Magnetic Reconnection in the Solar Atmosphere
ASP Conference Series, Vol. 111, 1996
R.D. Bentley and J.T. Mariska, (eds.)

Theory and Observations of X-Ray Jets

K. Shibata, M. Shimojo, T. Yokoyama, and M. Ohyama

National Astronomical Observatory, 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). The recent development of observations and theoretical modeling of X-ray jets are reviewed with emphasis upon the role of magnetic reconnection. The relation to X-ray plasma ejections (plasmoids) from large flares is also discussed.

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. 1992b, Strong et al. 1992). They are associated with microflares (Shimizu et al. 1992) or subflares, which occurred in X-ray bright points (XBPs), emerging flux regions, or active regions (see Figure 1 for a typical example). X-ray jets are important not only because they can be a prototype of astrophysical jets, but also because they may provide clues to understanding 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 (e.g., Feldman et al. 1993).

In this article, we will review recent development of observation and theory of these coronal X-ray jets with emphasis upon the role of magnetic reconnection.

2. Observations

2.1. Basic Properties of X-Ray Jets

According to a statistical study of 100 jets by Shimojo et al. (1996a), the length of the jets is 10^3–4×10^5 km (average $\simeq 1.5 \times 10^5$ km), the apparent velocity is 10–1000 km s^{-1} (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, and histograms (Figure 2) are similar to those of flares and EUV explosive events (Cook and Brueckner 1991). The temperature of jets ($\sim$ 3–6 MK) is comparable to that of microflares at the footpoints of the jets, the electron density is 3×10^8–3×10^9 cm^{-3}, and the kinetic energy is estimated to be 10^{25}–10^{28} erg.

2.2. Evidence of Magnetic Reconnection

There is much evidence for reconnection in jets (Shibata et al. 1994a,b, 1996):

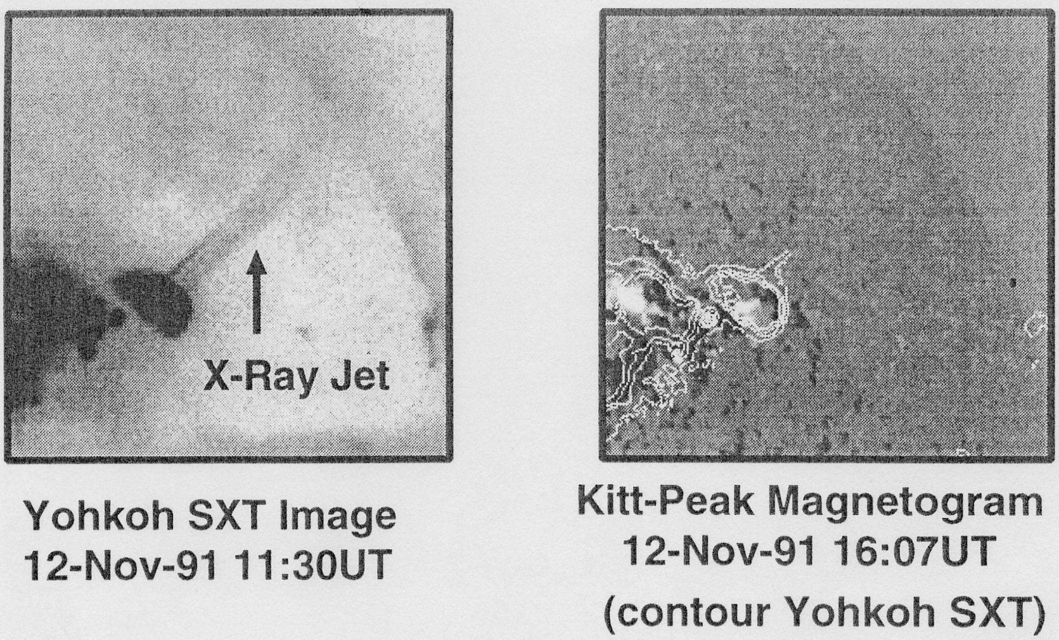

Figure 1. Left: An X-ray jet observed with the *Yohkoh*/SXT on 12 Nov. 1991 (Shibata et al. 1992b). Right: NSO/Kitt Peak magnetogram for the same region with overlay of contours of soft X-ray intensity distribution. Notice mixed polarities at the footpoint of the jet.

(a) *Two Types of Interaction between Emerging Flux and Coronal Field*: Shibata et al. (1994b) 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 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. (1996a) found that the width of the jets often decreases with height (i.e., *converging* shape), which is similar to the shape of Hα surges observed in emerging flux regions (Kurokawa and Kawai 1993) and EUV macrospicules. This shape suggests that the cross-section of the 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. This situation is expected also when the satellite spots appear in an opposite polarity region.

