have found even less energetic transient brightenings in polar regions, which they call *coronal flashes*. The absolute SXR intensity of flashes is about 10 DN/s at maximum, which is two orders of magnitude smaller than those of active region transient brightenings, and fluctuates on a time scale of a few - 5 min. The total (released) energy is probably comparable to 10^{24} erg, i.e., that of nanoflares. The polar coronal holes are found to be very active and full of these nanoflares, and even tiny X-ray jets often occur from these nanoflares (see Fig. 7).

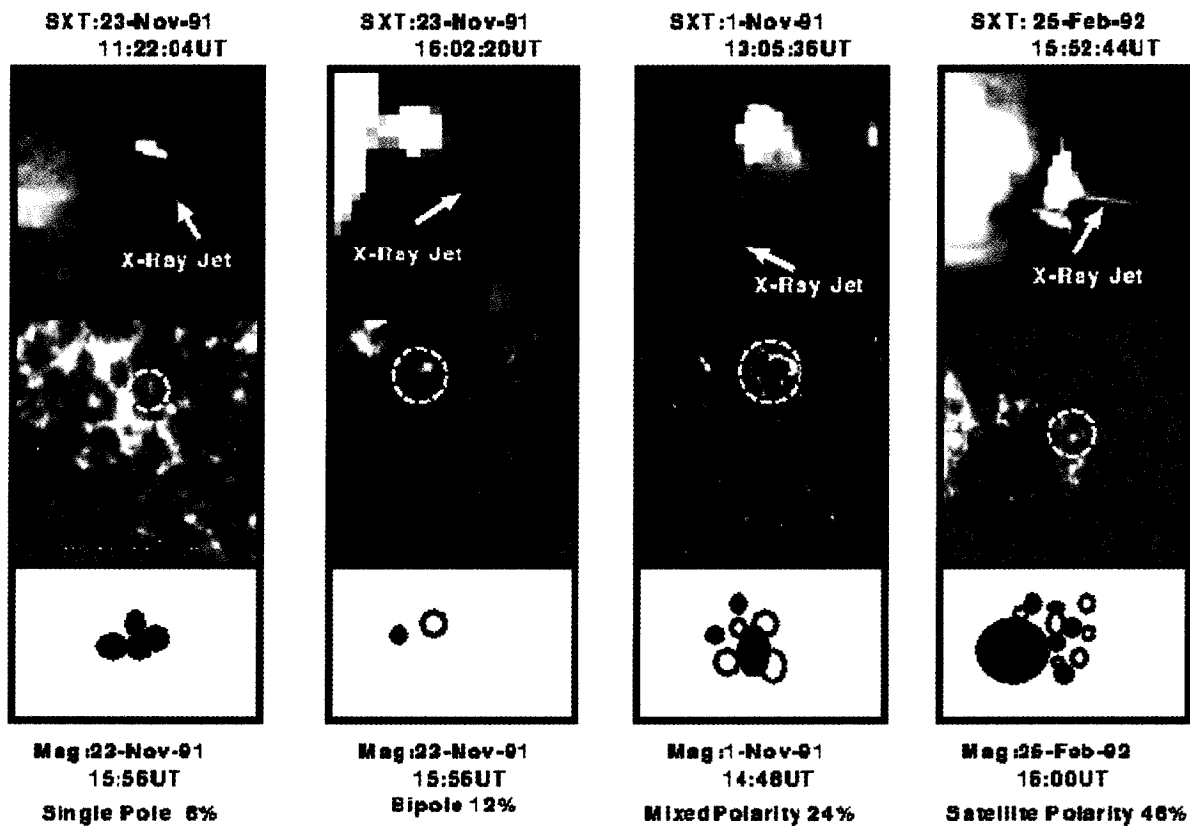


Figure 6. Examples of magnetic field properties of X-ray jets. First row shows X-ray jets images taken by Yohkoh SXT. The second row are the corresponding magnetograms with white circles indicating the footpoint of the jets. The third row shows schematic illustrations of magnetic field configuration types.

