Solar Flares, Jets, and Helicity

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Soft and hard X-ray telescopes aboard Yohkoh have revealed a variety of evidence of magnetic reconnection not only in large scale flares but also in small scale flares and jets. In particular, there is increasing evidence that plasmoid ejections are ubiquitous in flares and play a key role in producing flares. Plasmoids are confined in magnetic islands which are helically twisted tubes or flux ropes in three dimensional space. Thus they are a signature of magnetic helicity. There is also evidence that even small scale jets are consequences of reconnection between untwisted tubes and twisted tubes (plasmoids). Hence, a unified view has emerged on various flares, mass ejections, and jets (ranging from coronal mass ejections to X-ray jets and surges). We propose a unified model in which ejection or expulsion of magnetic helicity (plasmoids) from the system plays a key role to induce fast reconnection and results in violent energy release. In this scenario, what is important is not dissipation of helicity but ejection or expulsion of helicity from the system. It is also proposed that magnetic helicity is first transported by emerging flux (as a buoyant twisted flux tube) to the solar atmosphere and then redistributed to various parts of active regions through reconnection.

1. INTRODUCTION

Solar observers have long thought that there are two types of flares, i.e., long duration event (LDE) flares vs. 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 softer X-ray spectrum. It was also often argued that these two types might be a result of different physical origin.

After the launch of Yohkoh in 1991, it has gradually become clear that there are many common features between these two types of flares. In particular, there is increasing evidence of magnetic reconnection and associated mass ejections, such as X-ray plasmoid ejections and X-ray jets in both types of flares. It is now impossible to classify flares into two types, and we need to develop a unified model of flares.

In this article, we first review these new Yohkoh observations of flares, with emphasis on the evidence of reconnection and mass ejections, and then discuss the role of plasmoids in producing flares. It should be noted here that the *plasmoid* is plasma confined by a *magnetic island* in a two dimensional space, and is a *helically twisted flux rope* in a three dimensional space. Hence it is a signature of *magnetic helicity.* On the basis of Yohkoh observations and numerical simulations, we will discuss the *plasmoid-induced-reconnection model,* in which the ejection of plasmoids (helicity) plays a key

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role to induce flares (fast reconnection). We then review observations of jets associated with small scale flares, such as X-ray jets discovered by Yohkoh and spinning motion of Hα surges, and discuss how these observations can be understood by the reconnection model. Finally, a unified model is presented to account for apparently different plasmoids (from larges scale flares) and jets (from small scale flares) with a unified scheme based on the plasmoid-induced-reconnection model.

2. FLARES

2.1. *LDE Flares vs. Impulsive Flares*

The Yohkoh soft X-ray telescope (SXT) has revealed that many LDE flares show ***cusp-shaped loop or arcade*** structures (Tsuneta et al. 1992, 1996, Forbes and Acton 1996), which are quite similar to the magnetic field configuration predicted by the classical magnetic reconnection model (Carmichael 1964, Sturrock 1966, Hirayama 1974, Kopp and Pneuman 1976). This model, which is hereafter called CSHKP model, predicts that magnetic fields are first opened up by global MHD instability associated with filament (or plasmoid) eruption to form vertical current sheet, and then magnetic field lines in the current sheet succesively reconnect to form apparently growing flare loops with a temperature distribution that outer loops are hotter. There are a number of evidences of magnetic reconnection in these LDE flares, all of which have been predicted by the above reconnection model; (1) The temperature is systematically higher in outer loops. (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 plasmoid ejections are often associated with the rise phase of LDE flares (Fig. 1).

The SXT images of impulsive flares, however, show only ***simple loop*** structures, as already known from Skylab era. Hence it was first thought that these impulsive flares might be created by a different mechanism from that of LDE flares and the magnetic reconnection model was questioned. Masuda (1994a) changed this situation dramatically. He carefully coaligned the SXT and the HXT (hard X-ray telescope) images of some impulsive compact loop flares observed at the limb, and showed that there is an impulsive HXR (hard X-ray) source ***above*** the SXR (soft X-ray) loop in addition to footpoint double HXR impulsive sources (Masuda et al. 1994b, 1995). Since the impulsive HXR sources are produced by high energy electrons and hence are thought to be closely related to the main energy release mechanism, this means that ***the main energy release occurred above (outside) the SXR loop***. It means also that the flare models invoking the energy release mechanism inside the SXR loops (e.g., Alfven and Carqvist 1967, Spicer 1977, Uchida and Shibata 1988) must be discarded at least for these impulsive compact loop flares. Masuda et al. (1994b, 1995) 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 a very hot region as well as high energy electrons.