(c) *Magnetic Field Properties of Jets*: Shimojo et al. (1996b) found that more than 70 percent of jets show either *mixed polarity* or *satellite spots* at the footpoints of jets. This gives us direct evidence of existence of a neutral point or a current sheet near the footpoint of the jets.

(d) *A Gap Between Footpoint of a Jet and Brightest Part of a 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. 1996a). This characteristic is also seen in tiny XBP jets. Such a gap is expected for a magnetic reconnection mechanism, because

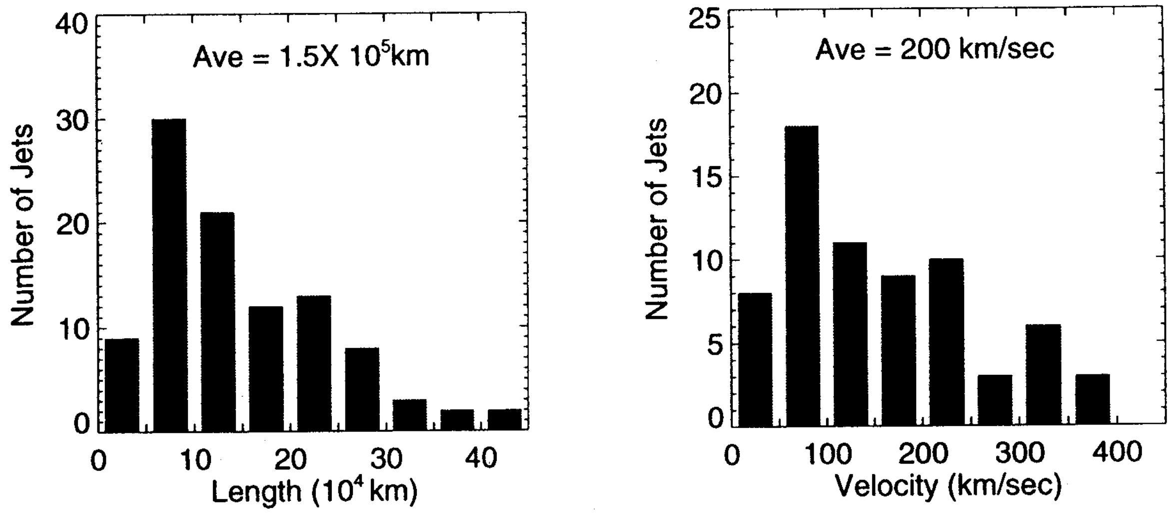

Figure 2. Histograms of velocity and length of X-ray jets (from Shimojo et al. 1996a).

the heated reconnected field lines are quickly ejected in opposite directions to form one bright loop and a separate jet in the other direction.

(e) *Change of Topology of Footpoint Active Region*: When the ARs at the footpoints of jets can be resolved well, their morphology changes substantially during the jets. For example, a loop system appeared during the 12 Nov. 1991 jet (Shibata et al. 1992b), while a loop system disappeared during the 11 Jan. 1992 jet (Shibata et al. 1994b).

(f) *Whip-like Motion of Jets*: In some cases, a jet moved perpendicularly to the jet axis at a few 10 km s^{-1} during the ejection of the jet, which has been referred to as *whip-like motion* of a jet (Shibata et al. 1992b, 1994b, Canfield et al. 1996). This might be an evidence of dynamical rearrangement of magnetic field configuration as a result of reconnection.

(g) *Hα Surges*: Canfield et al. (1996) found several examples of simultaneous ejection of X-ray jets and Hα surges in the same direction, and found new evidence of reconnection; *moving blue shift* and *converging footpoints*. These surges spin around their axis, as modeled by Shibata and Uchida (1986). (Note that there are also many Hα surges which are not associated with X-ray jets; e.g., Schmieder et al. 1995).

(h) *Type III bursts*: Kundu et al. (1995) found that a Type III burst was associated with an X-ray jet. 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.

3. Theory

3.1. Acceleration Mechanism

As seen above, there is increasing observational evidence of magnetic reconnection in X-ray jets. However, as for a specific acceleration mechanism, there are still questions even if the basic energy release mechanism is magnetic reconnection. There are three possible mechanisms (Shibata et al. 1992b).