3. X-RAY PLASMOIDS

3.1. LDE FLARES

Although no systematic study has been done for plasmoid ejections from LDE (long duration event) flares until now, plasmoid ejections have been found in some LDE flares with the Yohkoh SXT (e.g., Hudson 1994, Hiei et al. 1996).² According to those studies, the velocity of hot plasma ejections was of the order of 50 – 300 km/s. Their shape was either *ovoid* (e.g., 21 February 1992 LDE flare [Fig. 8, Hudson 1994]), *concave-outward bright* (e.g., 24 January 1992 helmet streamer event [Hiei et al. 1996]), or *helical loop* (e.g., 28 August 1992 LDE flare). Interestingly, these shapes were similar to those of some coronal mass ejections (Webb and Cliver 1995). It is also interesting to note that the acceleration of the ejections was almost simultaneous with the flare rise phase (cf. Kahler et al. 1988).

²In this article, any non-collimated X-ray plasma ejections are called *X-ray plasmoids*.

Table I Physical Quantities of X-ray Jets and X-ray Plasmoids (Ohya et al. 1997)

	X-ray Jets	X-ray Plasmoids
Temperature (10^6 K)	4 – 6	5 – 16
Density (cm^{-3})	$\sim 10^9$	$10^9 - 10^{10}$
Mass (g)	$10^{11} - 10^{12}$	$10^{13} - 10^{14}$
Thermal Energy (erg)	$10^{26} - 10^{27}$	$10^{28} - 10^{29}$
Kinetic Energy (erg)	$10^{25} - 10^{26}$	$10^{27} - 10^{28}$
Flare Energy (erg)	$10^{27} - 10^{28}$	$10^{29} - 10^{30}$
Goes Class	B – C class	M class

3.2. IMPULSIVE FLARES

Masuda et al. (1994, 1995) discovered a hard X-ray source well above the soft X-ray loop in some impulsive flares observed near the limb, and suggested

Polar Jet : 11-Dec-96
Yohkoh/Soft X-Ray Telescope

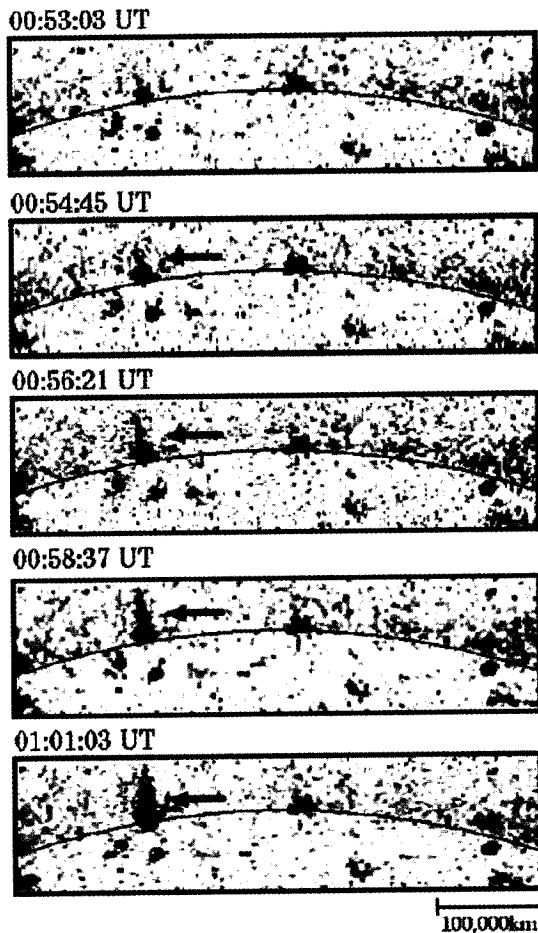


Figure 7. An X-ray jet ejected from a nanoflare in a polar coronal hole observed with Yohkoh SXT on 11 Dec 1996, 0053-0101 UT (courtesy of M. Shimojo).

that magnetic reconnection occurs above the soft X-ray loop. If the reconnection hypothesis similar to the CSHKP (Carmichael-Sturrock-Hirayama-Kopp-Pneuman) model is correct, the plasmoid ejection would be found high above the soft X-ray loop (Hirayama 1991) as illustrated in Figure 9. Shibata et al. (1995) searched for such plasmoid ejections in the Masuda flare on 13 Jan. 1992, and indeed discovered X-ray plasma ejections high ($\sim 10^5$ km) above the hard X-ray source.