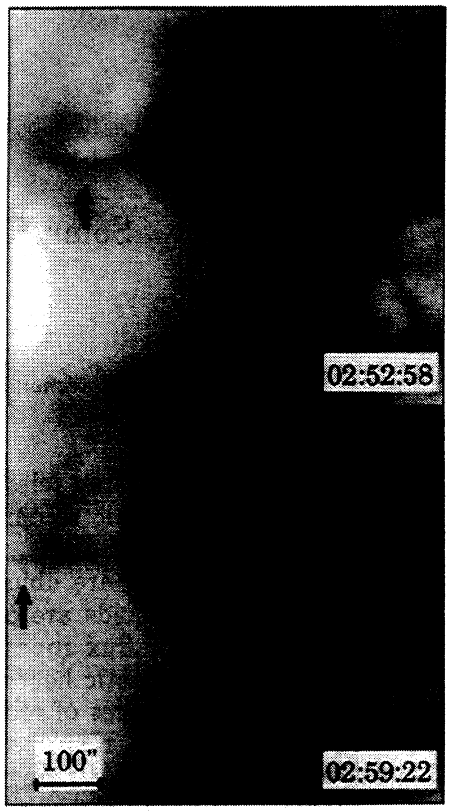

Figure 1. X-ray plasmoid ejections (indicated by an arrow) observed during the rise phase of the LDE flare on 21 Feb. 1992 (Hudson 1994).

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. Shibata et al. (1995) searched for such plasmoid ejections using SXT images in 8 impulsive compact loop flares observed at the limb, which were selected by Masuda (1994a) in an unbiased manner, and indeed found that ***all these flares were associated with X-ray plasma (or plasmoid) ejections***. The apparent velocities 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. 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 (Ohyama and Shibata 1997, 1998, Tsuneta 1997). The shape of these plasma ejections is usually loop-like or blob-like, which is somewhat similar to the shape of CMEs (e.g., Burkepile and St. Cyr 1993).

In many cases, strong acceleration of plasmoids occurs during the impulsive phase (Ohyama and Shibata 1997, 1998; Fig. 2), and the temporal relation between the plasmoid height and the HXR intensity is very similar to that between the CME height and the SXR intensity of an associated flare. Ohyama and Shibata (1997, 1998) also 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 can play a role to trigger the main energy release in impulsive phase, since in some events it is found that the plasmoid starts to be ejected (at 10 km/s) well before the impulsive phase (Fig. 2).

2.3. Plasmoid-Induced-Reconnection Model

On the basis of above observations, Shibata (1996, 1998) proposed the *plasmoid-induced-reconnection model*, by extending the classical CSHKP model. In this model, the plasmoid ejection plays a key role to trigger fast reconnection (see Fig. 3).

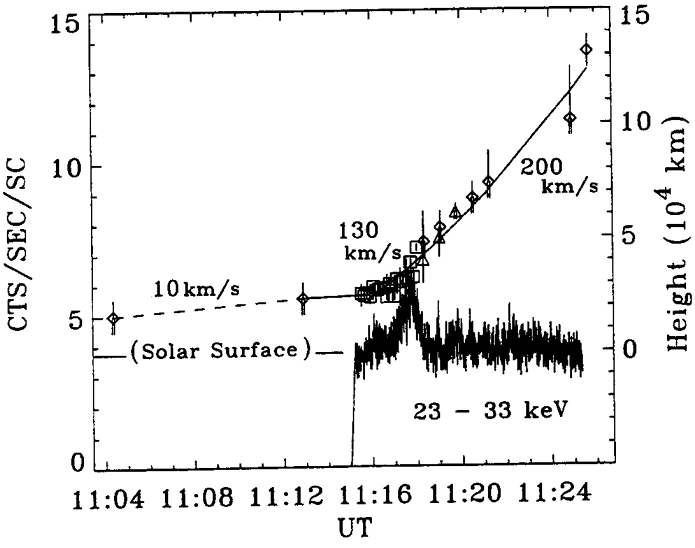

Figure 2. Temporal variations of the height of an X-ray plasmoid and the hard X-ray intensity in an impulsive flare on 11 Nov. 1993 observed by Yohkoh SXT and HXT (Ohyama and Shibata 1997).