(1) The *evaporation flow (jet)* (Hirayama 1974) as a result of a flare that is produced by the reconnection. In this case the jet is accelerated by the gas pressure gradient force which is enhanced by the flare. The maximum velocity of the evaporation jet (Landau and Lifshitz 1959, Shibata et al. 1992b) is of the order of

$$V_{ev\text{-}jet,max} \sim 3C_s \simeq 1500(T/10^7\mathrm{K})^{1/2} \ \ \mathrm{km\ s^{-1}}, \tag{1}$$

where C_s and T are the sound speed and temperature of the flaring plasma, respectively. The apparent velocity of the constant density part (or main part) of the jet is about 30–300 km s^{-1}, if the density of the jet is 20–40% of that of the flare, consistent with the apparent velocities of many X-ray jets.

(2) The *magnetic-twist jet* (Shibata and Uchida 1985, 1986), which is accelerated by the *magnetic pressure force* in relaxing magnetic twist as a result of reconnection between a twisted loop and an untwisted loop. If the density of the jet is much higher than that of the ambient corona, the maximum velocity of the magnetic-twist jet becomes

$$V_{mt\text{-}jet,max} \sim 2V_A \simeq 2000(B/10\mathrm{G})(n/10^9\mathrm{cm}^{-3})^{-1/2} \ \ \mathrm{km\ s^{-1}}, \tag{2a}$$

where V_A is the Alfvén speed, B is the magnetic flux density, and n is the hydrogen number density, but again the apparent velocity of the constant-density part of the jet is of order of 15–300 km s^{-1} if the density of the jet is 20–40% of that of the flare. On the other hand, if the density and gas pressure of the jet are comparable to those of the ambient corona and if the magnetic twist (B_φ/B_z) is not large (< 1), the velocity of the magnetic-twist jet (Shibata and Uchida 1985) becomes

$$V_{mt\text{-}jet} \sim 0.5V_A(B_\varphi/B_z)^2 \simeq 500(B/10\mathrm{G})(n/10^9\mathrm{cm}^{-3})^{-1/2}(B_\varphi/B_z)^2 \ \ \mathrm{km\ s^{-1}}. \tag{2b}$$

(3) The *reconnection jet* (e.g., Parker 1979, Shibata et al. 1992b) which is accelerated (like a slingshot) by the *magnetic tension force* in the reconnection process. The velocity of the jet is of the order of the local Alfvén speed

$$V_{rec\text{-}jet} \sim V_A \simeq 1000(B/10\mathrm{G})(n/10^9\mathrm{cm}^{-3})^{-1/2} \ \ \mathrm{km\ s^{-1}}. \tag{3}$$

The velocity of magnetic islands (or plasmoids or expanding helical loops ejected from current sheet) is also comparable to the local Alfvén speed.

Since the observed velocities of many jets are within the range of possible speeds of the above mechanisms, at present it is not possible to identify which jets belong to which type. We need more detailed theoretical modeling as well as finer observations such as Doppler shift measurement, which would be possible with *SOHO*.

3.2. Reconnection Models

Emerging Flux Model Heyvaerts et al. (1977) developed the emerging flux reconnection model for flares and proposed that surges correspond to reconnection jets. Shibata et al. (1989) succeeded in making a physically realistic emerging flux model, by studying the nonlinear evolution of the magnetic buoyancy