Shibata et al. (1995) further surveyed such ejections in 8 impulsive limb flares which were selected in an unbiased manner by Masuda (1994) with the following two selection criteria: (1) The peak count rate in the HXT M2-band (33 – 53 keV) exceeds 10 cts/s/subcollimator. (2) The heliocentric longitude exceeds 80 degrees. It is remarkable that plasma ejections were found in all 8 impulsive limb flares. The ejections were seen as *loop*-like (e.g., 13 January 1992 = the Masuda flare, 4 October 1992), *blob*-like (e.g., 17 February 1992, 2 December 1991, 5 October 1992 [Ohyama and Shibata 1998, Fig. 10]), or *jet*-like (e.g., 13 January 1992). The range of velocity of the ejections was 50 – 400 km/s. Interestingly, flares with hard X-ray sources well above (5 – 10 arcsec) the loop top showed systematically higher ejection velocities. The size of the ejections was typically (4

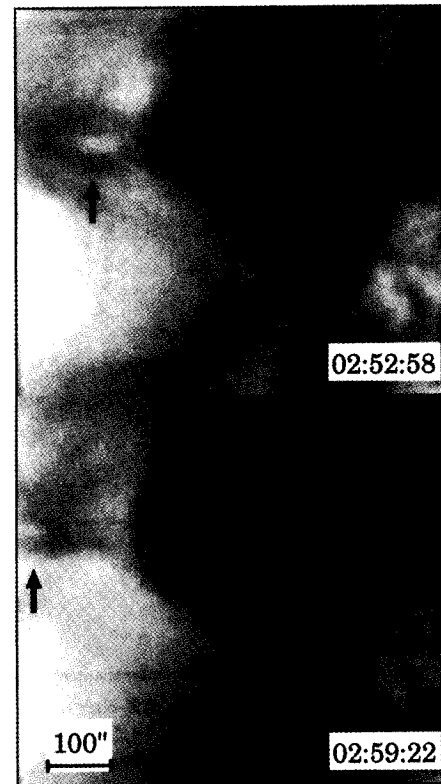


Figure 8. X-ray plasmoid ejection in LDE flare on 1992 February 21 (courtesy of M. Ohyama).

– 10) $\times 10^4$ km. The soft X-ray intensity of the ejections was 10^{-4} – 10^{-2} of the peak soft X-ray intensity in the bright soft X-ray loop. The strong acceleration of the ejections occurred nearly simultaneously with the hard X-ray impulsive peaks (Ohyama and Shibata 1998).

Ohyama and Shibata (1996, 1998) analyzed the temperature and emission measure distribution of the blob-like X-ray plasma (plasmoid) ejection in the 5 October 92 flare, and found the following. The temperature and electron density of the plasmoid were ~ 6 – 13 MK and ~ 8 – 15×10^9 cm $^{-3}$, respectively. The temperature of the plasmoid was lower than that of the region between the plasmoid and the flare loop (see also Tsuneta 1997), consistent with the reconnection model (e.g., Yokoyama and Shibata 1997, 1998). The thermal and kinetic energy of the plasmoid was an order of magnitude smaller than the thermal energy of the soft X-ray flare loop; i.e., $E_{kin} \leq 10^{28}$ erg $\ll E_{th}(flare) \sim 10^{30}$ erg in the case of the 5 October 1992 flare. This indicates that the kinetic energy of the plasmoid ejection cannot be a source of the flare energy. Instead, the plasmoid ejection could play a role to trigger the main energy release in impulsive phase, since in some events observed from the preflare phase it was found that the plasmoid ejection started (at 10 km/s) well before the impulsive phase (Ohyama and Shibata 1997; Fig. 11).

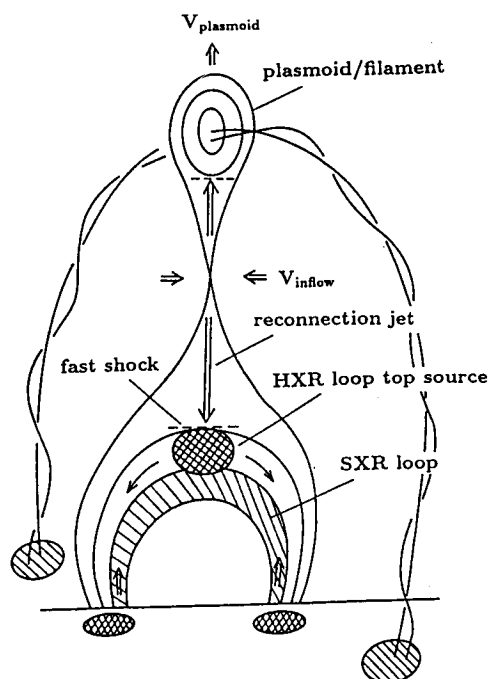


Figure 9. A unified model of flares: plasmoid-induced reconnection model (Shibata et al. 1995, Shibata 1996, 1997). This is an extension of the CSHKP (Carmichael-Sturrock-Hirayama-Kopp-Pneuman) model of flares (Hirayama 1991, Moore and Roumeliotis 1992). The cross-hatched region at the footpoints of the soft X-ray loop shows the bright hard X-ray/soft X-ray double sources. The hatched region at the footpoints of the expanding (helical) loop penetrating the plasmoid shows predicted hard X-ray/soft X-ray distant sources.

