EVIDENCE OF MAGNETIC RECONNECTION IN SOLAR FLARES AND A UNIFIED MODEL OF FLARES

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Abstract: The solar X-ray observing satellite Yohkoh has discovered various new dynamic features in solar flares and corona, e.g., cusp-shaped flare loops, above-the-loop-top hard X-ray sources, X-ray plasmoid ejections from impulsive flares, transient brightenings (spatially resolved microflares), X-ray jets, large scale arcade formation associated with filament eruption or coronal mass ejections, and so on. It has soon become clear that many of these features are closely related to magnetic reconnection. We can now say that Yohkoh established (at least phenomenologically) the magnetic reconnection model of flares. In this paper, we review various evidence of magnetic reconnection in solar flares and corona, and present unified model of flares on the basis of these new Yohkoh observations.

1. INTRODUCTION

A few years ago, Akasofu (1995) published a nice popular science book entitled "Introduction to Aurora" written in Japanese. In this book, he wrote "*Solar physicists have long tried to prove an assumption that flares are caused by magnetic reconnection, but not yet succeeded. They forgot that magnetic reconnection was simply an assumption*" ! This statement is a big challenge to solar physicists. Though this might have been partly true before launch of Yohkoh (Ogawara et al. 1991), the situation has been dramatically changed by Yohkoh observations of solar flares.

Yohkoh is a solar X-ray observing satellite launched on Aug. 30, 1991, under international collaboration between Japan, US, and UK. Yohkoh carries two X-ray telescopes, soft X-ray telescope (SXT) (Tsuneta et al. 1991) observing ~ 1 keV soft X-rays emitted from 2 – 20 MK thermal plasmas, and hard X-ray telescope (HXT) (Kosugi et al. 1991), for observations of

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10 – 100 keV hard X-rays emitted from nonthermal electrons and superhot plasmas. Yohkoh X-ray observations discovered a lot of evidence of magnetic reconnection in solar flares, e.g., cusps, plasmoids, loop top hard X-ray sources, etc. Yohkoh discovered also various new dynamic phenomena in the corona, such as X-ray jets, microflares, large scale arcade formation, etc. It has soon become clear that these new phenomena are also closely related to magnetic reconnection (e.g., Tsuneta et al. 1992a,b, Shibata et al. 1992b, 1995, Masuda et al. 1994, Shibata 1996, Kosugi and Shibata 1997).

The purpose of this paper is to review these new observations on evidence of magnetic reconnection to convince Akasofu that magnetic reconnection is not an assumption but physical process actually occurring in solar flares. Furthermore, on the basis of these new observations, we propose that various flares, including microflares, impulsive flares, LDE (long duration event) flares, and large scale arcade formation associated with coronal mass ejections, are all explained by a unified model, which we call the *plasmoid-induced-reconnection model* (Shibata 1996, 1997, 1998).

2. FLARES AND PLASMOIDS

2.1. LDE FLARES VS IMPULSIVE FLARES

Solar observers have long thought that there are two types of flares, e.g., long duration event (LDE) flares and impulsive flares. LDE flares typically last more than 1 hour, while impulsive flares are short lived, less than 1 hour. The latter is characterized by the impulsive hard X-ray emission whereas the former shows more softer X-ray spectrum.

Yohkoh soft X-ray telescope (SXT) has discovered that many LDE flares show *cusp-shaped loop* structures (Tsuneta et al. 1992a, Hanaoka 1994, Tsuneta 1996, Forbes and Acton 1996; Fig. 1a), which are quite similar to magnetic field cofiguration predicted by the classical magnetic reconnection model (Carmichael-Sturrock- Hirayama-Kopp-Pneuman model, hereafter called CSHKP model). There are a number of evidence of magnetic reconnection in these LDE flares (Tsuneta 1996): (1) The temperature is systematically higher in outer loops (as predicted by reconnection model; e.g., see Hori et al. 1997, Yokoyama and Shibata 1997, 1998). (2) The cusp-shaped loops apparently grow with time, i.e., the height of loops and the separation of two footpoints of loops increase with time. (3) The energy release rate and other physical quantities are consistent with the prediction by magnetic reconnection model. (4) The plasmoid ejections are often seen in the rise phase of LDE flares (e.g., Hudson 1994).

From these observations and analyses, it was established that LDE flares are produced by the CSHKP-type magnetic reconnection mechanism. [1] The same physical process can also be applied to *large scale arcade formation* associated with filament eruption or CMEs (e.g., Tsuneta et al. 1992b, Hiei et al. 1994, Hanaoka et al. 1994, McAllister et al. 1996).