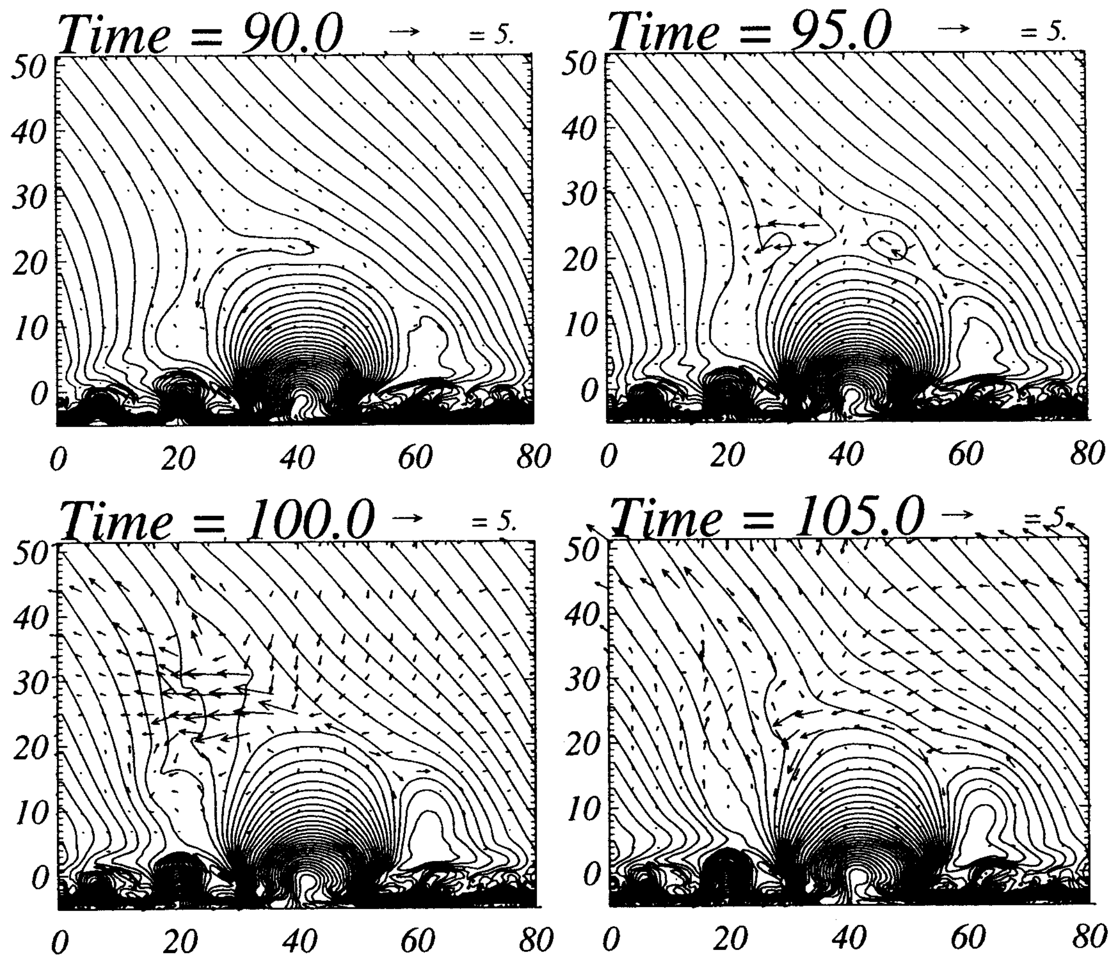

Figure 3. Emerging flux reconnection model of Yokoyama and Shibata (1995, 1996). Note that plasmoids (magnetic islands) are repeatedly created in the current sheet and are ejected upward.

(Parker) instability. Shibata et al. (1992a) then applied this model to reconnection between emerging flux and overlying coronal field in a realistic situation, and found that the reconnection began with formation and ejection of magnetic islands (plasmoids). Yokoyama and Shibata (1995,1996) extended Shibata et al.'s simulation to a greater extent, and succeeded in modeling coronal X-ray jets as well as Hα surges (see also Yokoyama 1995). Their main results are summarized in the following.

When the reconnection occurs between emerging flux and horizontal coronal field, two hot jets (or two hot loops) and one cool jet (or cool dense plasmoid) are produced (Figure 4a). The two hot jets (loops) might correspond to the *two-sided-loop* discussed in section 2.2. When the coronal field is not horizontal but vertical or oblique, there occurs a hot jet, a cool jet (originally from cool, dense plasmoid) to one side of the hot jet, and a small hot loop which is located separately from the footpoint of the jet. Both the hot and cool jet move perpendicularly to the coronal magnetic field. This may correspond to the *whip-like motion* observed in X-ray jets. The resulting magnetic field configuration is an *upside-down Y* shape, which is very similar to the shape of *anemone-jet* and the *converging jet.* The observed separation between footpoints of jets and flares (brightest part) can also be explained with this model. The observation of some

X-ray jets associated with Hα surges is also nicely explained by the theoretically predicted coexistence of a hot jet and a cool jet.

One of important findings by Yokoyama and Shibata (1995, 1996) is that the hot jet ejected from the current sheet region is not the reconnection jet itself, but the *secondary jet* accelerated by the enhanced gas pressure behind the *fast shock*. This is because the reconnection jets cannot directly escape from the current sheet region, and collide with the ambient magnetic field (or loop), then creating the fast shocks at both ends of the current sheet. Hence, according to this model, the X-ray jet is not the reconnection jet itself but the secondary jet.

Other Reconnection Models Priest et al. (1994) and Parnel et al. (1994) presented a slightly different reconnection model, i.e., a *converging flux* model, for X-ray bright points and jets. In this model, the magnetic reconnection is driven by the moving magnetic flux which collides with the preexisting vertical magnetic flux (often in the network). This model is based on the observation that about 2/3 of X-ray bright points are associated with cancelling magnetic flux rather than emerging flux (Harvey 1985). There is, however, a possibility that even the cancelling flux is driven by the emerging flux, or in other words, the driving force is magnetic buoyancy of the tube itself (as in the case of the emerging flux) rather than hydrodynamic force in convection flows.