4. UNIFIED MODEL

As we have seen above, *Yohkoh* observations have revealed various evidence of magnetic reconnection, especially common occurrence of X-ray mass ejections (plasmoids and/or jets), in LDE flares, impulsive flares, and microflares. These are summarized in Table II.

On the basis of this unified view, Shibata (1996a,b, 1997a,b) proposed a unified model, *plasmoid-induced-reconnection model*, to explain not only LDE and impulsive flares but also microflares and X-ray jets.

One may argue, however, that the shape of X-ray jets and $H\alpha$ surges (i.e., collimated jet-like structure) is very different from that of plasmoids. How can we relate these jets with plasmoids whose shapes are blob-like (or loop-like in three dimensional space)? The answer to this question has already been given by numerical simulations of Yokoyama and Shibata (1995, 1996); a blob-like plasmoid ejected from the current sheet soon collides with the ambient fields, and finally disappears (Fig. 13). The mass contained in the plasmoid is transferred into the reconnected open flux tube and forms a collimated jet along the tube.

Such a case, indeed, has been observed in an M-class

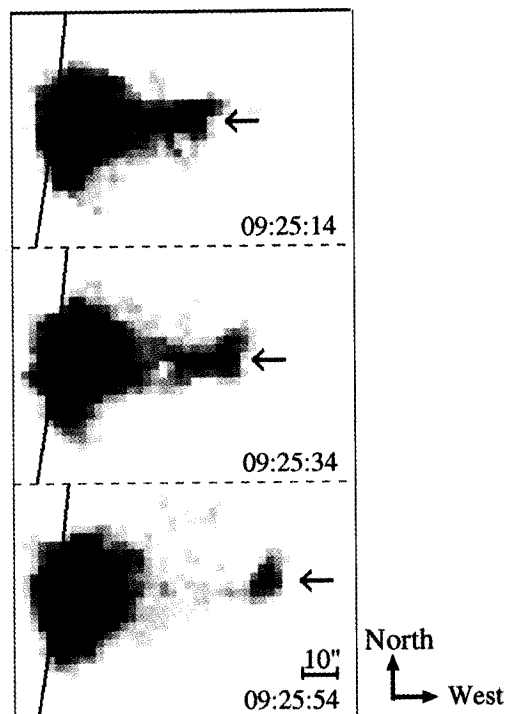


Figure 10. X-ray plasmoid ejections from an impulsive compact loop flare observed with *Yohkoh* SXT on 5 Oct. 1992 (Ohyama and Shibata 1996, 1998). The velocity of the ejections is 200 - 450 km/s.

flare occurred on 13 Nov. 1991 (Fig. 11; Shimojo, Yaji, Shibata 1996). In this case, a loop like mass ejection is first found, which then collides with ambient/overlying field and changes the configuration to a more straight jet-like structure along the global magnetic field.

If the plasmoid contains strong perpendicular component (i.e., helical field), this process would be observed as follows: an erupting helical loop (a plasmoid ejected from the current sheet) collides with an ambient loop to induce reconnection seen as a loop-loop interaction. Through this reconnection, magnetic twist (helicity) in the erupting loop is injected into the untwisted loop, resulting in the unwinding motion of the erupting loop/jet (Shibata and Uchida 1986), which may correspond to the spinning motion observed in some $H\alpha$ surges (Canfield et al. 1996, Schmieder et al. 1995). This also explains why we usually do not observe plasmoid-like (or loop-like) mass ejections in smaller flares (e.g., microflares). In smaller flares, the current sheet is short, so that a plasmoid soon collides with an ambient field to reconnect with it and disappear. Hence the lifetime of the plasmoid (or loop-like) ejection is very short, of order of $t \sim L/V_{\text{plasmoid}} \sim 10 - 100$ sec. It would be interesting to test this scenario using high spatial and