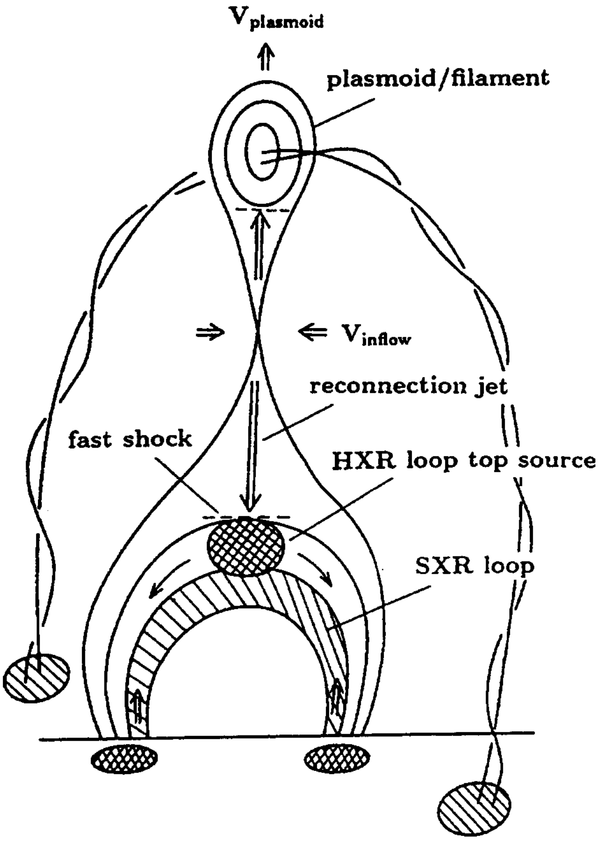

Figure 3. A unified model (*plasmoid-induced-reconnection* model) (Shibata et al. 1995).

Let us consider the situation where a plasmoid suddenly rises at velocity $V_{plasmoid}$. (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 in such a preflare phase as noted by Ohyama and Shibata (1997) even for accelerating plasmoids.) Since the plasma density does not change much during the eruption process, the inflow $V_{inflow} \sim V_{plasmoid}L_{plasmoid}/L_{inflow}$ must develop toward the X-point to compensate the mass ejected by the plasmoid, where $L_{plasmoid}$ and $L_{inflow} (> L_{plasmoid})$ are the typical sizes of the plasmoid and the inflow. We consider that the impulsive phase corresponds to the phase when $L_{inflow} \sim L_{plasmoid}$, i.e., $V_{inflow} \sim V_{plasmoid} \sim$ 50–400 km/s. 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. 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 greatly, leading to slow reconnection which corresponds to the decay phase.

The magnetic reconnection theory predicts two oppositely directed high speed jets from the reconnection point at Alfven speed, $V_{jet} \sim V_A \simeq 2000(B/100\mathrm{G})(n_e/10^{10}\mathrm{cm}^{-3})^{-1/2}$ km/s, where B is the magnetic flux density and n_e is the electron density. The downward jet collides with the top of the SXR loop, producing an 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 $T_{loop-top} \sim m_i {V_{jet}}^2/(6k) \sim 2 \times 10^8 \ (B/100\mathrm{G})^2 (n_e/10^{10}\mathrm{cm}^{-3})^{-1}$ K, 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 1994a). The magnetic energy release rate at the current sheet (with the length of $L_{inflow} \sim L_{plasmoid} \simeq 2 \times 10^4$ km) is estimated to be