Karpen et al. (1995) have developed a *sheared flux* model, in which the magnetic reconnection is driven by the shearing motion of the footpoints of the magnetic fields containing a neutral point, such as a quadrupole geometry. In this case, the magnetic pressure is increased by the shearing effect, which compresses the neutral point, creating a current sheet and thus magnetic reconnection. The origin of the shearing motion is either magnetic buoyancy or hydrodynamic force in convection flows.

Note that the basic physics of reconnection in these models (emerging flux model, converging flux model, and sheared flux model) is the same; i.e., in the current sheet, which is first created by compressing a neutral point, the tearing instability occurs to create the magnetic islands. These islands coalesce and are ejected out of the current sheet. Such ejected plasmas (i.e., plasmoids) are eventually transferred into open tubes to form a jet along the open tubes once the reconnection occurs between the plasmoids and the ambient open magnetic field. Since the plasmoids are helically twisted flux tubes in three dimensional space, such reconnection processes would be observed as a loop-loop interaction or the unwinding motion of a helical loop.

Magnetic Twist Model = 3D Reconnection Model On the basis of the idea of Shibata and Uchida (1985, 1986), Okubo et al. (1996) extended the simulation model of Yokoyama and Shibata (1995, 1996) to the cases including the effect of the perpendicular magnetic field in emerging flux using 2.5D MHD simulations. (The perpendicular field corresponds to the azimuthal component of a flux loop in 3D situation.) They found that acceleration of reconnected plasma is enhanced by the sudden release of magnetic twist (perpendicular field) into the open field as a result of reconnection. Canfield et al. (1996) applied the same idea to the Hα surges (Figure 5).