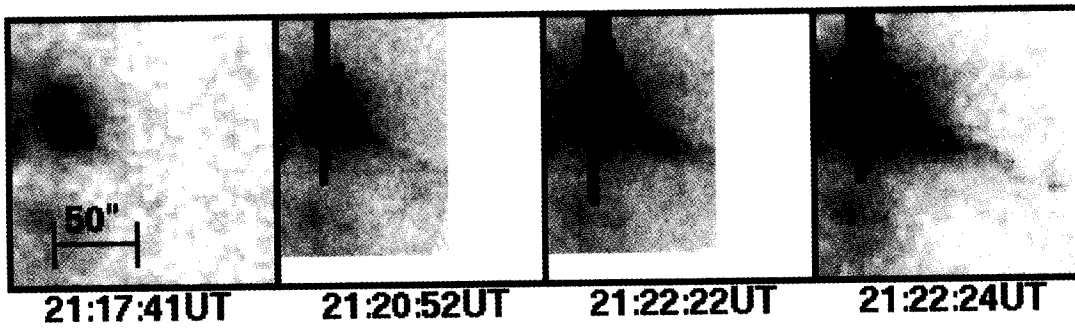


Figure 12. A jet ejected from M-class flare on 13 Nov. 1991 (Shimojo, Yaji, Shibata 1996).

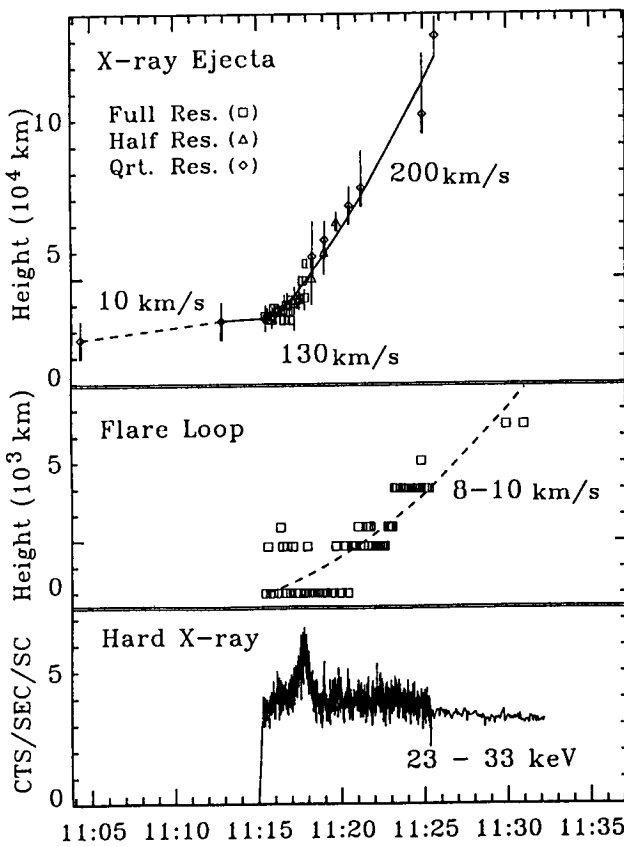


Figure 11. Temporal variations of the height of an X-ray plasmoid and the hard X-ray intensity in an impulsive flare on 11 Nov. 1993 observed by Yohkoh SXT and HXT (from Ohyama and Shibata 1998).

temporal resolution observations with Doppler shift measurement with SOHO/SUMER and/or CDS.

Finally, we note that the essentially the same physical process (magnetic reconnection associated with plasmoid ejections) can occur even below the transition region (see Table 1 and Fig. 14). If the reconnection occur in the upper chromosphere, the temperature of heated plasma is of order of $10^5 - 10^6$ K since the pre-heated plasma temperature is low ($\sim 10^4$ K) and the local plasma $\beta (= p_{gas}/p_{mag})$ is not low (> 0.01); note that the temperature of the reconnection-heated