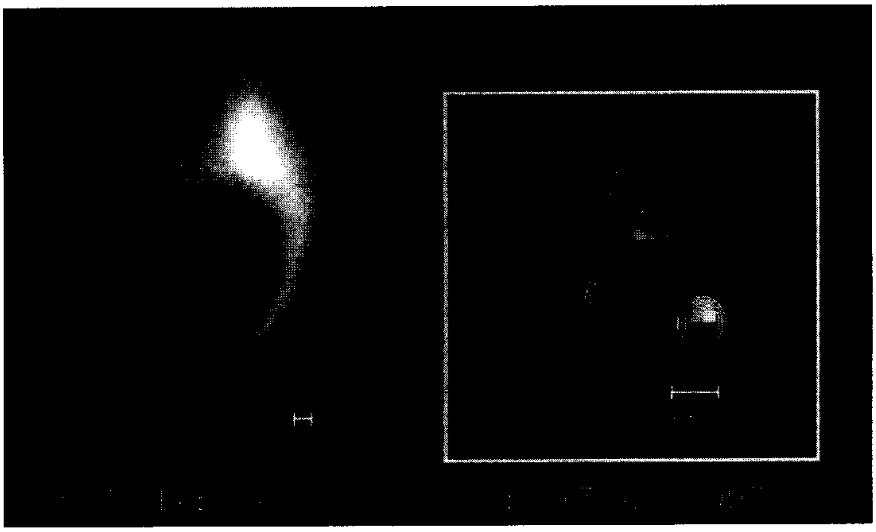

Figure 1. (a) LDE flare on 21 Feb. 1992 observed with SXT (Tsuneta et al. 1992a). (b) Impulsive flare on 13 Jan. 1992 which shows a loop top hard X-ray source above soft X-ray loop (Masuda et al. 1994). Contours of hard X-ray (33 – 53 keV) intensity distribution are overlaid on the soft X-ray ($\sim$ 1 keV) image.

The SXT images of impulsive flares, however, show only *simple loop* structures, as already known from Skylab observations. Hence it was first thought that these impulsive flares might be created by the mechanism different from that for LDE flares, and the magnetic reconnection model was questioned.

It was Masuda (1994) who changed this situation dramatically. He carefully coaligned the SXT and the HXT images of some impulsive compact loop flares observed at the limb, and showed that there is an impulsive HXR source *above* the SXR loop, in addition to the footpoint impulsive

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[1] Here, the "CSHKP-type magnetic reconnection mechanism" simply means the *reconnection occurring in a helmet-streamer (or inverted Y type) field configuration* in which a vertical current sheet is situated above a closed loop. We should keep in mind that there was no agreement on the formation process of this geometry in Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp and Pneuman (1976). For example, Hirayama (1974) considered that MHD instability (causing filament eruption) is a key to form this geometry, while Kopp and Pneuman (1976) thought that the solar wind opens the closed field to form a current sheet. Only common point in these *classical models* is a helmet-streamer (or inverted Y type cusp-shaped) field configuration. I take this standpoint in this review for a definition of the "CSHKP" model. This model has been extended by many authors (e.g., some of such extended models are Cargill and Priest 1983, Cliver 1983, Forbes and Priest 1984, Martens and Kuin 1990, Moore and Roumeliotis 1992). As a historical remark, the term "CSHKP model" was first introduced by Sturrock (1992), and has been often used in solar physics community.

double hard X-ray (HXR) sources (Masuda et al. 1994; Fig. 1b). Since the impulsive HXR sources are produced by high energy electrons, which are closely related to the main energy release mechansim, this means that *the main energy release occurred above (outside) the soft X-ray (SXR) loop.* This means also that the flare models invoking the energy release mechanism inside the SXR loops (e.g., Alfven and Carlqvist 1967, Spicer 1977, Uchida and Shibata 1988) must now be discarded at least for these impulsive compact loop flares.

What is the energy release mechanism in these compact loop flares ? Masuda et al. (1994) postulated that the basic magnetic field configuration is similar to that of LDE flares and that the high speed jet produced by the reconnection collides with the top of the reconnected loop to produce very hot region as well as high energy electrons. (See Aschwanden et al. 1996 for independent observational evidence for acceleration site of high energy electrons high above the SXR loops.)

2.2. X-RAY PLASMOID EJECTIONS FROM IMPULSIVE FLARES

If the impulsive compact loop flares occur as a result of reconnection in a geometry similar to that for LDE flares, plasmoid ejections would be observed high above the loop top HXR source (Fig. 2). Shibata et al. (1995) searched for such plasmoid ejections using SXT images in 8 impulsive compact loop flares observed at the limb, and indeed found that *all these flares were associated with X-ray plasma (or plasmoid) ejections.* The apparent velocity of these ejections are 50 – 400 km/s, and their height ranges are $4 - 10 \times 10^4$ km. Interestingly, flares with HXR source well above the loop top show systematically higher velocity. It is also interesting that there is a positive correlation between the plasmoid velocity ($V_{plasmoid}$) and the apparent rise velocity of the SXR loop (V_{loop}):

$$V_{plasmoid} \simeq (8 - 20) \times V_{loop}. \tag{1}$$

The SXR intensity of the ejections is very low, typically $10^{-4} - 10^{-2}$ of the bright SXR loop. The shape of these plasma ejections is loop-like, blob-like, or jet-like, which are somewhat similar to the shape of CMEs. In many cases, strong acceleration of plasmoids occur during the impulsive phase (Ohyama and Shibata 1997, 1998; Fig. 4), and the temporal relation between height of the ejections and the HXR intensity is very similar to that between CME height and the SXR intensity of an associated flare.