$$dW/dt = 2 \times L^2_{plasmoid} B^2 V_{inflow}/4\pi$$

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

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

2.4. Numerical Simulations of Plasmoid Dynamics

Magara, Shibata, & Yokoyama (1997) studied the dynamics of fast reconnection induced by plasmoid ejection during the impulsive phase of flares, peforming 2.5D MHD numerical simulations. They initially assumed a linear force free arcade in a uniform plasma without gravity and added resistive localized perturbation for a finite time. As a result of finite resistivity, a global resistive MHD instability (like the tearing instability) is excited and a thin current sheet is developed in the nonlinear stage of this instability. After some time, the current density increases enormously, so that the anomalous resistivity sets in, leading to fast reconnection (Ugai 1986). They modeled the anomalous resistivity with the formula $\eta = \eta_0(|v_d| - v_c)/v_c$ (if $v_d > v_c$), where $v_d = j/\rho$ is a relative ion-electron drift velocity and v_c is a threshold parameter. The magnetic island (plasmoid) is created as a result of reconnection and is ejected upward after the onset of anomalous resistivity. Figure 4 shows the temporal relation between the height of plasmoid and the reconnection rate ($= E_y = \eta j$), revealing that the plasmoid is accelerated during the phase of large reconnection rate. It is interesting to note that the start of plasmoid acceleration is before the peak of the reconnection rate. If the hard X-ray intensity is a measure of reconnection rate, this figure is very similar to the observed relation between the plasmoid height and the hard X-ray intensity. (In fact, the impulsive hard X-ray intensity is a measure of the total energy release rate (Masuda 1994a). Since the reconnection rate ($\propto$ inflow speed $= v_i$) is also in proportion to the total energy release rate ($dE/dt \propto v_i B^2/4\pi$), this similarity is not a mere chance coincidence.)

What is the mechanism to cause this kind of temporal relation between the plasmoid height and the reconection rate ? Magara et al. (1997) found that the reconnection rate is very small when there is a finite perpendicular magnetic field (B_y) in the current sheet. Only after the ejection of B_y (with a plasmoid), the current sheet can become very thin, so that the anomalous resistivity can set in, leading to large reconnection rate. Hence the perpendicular field (B_y) (or equivalently magnetic helicity) plays a role to inhibit current sheet thinning or collapse, and hence to inhibit fast reconnection.

If the injection of magnetic helicity continues during the preflare slow reconnection phase (i.e., when the fast reconnection is inhibited by the perpendicular field), the excess magnetic energy can be stored around the current sheet. Hence we can say that the plasmoid (helicity) plays a role of energy storage. After the ejection of plasmoid (helicity), the system settles to a lower energy state, and the same process repeats again. Eventually this leads to intermittent plasmoid ejection and associated impulsive energy release. A very nice numerical simulation of this process has been done by Kusano (1998). This explains observed recurrent and homologous behavior of solar flares.

3. JETS

3.1. X-ray Jets

Yohkoh SXT has revealed that mass ejections are also common in tiny flares, called *microflares*, whose total energy is around 10^{-6} (micro-) that of large scale flares. In these microflares, mass ejections often take the form of jets (collimated mass flow), called *X-ray jets* (Shibata et al. 1992b, 1994, 1996, Strong et al. 1992, Shimojo et al. 1996), which are quite different from blob or loop-like plasmoid ejections from large scale flares.

The occurrence frequency of microflares (and also X-ray jets) increases with decreasing their energies, and the distribution function is a power-law (Shimizu 1995), which is basically the same as that of normal flares. From a statistical point of view, it is not possible to classify *microflares* and *flares*. Nevertheless, it seems that X-ray jets tend to be ejected from microflares, whereas blob or loop like plasmoids tend to be ejected from normal flares. Why does this kind of different morphology appear in both type of mass ejections ? What is the difference between jets and plasmoids ?

We will postpone answering these questions until section 4, and now we briefly summarize basic properties of X-ray jets. The length of X-ray jets 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 kinetic energy was estimated to be $10^{25} - 10^{29}$ erg. Figure 5 shows a typical example of X-ray jets.