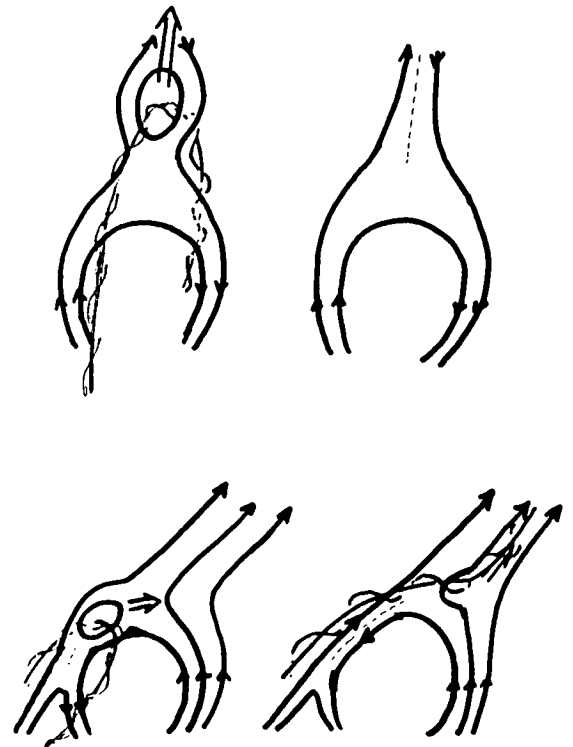


Figure 13. Unification of CSHKP model and emerging flux model by the plasmoid-induced-reconnection model (Shibata 1997a,b). Note that a plasmoid (a magnetic island or a helically twisted flux rope) collides and reconnects with the ambient magnetic field to disappear in a short time scale (10 - 100 sec) in the case of small scale flares such as microflares.

plasma is $\sim T_0/\beta$. EUV explosive events/jets (e.g., Dere et al. 1991, Innes et al. 1997) may correspond to these reconnection events. If the reconnection occurs in the photosphere as suggested by recent MDI results (Title and Tarbel 1997), we would observe photospheric bright points (nanoflares) as well as mass

flow with a velocity of a few – 10 km/s. This impulsive mass flow as well as large amplitude Alfvén waves generated by the reconnection could be a source of energy to produce spicules and coronal heating (Kudoh and Shibata 1998).

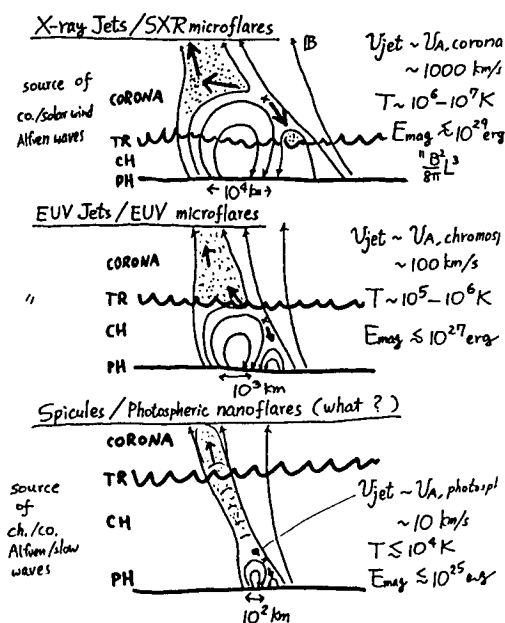


Figure 14. Various jet phenomena in quiet regions of the Sun; X-ray jets/SXR microflares, EUV jets/EUV microflares, and spicules/photospheric nanoflares. All these jet phenomena may be generated by magnetic reconnection. Note also that the reconnection is a source of large amplitude (high frequency) Alfvén waves.

Table II Unified View of Various “Flares”

“flares”	mass ejections (cool)	mass ejections (hot)
giant arcades	H α filament eruptions	CMEs
LDE flares	H α filament eruptions	X-ray plasmoid ejections/CMEs
impulsive flares	H α sprays	X-ray plasmoid ejections
transient brightenings (microflares)	H α surges	X-ray jets
EUV microflares	surges/spicules	EUV jets
facular points (nanoflares?)	spicules	(Alfvén waves)

5. REMAINING QUESTIONS

Recent MHD numerical simulations of jets based on magnetic reconnection model (Yokoyama and Shibata 1995, 1996, Yokoyama 1998) have reproduced many observed properties of not only hot jets (X-ray jets) but also cool jets (H α surges) (see also related simulation study by Okubo et al. 1997, Karpen et al. 1998 as well as analytical study by Priest et al. 1996). The study on the origin of plasmoids (and similar coronal mass ejections) has also been advanced greatly by extensive MHD numerical simulations (e.g., Mikic and Linker 1994, Kusano et al. 1995, Choe and Lee 1997, Magara et al. 1997). Nevertheless, there remains some fundamental questions as listed below: I hope these questions will be answered by future collaborative study with *Yohkoh*, SOHO, TRACE, ground-based observations, and Solar B.