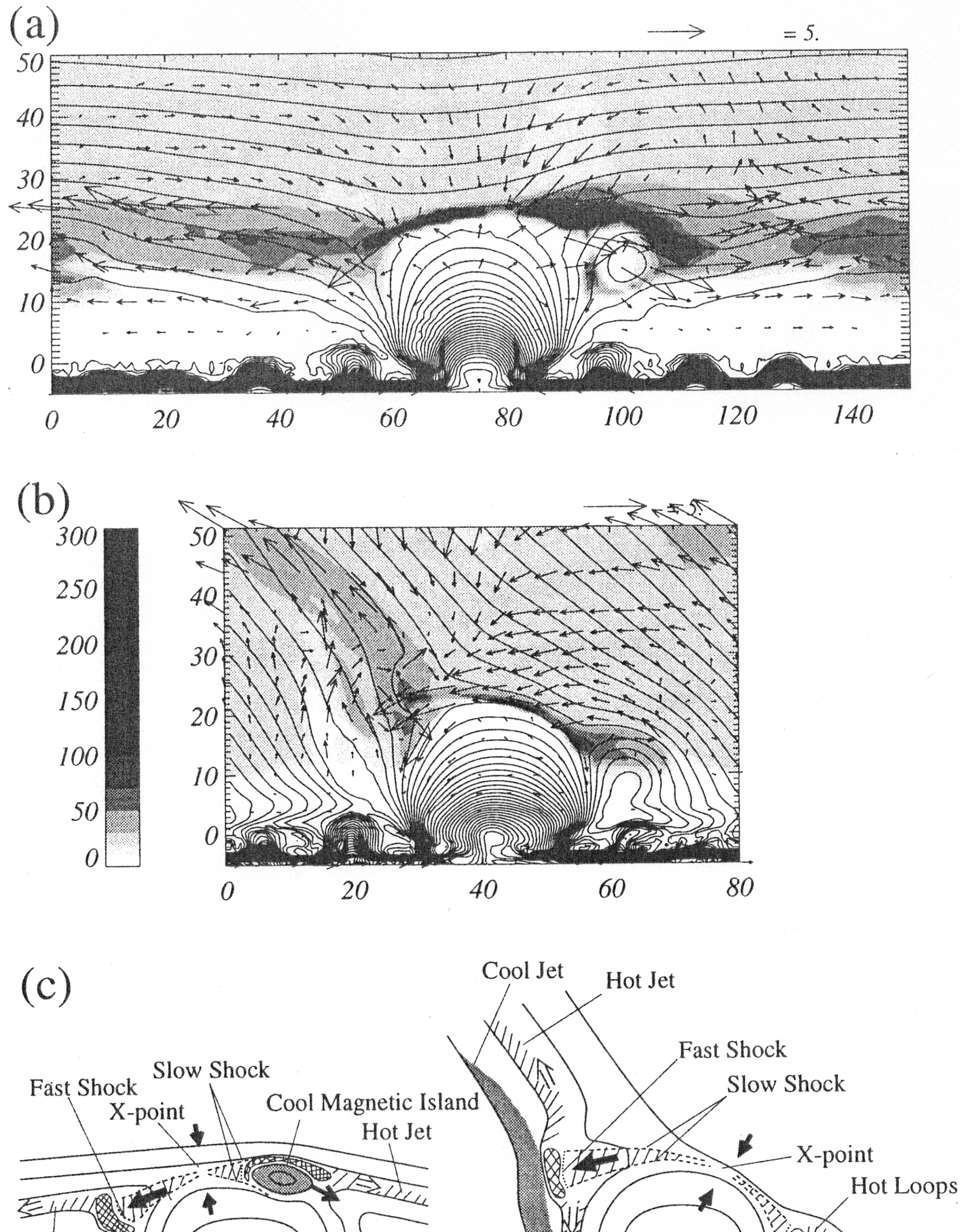

Figure 4. MHD numerical simulation of magnetic reconnection model for X-ray jets (from Yokoyama and Shibata 1995, 1996). (a) *Two-sided-loop type*, in which the initial coronal field is horizontal. (b) *Anemone-jet type*, in which the initial coronal field is oblique. Both figures show the temperature distribution (grey scale; darker region is hotter), magnetic field lines (lines), and velocity vectors. The unit of length is ~ 200 km. The velocity of the hot jet is about 0.3–1.0 in units of the coronal Alfvén speed $V_{A,cor}$ (~ 1000 km s^{-1}). (c) Schematic illustration of physical processes found from numerical simulations.

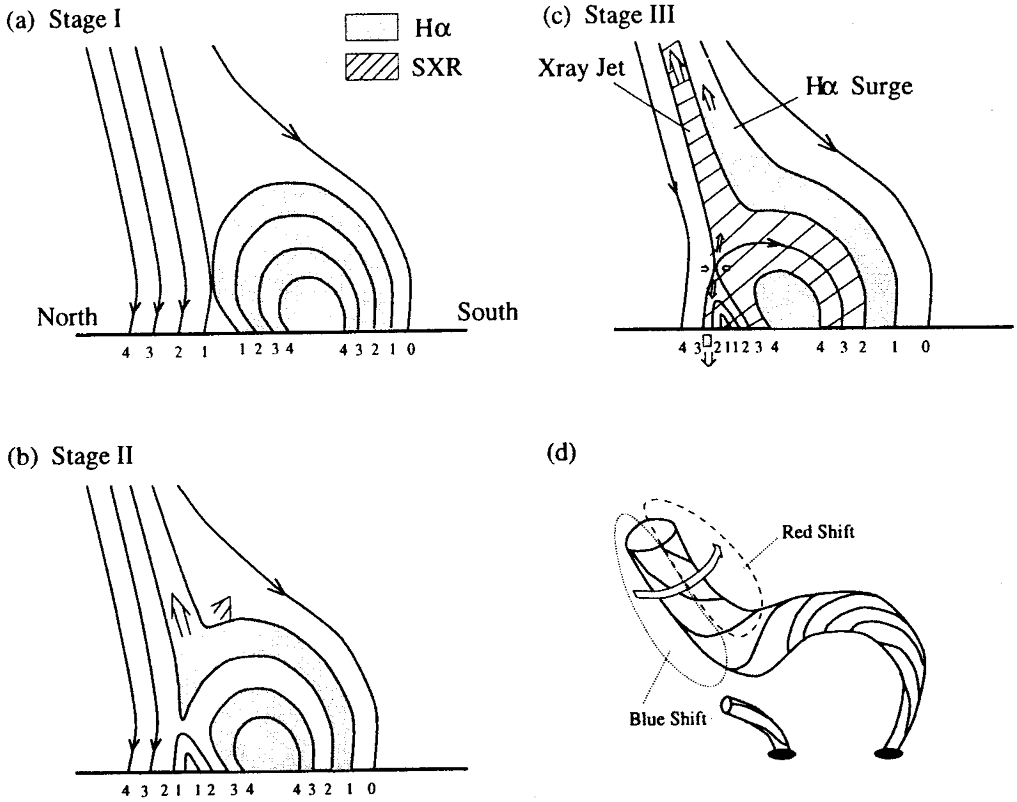

Figure 5. A magnetic twist – reconnection model for Hα surges (Canfield et al. 1996)

4. Discussion: What is the Relation to Plasmoid Ejections Observed in Large Flares?

As we discussed before, most of jets are ejected from small flares (microflares - subflares). Why do jets occur in small flares? What is found in large flares instead of jets?