Many jets show a constant or converging shape, implying the magnetic field configuration with a neutral point near the footpoint of a jet. In some jets (27 percent), a gap is seen between the footpoints of jets and the brightest part of the footpoint flares. This is also nicely explained by the reconnection model (Shibata, Yokoyama, & Shimojo 1996), since the reconnection creates two hot reconnected field lines (a loop and a jet) with a gap between them. Shimojo, Shibata, & Harvey (1998) have examined the magnetic field properties of the footpoint of jets, and found that the footpoints usually correspond to mixed polarities or satellite spots. This is a direct evidence of existence of neutral points or a current sheet at the footpoint of jets.

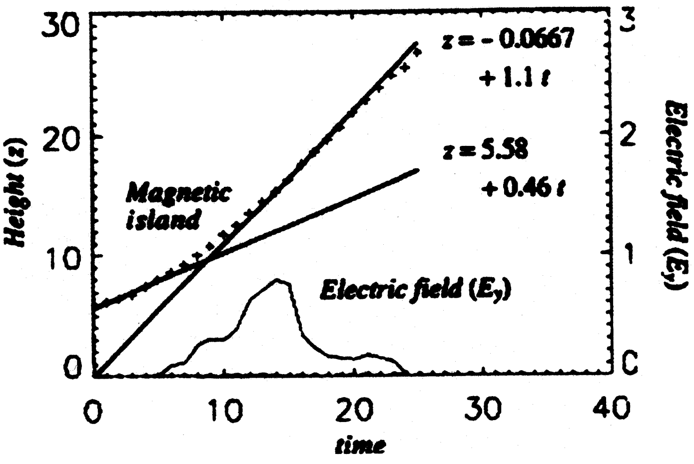

Figure 4. Temporal variations of both the y-component of electric field (E_y) at the neutral point (X-point) and the height of the magnetic island (Magara et al. 1997).

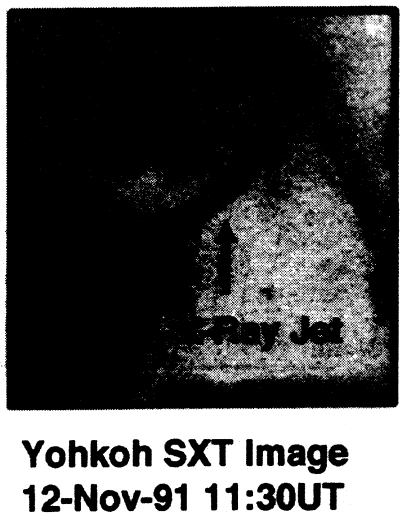

Figure 5. An X-ray jet observed with the Yohkoh/SXT on 12 Nov. 1992 (Shibata et al. 1992b).

3.2. Spinning Motion of Hα Surges

Canfield et al. (1996) studied the relation between Hα surges and X-ray jets and found that all Hα surges (9 events) in their observations are associated with X-ray jets. They found new evidence of reconnection in surges, such as a *moving blue shift* (as evidence of cool plasma accelerated by sling-shot effect) and *converging footpoint motion* (as evidence of a *reconnecting* loop). (Note that diverging footpoint motion is observed in *reconnected* loops.)

Moreover, they found that all Hα surges are spinning at a few 10 km/s with direction consistent with that of unwinding motion of helically twisted flux tubes observed in the same active region 7260 (Leka et al. 1996). Figure 6 shows schematic cartoons of reconnection associated with X-ray jets and Hα surges observed by Canfield et al. (1996), showing how a spinning Hα surge is created as a result of reconnection between a twisted tube and an untwisted tube. Similar observations of spinning jets have been reported by Kurokawa et al. (1987), Schmieder et al. (1995), and Mason et al. (1998).

3.3. Emerging Flux Model

Yokoyama and Shibata (1995, 1996) developed a magnetic reconnection model of X-ray jets using 2.5D MHD