- What is the true velocity of X-ray jets and X-ray plasmoids? The velocity of both X-ray jets and X-ray plasmoids is usually of order of a few 100 km/s which is much smaller than coronal Alfvén speed. Is this true? Since *Yohkoh* cannot perform Doppler shift measurement of velocity of jets and plasmoids, we must await for future observations of Doppler shift velocity of jets and plasmoids with SOHO and/or Solar B.
- What is the acceleration mechanism of X-ray jets? Even if the reconnection model is true for main energy release mechanism in X-ray jets, there still remains a question on the specific acceleration mechanism of X-ray jets. Namely, in addition to the possibility of reconnection secondary outflow,³ there is also a possibility that X-ray jets are chromospheric evaporation flows induced by sudden reconnection heating (see Shimojo et al. 1998b).
- Where are high speed reconnection jets? The reconnection theory predicts bi-directional high speed jets with Alfvén speed (~ 1000) km s⁻¹ from the reconnection point. Although *Yohkoh*/SXT discovered many hot plasma ejections from flares, they are uni-directional and their velocities (40–500 km s⁻¹) are much less than the Alfvén speed.
- Do X-ray jets show spinning motion?
- What is the relation of X-ray jets to other jet-like phenomena such as macrospicules, EIT jets, and EUV jets?
- What is the relation of X-ray jets/plasmoids to coronal mass ejections?

ACKNOWLEDGMENTS

The author would like to thank M. Ohyama, M. Shimojo, T. Yokoyama, T. Kudoh, and other *Yohkoh* col-

³Yokoyama and Shibata (1996) showed that the reconnection jet itself collides with the ambient field to form fast shock. Hence an X-ray jet cannot be a reconnection jet itself but must be large scale field aligned flow accelerated by the enhanced gas pressure just behind the fast shock.

leagues for their various help and interesting discussions.