In large flares (especially, in LDE flares), X-ray plasma ejections (loop-like or blob-like) are often observed. Shibata et al. (1995) discovered X-ray plasma ejections even from impulsive compact loop flares (e.g., the Masuda (1994) flare) which have been considered to be *confined.* Such plasma ejections are often called *plasmoid ejections.*

Figure 6 shows a typical example of X-ray plasma (plasmoid) ejections from an M-class impulsive compact flare (Ohyama and Shibata 1996). We see that a hot ($\sim$ 5–16 MK) and dense ($\sim 10^9$–10^{10} cm^{-3}) blob-like plasma is ejected from above the top of the flare loop at a velocity of 200–450 km s^{-1}. This blob is similar to a plasmoid accelerated along a current sheet (e.g, see Figure 4). In 3D space, it would be observed as a loop (or a helically twisted loop). This kind of mass ejection has been considered to be different from jets. However, if the plasmoid collides and reconnects with ambient/overlying global field, then the plasma flow become a jet along the global magnetic field configuration. Such

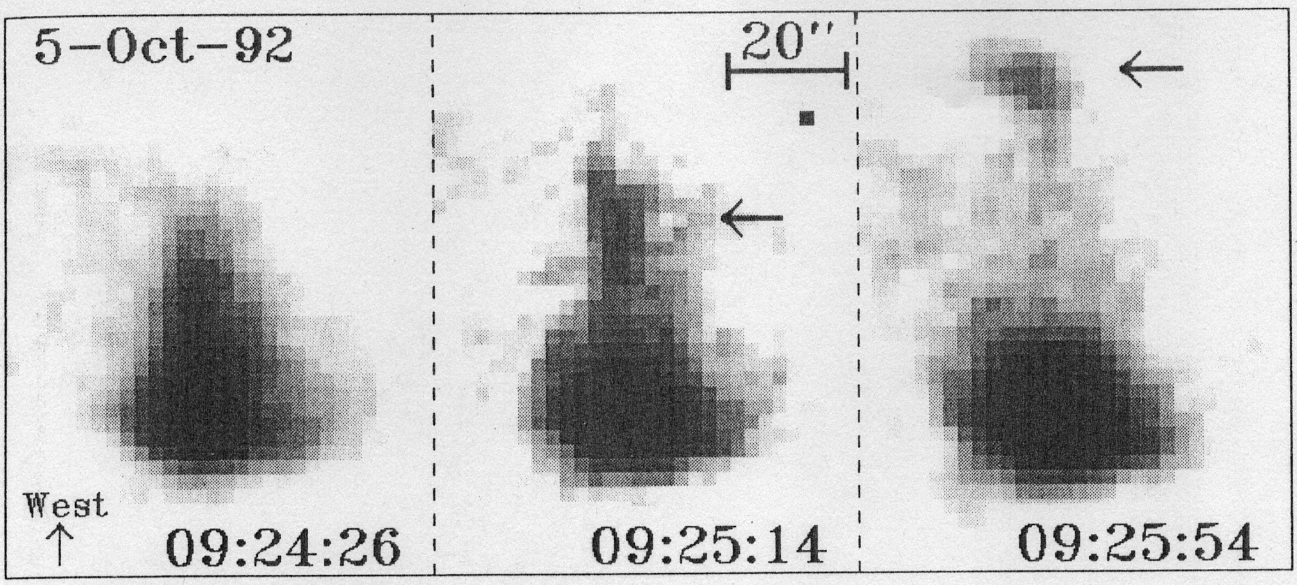

Figure 6. Hot plasma (plasmoid) ejections from an impulsive compact loop flares observed with the *Yohkoh*/SXT on 5 Oct. 1992 (Ohyama and Shibata 1996). The velocity is 200–450 km s^{-1}.