Ohyama and Shibata (1997, 1998) and Tsuneta (1997) analyzed the temperature distribution of plasmoids, flare loops, and ambient structure, and have revealed that the temperature of plasmoids is $\sim 6-13$ MK, slightly less than that of flare loops, and the overall temperature distribution is consistent with that predicted by the reconnection model.

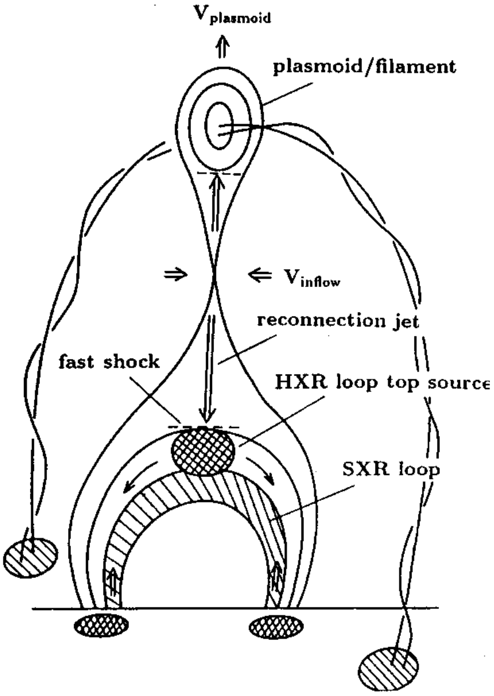

Figure 2. A unified model of flares: *plasmoid-induced-reconnection model* (Shibata et al. 1995, Shibata 1996, 1997).

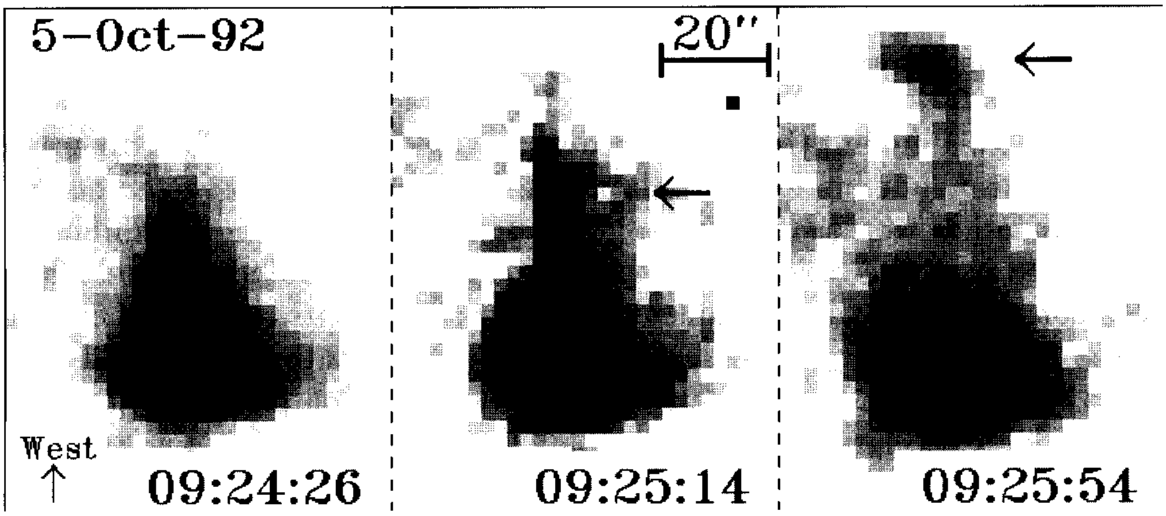

Figure 3. X-ray plasmoid ejections from an impulsive compact loop flare observed with Yohkoh SXT on 5 Oct. 1992 (Ohyama and Shibata 1998). The velocity of the ejections is 200 – 450 km/s.

Ohyama and Shibata (1997, 1998) showed that the kinetic energy of plasmoids is much smaller than that of the total flare energy. This means that the kinetic energy of the plasmoid ejection cannot be the source of flare energy. Instead, the plasmoid ejection could play a role to trigger the main energy release in impulsive phase, since in some events observed in the preflare phase, the plasmoid starts to be ejected (at 10 km/s) well before the impulsive phase (Ohyama and Shibata 1997; Fig. 4).