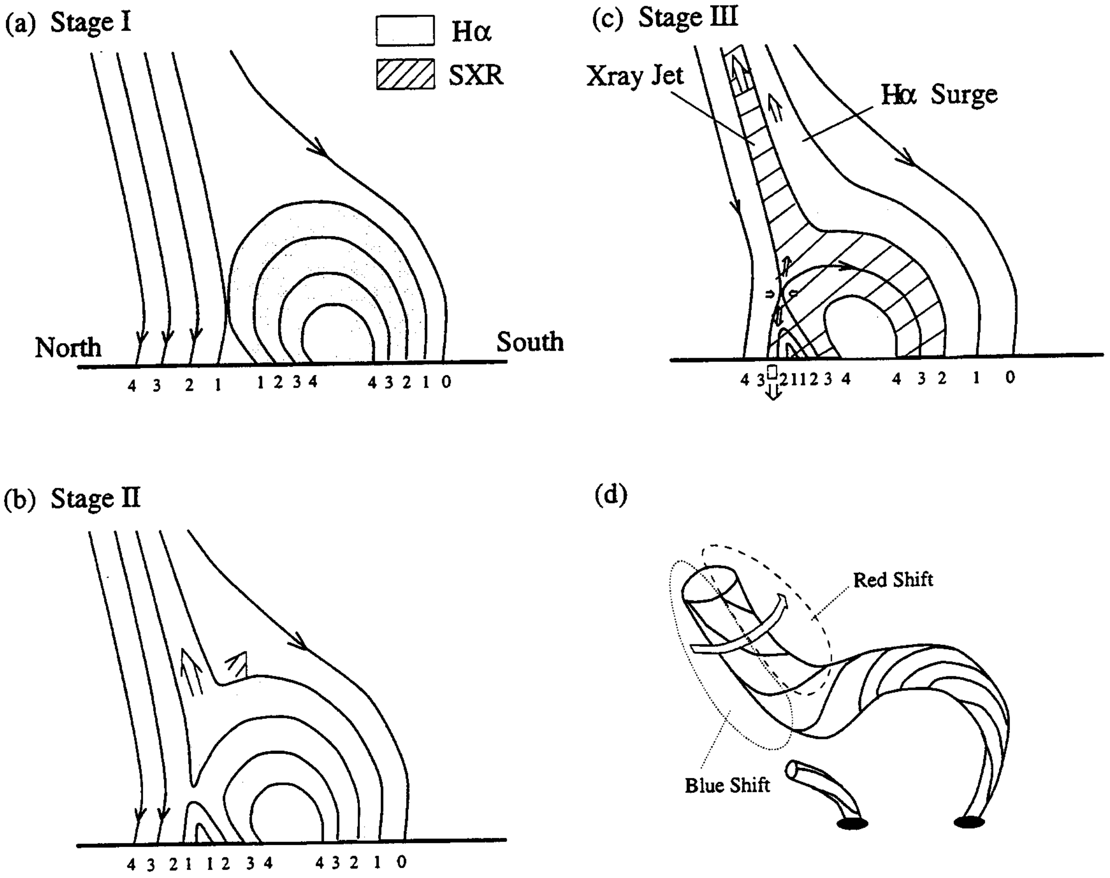

Figure 6. A magnetic twist - reconnection model for Hα surges (Canfield et al. 1996).

numerical simulations. In their model, magnetic reconnection occurs in the current sheet between emerging flux and the overlying coronal field as in the classical emerging flux model (Heyvaerts et al. 1977, Forbes and Priest 1984, Shibata et al. 1992a). They found several interesting features in their simulation results.

The reconnection starts with the formation of magnetic islands (i.e., plasmoids). These islands coalesce with each other and are finally ejected out of the current sheet. After the ejection of the biggest island, the largest energy release occurs. Not only hot jets ($T > 10^6$ K) but also cool jets ($T \sim 10^4 - 10^5$ K) are accelerated by the J×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). These cool jets start to be accelerated just before hot jets are formed, and are ejected originally as plasmoids and form an elongated structure after the plasmoids collides with ambient fields. The initial phase of the ejection of both cool and hot jets are seen as *whip-like motion*. In the main phase, the cool jets are situated just outside 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).