REFERENCES

- Aurass, H., Klein, K. -L., and Martens, P. C. H., 1995, *Solar Phys. Lett.*, 155, 203.
- Burgarella, D., M. Livio, and C. P. O'Dea (eds.), *Astrophysical Jets*, Cambridge Univ. Press, 1993.
- Canfield, R. C., Reardon, K. P., Leka, K. D., Shibata, K., Yokoyama, T., and Shimojo, M., 1996, *ApJ*, 464, 1016.
- Choe, G. S., and Lee, L. C. 1996, *ApJ*, 472, 360.
- Cook, J. W. and Brueckner, G. E., 1991, in *Solar Interior and Atmosphere*, A. N. Cox et al. (eds.), Univ. Arizona Press, p. 996.
- Dere, K., et al., 1991, *JGR*, 96, 9399.
- Feldman, W.C., J.T. Gosling, D.J. McComas, and J.L. Phillips, *J. Geophys. Res.*, 98, 5593-5605, 1993
- Hammond, C.M., Feldman, W.C. Phillips, J.L. Goldstein, B.E. and Balogh, A. *J. Geophys. Res.*, 100, 7881-7889, 1995.
- Hanaoka, Y., 1996, *Solar Phys.*, 165, 275.
- Hiei, E., Hundhausen, A. J., Burkepile, J., 1996, in *Magnetic Reconnection in the Solar Atmosphere*, ASP Conf. ser. Vol. 111, p. 383.
- Hirayama, T., 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., 1994, in *Proc. Kofu meeting*, eds. S. Enome, and T. Hirayama, Nobeyama Radio Observatory, p. 1.
- Innes, D. E., et al., 1997, *Nature*, 386, 811.
- Kahler, S. W., Moore, R. L., Kane, S. R., and Zirin, H., 1988, *ApJ*, 328, 824.
- Karovska, M. and Habbal, S. R., *ApJ* 431, L59, 1994.
- Karpen, J. T., Antiochos, S. K., and DeVore, C. R., 1998, *ApJ*, in press.
- Koutchmy, S., et al., 1997, *A Ap*, 320, L33.
- Kudoh, T., and Shibata, K., 1998, in these proceedings.
- Kundu, M. R., Raulin, J. P., Nitta, N., et al., 1995, *ApJ Let*, 447, L135.
- Kurokawa, H. and Kawai, G., *Proc. The Magnetic and Velocity Fields of Solar Active Regions, ASP Conf. Series 46*, ed. H. Zirin et al., pp. 507-510, 1993.
- Kusano, K., Suzuki, Y., and Nishikawa, K. 1995, *ApJ*, 441, 942.
- Magara, T., Shibata, K., Yokoyama, T., 1997, *ApJ*, 487, 437.
- Masuda, S., 1994, Ph. D. Thesis, U. Tokyo.
- Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., and Ogawara, Y., 1994, *Nature*, 371, 495.
- Masuda, S., Kosugi, T., Hara, H., et al., 1995, *PASJ*, 47, 677.
- Mikic, Z., and Linker, J. A., 1994, *ApJ*, 430, 898.
- Moore, R. L., and Roumeliotis, G. 1992, in *Lecture Note in Physics, No. 399, Eruptive Flares*, ed. Z. Svestka, B. V. Jackson, and M. E. Machado (New York, Springer), 69.
- Nitta, N., 1996, *Proc. Bath Conf., Observations of Magnetic Reconnection in the Solar Atmosphere*, Bentley, R. and Mariska, J. T. (eds.), ASP conf. ser., vol. 111, p. 156.
- Ohyama, M., Shibata, K., Yokoyama, T., Shimojo, M., 1997, *Adv. Space Res.* 19, 1849.
- Ohyama, M., and Shibata, K. 1997, *PASJ*, 49, 249.
- Ohyama, M., and Shibata, K. 1998, *ApJ*, 499, in press.
- Okubo, A. et al., 1996, *Proc. Bath Conf., Observations of Magnetic Reconnection in the Solar Atmosphere*, Bentley, R. and Mariska, J. T. (eds.), ASP conf. ser., vol. 111, p. 39.
- Priest, E. R., Parnell, C. E., and Martin, S. F., 1994, *ApJ*, 427, 459.
- Raulin, J. P., Kundu, M. R., Hudson, H. S. et al., 1996, *AA*, 306, 299.
- Schmieder, B., K. Shibata, L. van Driel-Gesztelyi, and S. Freeland, 1995, *Solar Phys.*, 156, 245.
- Shibata, K., and Uchida, Y., 1986, *Solar Phys.*, 103, 299.
- Shibata, K., Ishido, Y., Acton, L., et al., 1992, *PASJ*, 44, L173.
- Shibata, K., Nitta, N., Strong, K. T., et al., 1994a, in *"X-ray Solar Physics from Yohkoh"*, eds. Y. Uchida et al., *Univ. Academy Press*, p. 29.
- Shibata, K., Nitta, N., Strong, K. T., et al., 1994b, *ApJ*, 431, L51.
- Shibata, K., Masuda, S., Shimojo, M., et al., 1995, *ApJ*, 451, L83.
- Shibata, K., Yokoyama, T., and Shimojo, M., 1996, *J. Geomag. Geoelectr.*, 48, 19.
- Shibata, K., 1996a, *Adv. Space Res.*, 17, (4/5)9.
- Shibata, K., 1996b, in *Magnetodynamic Phenomena in the Solar Atmosphere*, *Proc. IAU Colloq. No. 153*, Y. Uchida et al. (eds.), Kluwer, p. 13.
- Shibata, K., 1997a, *Proc. of Hitachi Solar Flare workshop*, T. Sakurai et al. (eds.) in press.
- Shibata, K., 1997b, *ApJ*, submitted.
- Shimizu, T., Tsuneta, S., Acton, L. W., Lemen, J. R., Uchida, Y., 1992, *PASJ*, 44, L147.
- Shimojo, M., Hashimoto, S., Shibata, K., et al., 1996, *PASJ*, 48, 123.
- Shimojo, M., Shibata, K., Harvey, K., 1998a, *Solar Phys.*, in press.
- Shimojo, M., Hori, K., Yokoyama, T., Shibata, K., 1998b, in these proceedings.
- Strong, K. T., Harvey, K., Hirayama, T., et al., 1992, *PASJ*, 44, L161.
- Tsuneta, S., 1997, *ApJ*, 483, 507.
- Webb, D. F., and Cliver, E. W., Evidence of Magnetic Disconnection of Mass Ejections in the Corona, *J. Geophys. Res.*, 100, 5853, 1995.
- Yokoyama, T. 1998, in these proceedings.
- Yokoyama, T., and Shibata, K., 1995, *Nature*, 375, 42.
- Yokoyama, T., and Shibata, K., 1996, *PASJ*, 48, 353.
- Yokoyama, T., and Shibata, K., 1997, *ApJ*, 474, L61.
- Yokoyama, T., and Shibata, K., 1998, *ApJ*, 494, L113.