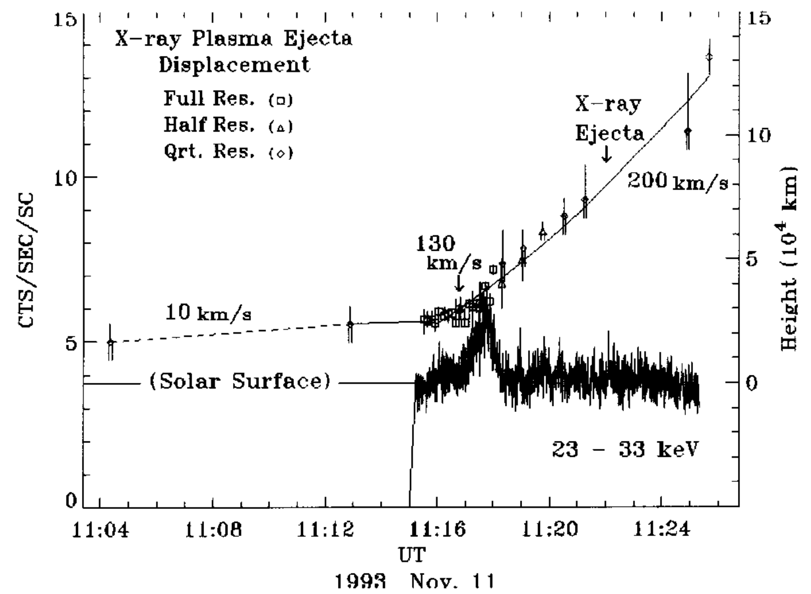

Figure 4. Temporal variations of the height of an X-ray plasmoid and the hard X-ray intensity in an impulsive flare on 11 Nov. 1993 observed by Yohkoh SXT and HXT (from Ohyama and Shibata 1997).

2.3. RECONNECTION MODEL: PLASMOID-INDUCED-RECONNECTION MODEL

On the basis of above observations, Shibata (1996, 1997) proposed the *plasmoid-induced-reconnection model*, by extending the classical CSHKP model. In this model, the plasmoid does not open magnetic field to create current sheet, but instead the plasmoid *is already situated in the current sheet.* In other words, the plasmoid (= flux rope in 3D view) inhibit the reconnection at the current sheet, as in Uchida et al. (1998)'s model where they considered that dark filament ($\sim$ flux rope) inhibits collapse of current sheet. Hence if the plasmoid starts to move, the anti-parallel field lines begin to contact and reconnect. Once the reconnection starts, the released energy help accelerating the plasmoid, leading to faster inflow into the current sheet (i.e., faster reconnection), and the further released energy again accelerate the plasmoid, and so on. This process is a kind of global nonlinear instability (Ugai 1986). In this sense, the plasmoid ejections plays only a role of triggering fast reconnection.

Let us consider the situation that a plasmoid suddenly rises at velocity $V_{plasmoid}$.[2] Since the plasma density does not change much during the eruption process, the plasma inflow with a velocity

$$V_{inflow} \sim V_{plasmoid} L_{plasmoid} / L_{inflow} \tag{2}$$

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[2] In this model, on the basis of observations, we *assume* that the plasmoid is already created before the flare, and is suddenly accelerated by some mechanism. Magnetic reconnection could also play a role to form a plasmoid and accelerate it in such preflare phase as noted by Ohyama and Shibata (1997).

must develop toward the X-point to compensate the mass ejected by the plasmoid (e.g., Ugai 1986, Magara et al. 1997), where $L_{plasmoid}$ and $L_{inflow}(> L_{plasmoid})$ are the typical sizes of the plasmoid and the inflow. We consider that the impulsive phase correspond to the phase when $L_{inflow} \sim L_{plasmoid}$, i.e.,

$$V_{inflow} \sim V_{plasmoid} \sim 50 - 400 \text{ km/s}. \tag{3}$$

Since the reconnection rate is determined by the inflow speed, the ultimate origin of fast reconnection in this model is the fast ejection of the plasmoid. (Of course, the force to compress the current sheet is magnetic pressure around the initial current sheet containing plasmoid.) The equation (2) predicts

$$V_{plasmoid} \propto V_{loop}, \tag{4}$$

since $V_{loop} \sim (B_{inflow}/B_{loop})V_{inflow}$ from conservation of magnetic flux. This nicely explains the observed relation, eq. (1). After the impulsive phase, we expect that L_{inflow} becomes larger than $L_{plasmoid}$ because the distance between the plasmoid and the X-point increases, and hence the inflow speed V_{inflow} would decrease much, leading to slow reconnection which corresponds to the decay or late phase.

In this model, the electric field at the X-point (and surrounding region) becomes $E \sim V_{inflow}B/c$ and is largest during the impulsive phase. Hence, it naturally explains acceleration of higher energy electrons in impulsive phase than in decay phase.

The magnetic reconnection theory predicts two oppositely directed high speed jets from the reconnection point at Alfven speed,

$$V_{jet} \sim V_A \simeq 2000\left(\frac{B}{100\text{G}}\right)\left(\frac{n_e}{10^{10}\text{cm}^{-3}}\right)^{-1/2} \text{km/s}, \tag{5}$$

where B is the magnetic flux density and n_e is the electron density (= ion density). The downward jet collides with the top of the SXR loop, producing MHD fast shock, superhot plasmas and/or high energy electrons at the loop top, as observed in the HXR images. The temperature just behind the fast shock becomes

$$T_{loop-top} \sim m_i {V_{jet}}^2/(6k) \sim$$

$$2 \times 10^8 \left(\frac{B}{100\text{G}}\right)^2\left(\frac{n_e}{10^{10}\text{cm}^{-3}}\right)^{-1} \text{K}, \tag{6}$$

where m_i is the hydrogen ion mass and k is the Boltzmann constant. This explains the observationally estimated temperature of the loop top HXR source (Masuda 1994). We would expect similar physical process for the upward directed jet (see Fig. 2). Indeed we find an SXR bright point during the impulsive phase somewhat far from the SXR loop. This bright point seems to be located at the footpoint of the erupting loop.