3.4. Generation of Alfven Waves and Helical Jets by Magnetic Reconnection

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 the overlying field (see also Karpen et al. 1998). They found that shear Alfven waves are generated and propagate along the reconnected flux tube, as a result of reconnection between twisted (sheared) field and untwisted field. Since these Alfven waves have large amplitude, they excite large transversal motion (or spinning motion) of jets and exert nonlinear magnetic pressure force on cool/hot jets to cause further acceleration of these jets, as originally suggested by Shibata and

Uchida (1986). More recently, Yokoyama (1998) analyzed this simulation model in detail, and found that (1) the Alfven wave energy flux emitted from the reconnection region is about 3 percent of the total energy released by the reconnection, (2) the frequency spectrum of the Alfven wave is a continuum and includes high frequency modes. These Alfven waves and jets may play an important role in the acceleration of high speed solar wind.

4. UNIFIED MODEL

4.1. Unification of Emerging Flux Model and CSHKP Model

As we have seen above, Yohkoh SXT/HXT observations have revealed evidence of magnetic reconnection, especially in the common occurrence of X-ray mass ejections (plasmoids and/or jets), in LDE flares, impulsive flares, and microflares. These are summarized in Table 1. On the basis of this unified view, Shibata (1996, 1998) 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 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); a blob-like plasmoid ejected from the current sheet soon collides with the ambient fields, and finally disappears (Fig. 7). The mass contained in the plasmoid is transferred into the reconnected open flux tube and forms a collimated jet along the tube. Through this reconnection, magnetic twist (helicity) is injected into the untwisted loop, resulting in the unwinding motion of the 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).

Table I Unified View of Various "Flares"

"flares"	mass ejections (cool)	mass ejections (hot)
giant arcades	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

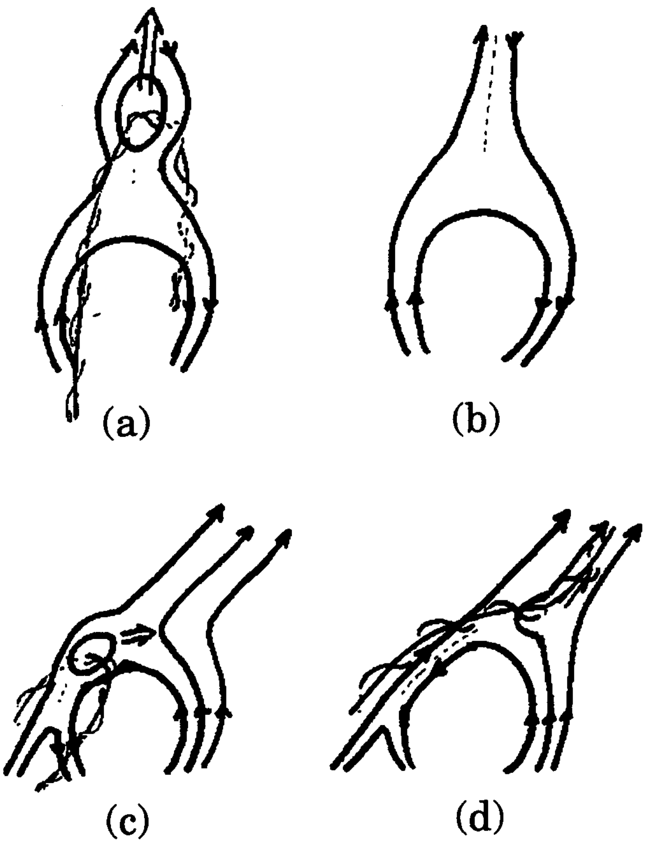

Figure 7. Unification of CSHKP model and emerging flux model by the *plasmoid-induced-reconnection* model (Shibata 1996, 1998). (a), (b): The case of a large scale flare induced by the ejection of a plasmoid. In this case, a cusp-shaped loop is remained after the ejection of the plasmoid. (c), (d): The case of a small scale flare associated with a jet. In this case, 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), generating a jet with unwinding twist (torsional Alfven waves) along global field lines.