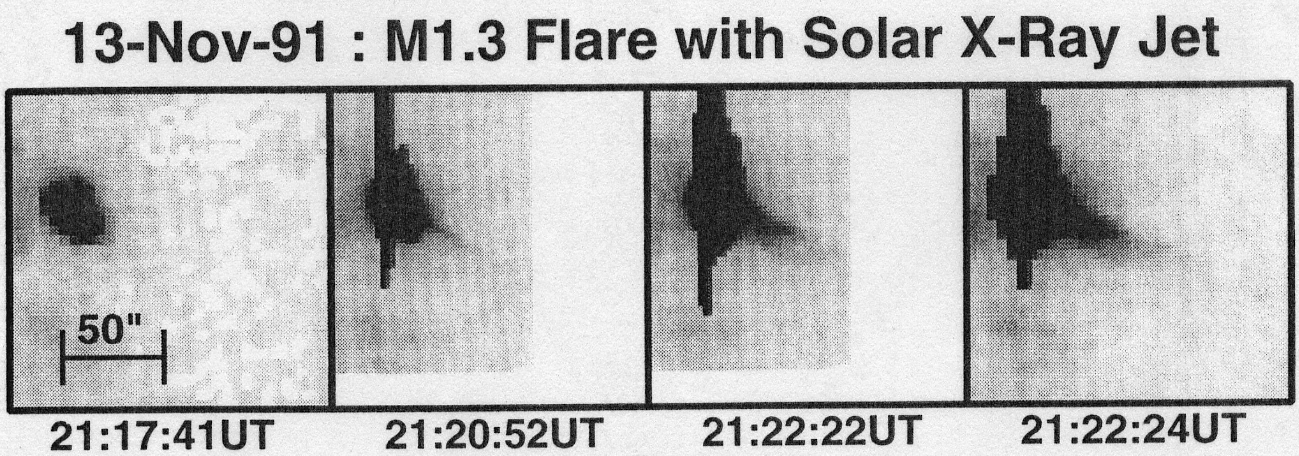

Figure 7. A jet ejected from M-class flare on 13 Nov. 1991 (Shimojo, Yaji, Shibata 1996, in preparation).

a case, indeed, is found in an M-class flare occurred on 13 Nov. 1991 (Figure 7). 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.

These observations suggest that both X-ray jets and X-ray plasma (plasmoids) ejections are basically the same. The only difference is that X-ray jets are formed after the *secondary reconnection* while X-ray plasmoids are seen before the *secondary reconnection.* Based on these findings, Shibata (1996) presented a unified model to explain LDE flares, impulsive flares, and microflares/jets with a single physical mechanism, *magnetic reconnection triggered by plasmoid ejection.*

References

Canfield, R. C. et al. 1996, ApJ, 464, 1016

Cook, J. W. and G. E. Brueckner 1991, in Solar Interior and Atmosphere, A. N. Cox et al. (eds.), Univ. Arizona Press, p. 996
Feldman, W.C., et al. 1993, J. Geophys. Res., 98, 5593
Heyvaerts, J., Priest, E. R. and Rust, D. M. 1977, ApJ, 216, 123
Hirayama, T. 1974, SP, 34, 323
Karpen, J. T., Antiochos, S. K., and DeVore, C. R. 1995, ApJ, 450, 422
Kurokawa, H. and Kawai, G. 1993, Proc. The Magnetic and Velocity Fields of Solar Active Regions, ASP Conf. Series 46, ed. H. Zirin et al., p. 507
Kundu, M. R. et al. 1995, ApJ, 447, L135
Ohyama, M. and Shibata, K. 1996, Proc. IAU Colloq. No. 153, in press
Okubo, A. et al. 1996, Proc. IAU Colloq. No. 153, in press
Schmieder, B. et al. 1995, SP, 156, 245
Shibata, K. 1996, Adv. Space Res., 17, (4/5)9
Shibata, K., and Uchida, Y. 1986, SP, 103, 299
Shibata, K., Tajima, T., Steinolfson, R., and Matsumoto, R. 1989, ApJ, 345, 584
Shibata, K., Nozawa, S., and Matsumoto, R. 1992a, PASJ, 44, 265
Shibata, K. et al. 1992b, PASJ, 44, L173
Shibata, K. et al. 1994a, Proc. "X-ray Solar Physics from Yohkoh, eds. Y. Uchida et al., Univ. Academy Press, p. 29
Shibata, K. et al. 1994b, ApJ, 431, L51
Shibata, K. et al. 1995, ApJ, 451, L83
Shibata, K., Yokoyama, T., and Shimojo, M. 1996, Adv. Space Res., 17, (4/5)197
Shimizu, T. et al. 1992, PASJ, 44, L147
Shimojo, M. et al. 1996a, PASJ, 48, 123
Shimojo, M., Harvey, K., and Shibata, K. 1996b, to be submitted
Shimojo, M. et al. 1996c, IAU Colloq. 153, in press
Sterling, A. C., Shibata, K., and Mariska, J. T. 1993, ApJ, 407, 778
Strong, K. T. et al. 1992, PASJ, 44, L161
Yokoyama, T., and Shibata, K. 1994, ApJ, 436, L197
Yokoyama, T., and Shibata, K. 1995, Nature, 375, 42
Yokoyama, T. and Shibata, K. 1996, PASJ, 48, 353
Yokoyama, T., 1995 Ph. D. Thesis, The Graduate University for Advanced Studies