The magnetic energy stored around the current sheet and the plasmoid is suddenly released through reconnection into kinetic and thermal/nonthermal energies after the plasmoid is ejected. The magnetic energy release rate at the current sheet (with the length of $L_{inflow} \sim L_{plamoid} \simeq 2 \times 10^4$ km) is estimated to be

$$dW/dt = 2 \times L_{plasmoid}^2 B^2 V_{inflow}/4\pi$$
$$\sim 4 \times 10^{28} \left(\frac{V_{inflow}}{100\ \mathrm{km/s}}\right)\left(\frac{B}{100\ \mathrm{G}}\right)^2\left(\frac{L_{plasmoid}}{2 \times 10^9\ \mathrm{cm}}\right)^2 \mathrm{erg/s}. \qquad (7)$$

This is comparable with the energy release rate during the impulisve phase, $4 - 100 \times 10^{27}$ erg/s, estimated from the HXR data, assuming the lower cutoff energy as 20 keV (Masuda 1994).

The reason why the HXR loop top source is not bright in SXR is that the evaporation flow has not yet reached the colliding point and hence the electron density (and so the emission measure) is low. The key physical parameter discriminating impulsive flares and LDE flares (or impulsive phase and gradual phase) is the velocity of the inflow, V_{inflow}. If V_{inflow} is large, the reconnection is fast, so that the reconnected field lines accumulate very fast and hence the MHD fast shock (i.e., HXR loop top source) is created well above SXR loop which is filled with evaporated plasmas. On the other hand, if V_{inflow} is small, the reconnection is slow and hence the fast shock is produced at the SXR loop.

3. MICROFLARES AND JETS

3.1. TRANSIENT BRIGHTENINGS (MICROFLARES)

Shimizu et al. (1992) analyzed active region transient brightenings (ARTBs) in detail, and found that these correspond to soft X-ray counter part of hard X-ray microflares (Lin et al. 1984). The total thermal energy content of ARTBs is $10^{25} - 10^{29}$ erg, their lifetime ranges from 1 to 10 min, their length is $(0.5 - 4) \times 10^4$ km, and the temperature is about $6 - 8$ MK. According to recent analysis of Shimizu (1996) on the comparison of Yohkoh SXT images of ARTBs with LaParma ground based data, some ARTBs indeed occur in association with emergence of tiny magnetic bipole, suggesting the reconnection between emerging flux and pre-existing field. The occurrence frequency of these ARTBs (SXR microflares) decreases with increasing their total energy and shows power-law distribution; $dN/dE \propto E^{-\alpha}$, where dN is the number of ARTBs per day in the energy range between $E + dE$ and E, and $\alpha \simeq 1.5 - 1.6$ (Shimizu 1995). This is nearly the same as that of HXR microflares and larger flares. Since the index α is less than 2, the SXR microflares alone cannot explain coronal heating. The universal power-law distribution seems to suggest the universal phyiscal origin of both microflares and large scale flares (Watanabe 1994).

3.2. X-RAY JETS

X-ray jets are defined as transitory X-ray enhancements with apparent collimated motion (Shibata et al. 1992b, 1994, 1996, Strong et al. 1992, Shimojo et al. 1996; see Fig. 5). Almost all jets are associated with microflares or subflares, and the length ranges from 1000 to 4×10^5 km. Their apparent velocity is 10 – 1000 km/s. The temperature of X-ray jets is about 4 – 6 MK, which is comparable to those of the footpoint microflares. The electron density ragnes from 3×10^8 to 5×10^9 cm^{-3} and the kinetic energy was estimated to be $10^{25} - 10^{29}$ erg.

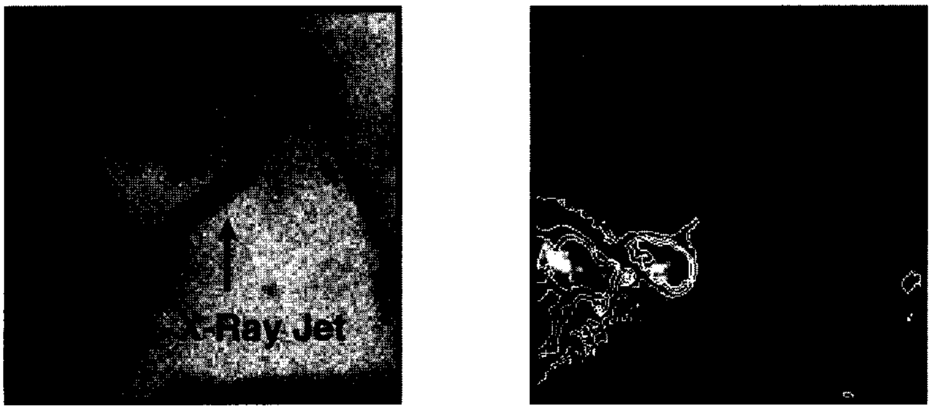
There are a number of evidence of magnetic reconnection in X-ray jets.