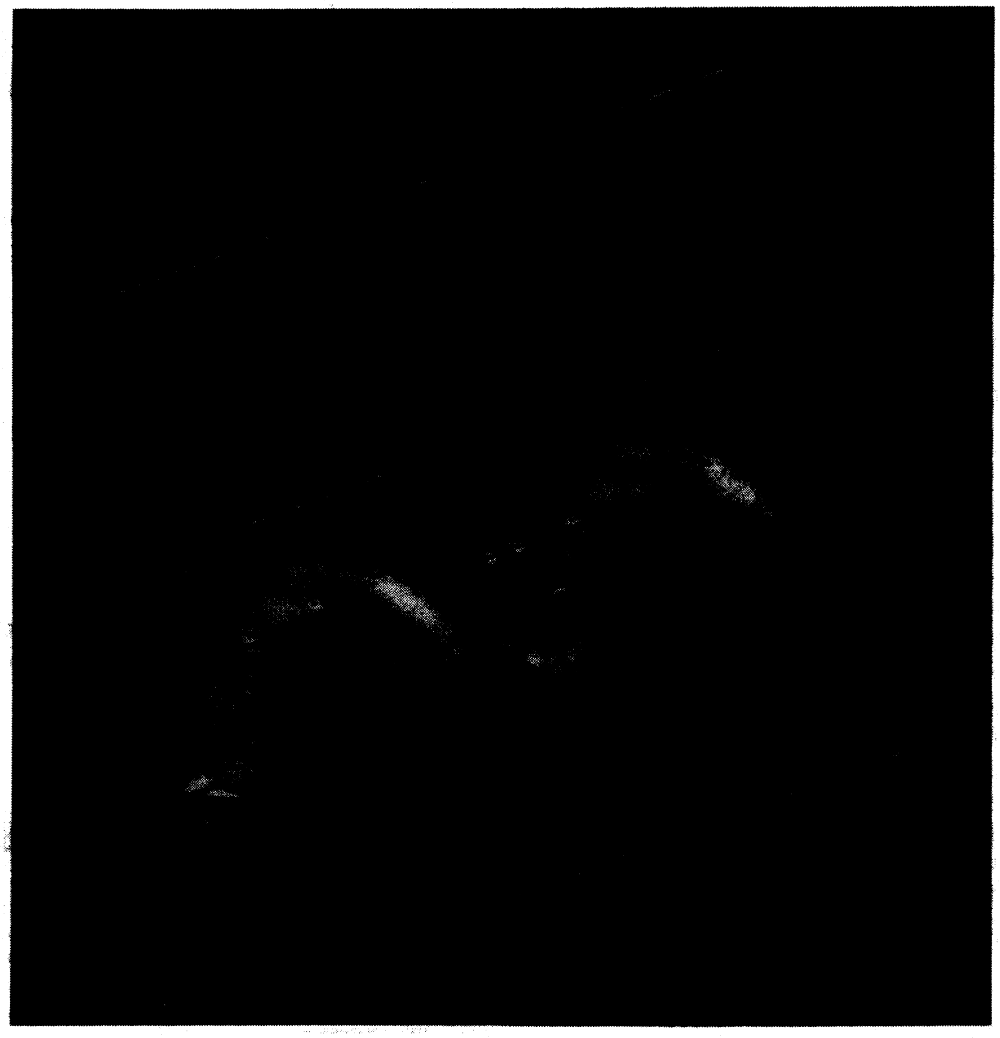

Figure 8. Results of 3D MHD simulation of emergence of twisted flux tubes (Matsumoto et al. 1998). The grey surface shows the isosurface of magnetic field strength, and arrows are velocity vectors. Grey curves show magnetic field lines.

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 future solar mission such as Solar-B.

4.2. Emergence of Twisted Flux Tube

Ground based observations suggest that emerging flux plays an important role in driving flares (e.g., Kurokawa 1987). 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 one 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 if we consider successive emergence of twisted flux tubes and associated reconnection.

Matsumoto et al. (1998) peformed a 3D MHD numerical simulation of emergence of a twisted flux tube, and found that the resulting magnetic flux tube shows the double helix pattern (Fig. 8) and that their results explain various observations such as the peculiar motion of sunspots and the apparent sheared S structure of coronal loops found by Yohkoh. It is well known that such a sheared S structure is an actively flare producing site. From this, there is no doubt that the generation and emergence of twisted flux tubes (i.e., magnetic helicity) and resulting 3D reconnection are one of the central keys to understanding the origin of flares.

Acknowledgments. The author would like to thank R. Matsumoto, M. Ohyama, T. Yokoyama, and M. Shimojo for preparation of figures in this article.

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