(1) Morphology: Many jets show constant or converging shape (Shimojo et al. 1996), implying the magnetic field configuration with a neutral point near the footpoint of a jet as shown in Figure 6. In some jets (27 percent), a gap is seen between footpoints of jets and brightest part of the footpoint flares. This is also nicely explained by the reconnection model (Shibata et al. 1996), since the reconnection creates two hot reconnected field lines (a loop and a jet) with a gap between them. Shibata et al. (1996) noted that there are two types of interaction between emerging flux and overlying coronal field; one is the *anemone* type, in which emerging flux appears in coronal hole and a jet is ejected vertically, and the other is the *two-sided-loop* type, which occurs when the emerging flux appears in closed loop region, producing two-sided loops (or jets). The morphology of these types suggests the reconnection between emerging flux and overlying coronal field and resulting formation of jets (or loop brightenings).

(2) Magnetic field: Shimojo, Shibata, and Harvey (1998) have revealed that the magnetic field properties of the footpoint of jets are mainly mixed polarities or satellite spots. This gives a direct evidence of the presence of neutral points (or current sheets) near the footpoint of jets.

(3) Hα surges: Often Hα surges are associated with X-ray jets (e.g., Shibata et al. 1992b, Canfield et al. 1996), though there are also negative cases (e.g., Schmieder et al. 1995). From observations of Hα surges associated with X-ray jets, Canfield et al. (1996) found several new evidence of reconnection.

(4) Type III bursts: Some X-ray jets are associated with type III bursts (Auras et al. 1995, Kundu et al. 1995). This indicates that high energy electrons are accelerated in these small scale microflare/jet events, suggest-



Yohkoh SXT Image
12-Nov-91 11:30UT

Kitt-Peak Magnetogram
12-Nov-91 16:07UT
(contour Yohkoh SXT)

Figure 5. Left: An X-ray jet observed with 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. Note mixed polarities at the footpoint of the jet.

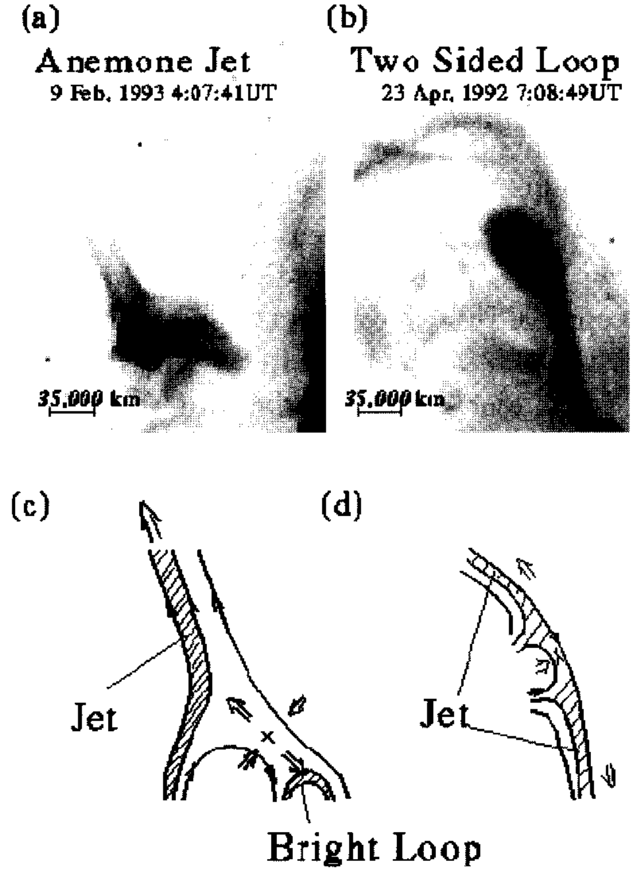


Figure 6. Two types of interaction between emerging flux and overlying coronal fields (from Yokoyama and Shibata 1995).

ing that the same physical process as that of larger flares (i.e., magnetic reconnection) might be occurring in these events.

3.3. MAGNETIC RECONNECTION MODEL: EMERGING FLUX MODEL

Yokoyama and Shibata (1995, 1996) developed magnetic reconnection model of X-ray jets using 2.5D MHD numerical simulations (Fig. 7). In their model, magnetic reconnection occurs in the current sheet between emerging flux and overyling coronal field as in the classical emerging flux model (Heyvaerts et al. 1977, Forbes and Priest 1984, Shibata et al. 1992a). The basic driving force is magnetic buoyancy, though the reconnection rate is not uniquely determined by the rise velocity of emerging flux but affected by the local plasma condition such as the resistivity and dynamics (Ugai 1986, Scholer 1989, Yokoyama and Shibata 1994). Yokoyama and Shibata (1995, 1996) found following interesting features in their simulation results based on the emerging flux model.

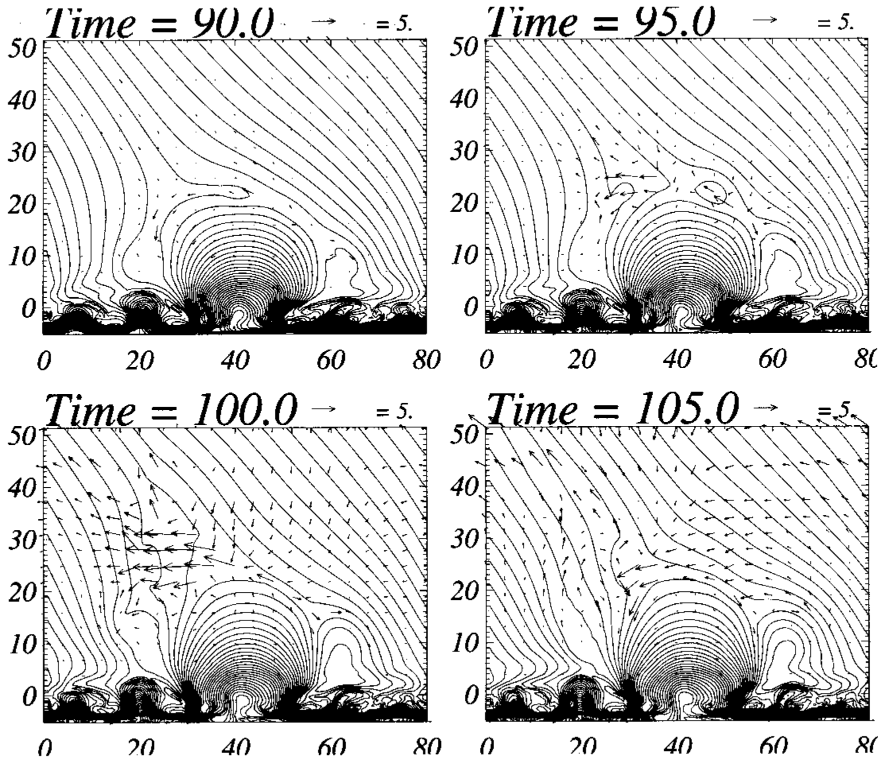


Figure 7. Emerging flux reconnection model of Yokoyama and Shibata (1995, 1996). Note that plasmoids (magnetic islands) are repeatedly created in the current sheet and are ejected upward.

The reconnection starts with the formation of magnetic islands (i.e., plasmoids). (In three dimension, they are seen as helically twisted flux rope.) These islands coalesce with each other and finally are ejected out of the current sheet. After the ejection of the biggest island, the largest energy release occur. The reconnection jets from the X-point soon collides with the ambient field to form fast shocks. The global jets are emanating from the high pressure region just behind the fast shock, and propagate along the reconnected field line. This suggests that *observed X-ray jets are* *not the reconnection jet itself, but hot jets accelerated by the enhanced gas pressure behind the fast shock.*

The emission measure of the X-point is the smallest at the X-point, since the volume of the X-point is very small (Yokoyama and Shibata 1996). Thus the X-point is not bright and hence is not easy to be detected. This may be the reason why we observe a gap between a jet and the brightest part of a footpoint flare. In relation to this, Innes et al. (1997) recently reported interesting observations of bi-directional plasma jets using SOHO/SUMER. They interpreted that these jets corresponded to reconnection jets because the intensity between two jets was largest and hence (they thought) the brightest region corresponded to X-point. However, as discussed above, the X-point cannot be a bright region, and hence it is likely that Innes et al. (1997) observed different phenomena, e.g., bi-directional jets ejected from high pressure region just behind the fast shock.

Yokoyama and Shibata found that not only hot jets ($T > 10^6$ K) but also cool jets ($T \sim 10^4 - 10^5$ K) are accelerated by the J x B force in association with reconnection. The cool jets might correspond to Hα surges associated with X-ray jets (Shibata et al. 1992b, Canfield et al. 1996, Okubo et al. 1996). These cool jets start to be accelerated just before hot jets are formed, and are ejected originally as plasmoids (or helically twisted flux rope in three dimension) and form an elongated structure after the plasmoids collides and reconnects with ambient fields. The initial phase of the ejection of both cool and hot jets are seen as *whip-like motion*. In main phase, the cool jets are situated just side of the hot jets with nearly the same orientation. These features are indeed observed in several Hα surges associated with X-ray jets (Canfield et al. 1996).

Okubo et al. (1996) extended Yokoyama and Shibata (1996)'s simulations to the case in which twisted or sheared magnetic flux emerges to reconnect with overlying field. They found that as a result of reconnection between twisted (sheared) field and untwisted field, shear Alfven waves are generated and propagate along reconnected flux tube. Since these Alfven waves have large amplitude, they excite large transversal motion (or spinning motion) of jets and exert nonlinear magnetic pressure force to cool/hot jets to cause further acceleration of them, as originally suggested by Shibata and Uchida (1986). Canfield et al. (1996) found that all Hα surges (9 events) in his observations showed spinning motion at a few 10 km/s (consistent with prediction from numerical simulation) whose direction is also consistent with the direction of unwinding motion of helically twisted flux tubes observed in the same active region 7260. (Schmieder et al. 1995 and Kurokawa et al. 1987 observed similar spinning motion of surges. See also related numerical simulation by Karpen et al. 1998 on the reconnection between sheared and unsheared fields and resulting formation of cool jets.)

4. Summary: Unified View and Unified Model

As we have seen above, Yohkoh SXT/HXT 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 1.

Table I Unified View of Various "Flares"

"flares"	mass ejections (cool)	mass ejections (hot)
global restructuring (giant arcade)	Hα filament eruptions	CMEs
LDE flares	Hα filament eruptions	X-ray plasmoid ejections/CMEs
impulsive flares	Hα sprays	X-ray plasmoid ejections
transient brightenings (microflares)	Hα surges	X-ray jets

On the basis of this unified view, Shibata (1996, 1997, 1998) proposed a unified model, *plasmoid-induced-reconnection model*, to explain not only LDE fires and impulsive flares but also microflares and X-ray jets.

One may argue, however, that the shape of X-ray jets and Hα 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 is already given by numerical simulations of Yokoyama and Shibata (1995, 1996; Fig. 6); a blob-like plasmoid ejected from the current sheet soon collides with the ambient fields, and finally disappears (Fig. 8). The mass contained in the plasmoid is transferred into the reconnected open flux tube and forms a collimated jet along the tube. In three dimensional space, 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 Hα 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 $t \sim L/V_{plasmoid} \sim 10 - 100$ sec. It would be interesting to test this scenario using high spatial and temporal resolution observations with Doppler shift measurement in a future mission such as Solar B.

Ground based observations suggest that emerging flux plays an important role in driving flares (e.g., Kurokawa 1987, Zhang et al 1998, Nishio et al. 1997, Hanaoka 1997). For example, a famous X-class impulsive flare, the 15 Nov 1992 flare (e.g., Sakao et al. 1992), was driven by a moving satellite spot (or emerging flux). Even the 21 Feb 1992 LDE flare (e.g., Tsuneta 1996), and a homologous to it on 24 Feb 1992 (Morita et al. 1998) seem to be driven by growing flux (or emerging flux) (Zhang et al. 1998). Nevertheless, these flares clearly show filament or plasmoid ejections as well as the morphology predicted by the CSHKP model. Thus there is a need to unify the CSHKP and the emerging flux models. Such a unification is indeed possible in our *plasmoid-induced-reconnection model* as shown in Fig. 8.

Finally, it should be noted that the basic physics of reconnection has not yet been solved. In particular, the ion gyro radius and collisionless skin depth (c/ω_{pe}) in the solar corona ($\approx 10 - 100$ cm), which is a possible minimum thickness of current sheet, is much smaller than the flare size (≈ 10000 km). The gap between these microscopic and macroscopic scales is huge, so that it is difficult to connect microscopic plasma process (such as anomalous resistivity and collisionless reconnection) and macroscopic dynamics. The turbulent (or fractal) current sheet could be a key to connect these vastly different spatial scales (e.g., Tajima and Shibata 1997, Pustlnik 1998).

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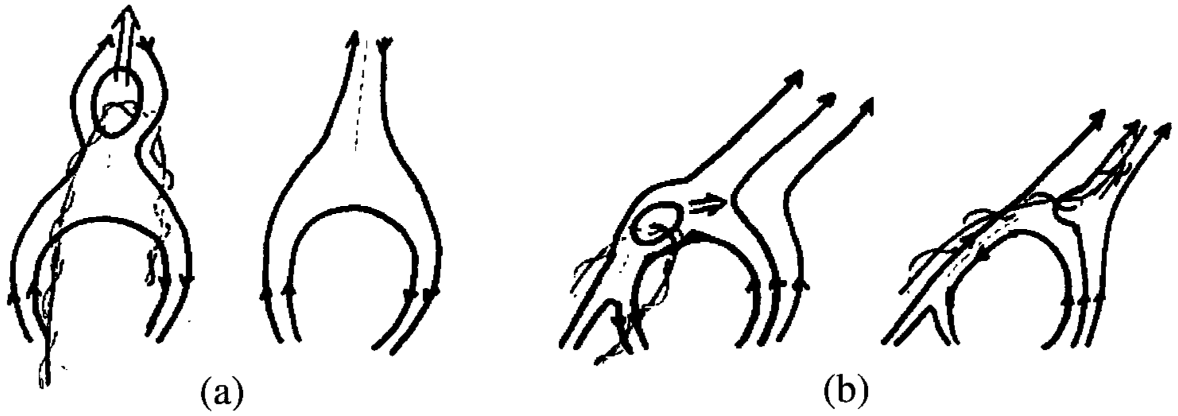

Figure 8. Unification of the CSHKP model (a) and the emerging flux model (b) by the *plasmoid-induced-reconnection* model (Shibata 1997, 1998). Note that a plasmoid (a magnetic island or a helically twisted flux rope) collides and reconnects with the ambient magnetic field to disappear in a short time scale (10 – 100 sec) in microflares.

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