# DYNAMICAL PROCESSES IN THE SOLAR CORONA

## – *X-ray Jets and X-ray Plasma Ejections from Impulsive Flares* –

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**Abstract:** *Yohkoh*/SXT discovered *X-ray jets* ejected from microflares and *X-ray plasma ejections* (loop-like or blob-like ejections; the latter are often referred to as *plasmoids*) from impulsive compact loop flares. The fundamental properties of these newly discovered hot plasma ejections are reviewed. A unified scheme based on the magnetic reconnection hypothesis is presented to understand these mass ejections.

## 1. Introduction

*Yohkoh*/SXT (Tsuneta et al. 1991) has revealed that the solar corona is much more dynamic than had been thought; i.e., the corona is full of transient loop brightening (microflares), jets, various mass ejections, and so on. They are important not only for understanding coronal dynamics but also for clarifying coronal heating mechanism and solar wind acceleration mechanism.

In this article, I would like to review the fundamental properties of the newly discovered mass ejections in the corona, i.e., (1) X-ray jets ejected from microflares, and (2) X-ray plasma ejections from impulsive compact loop flares. On the basis of these observations, I will propose that these mass ejections and various flares (microflares, impulsive flares, and LDE flares) can be understood in a unified scheme in which the magnetic reconnection associated with plasmoid ejections plays a key role (Shibata 1996).

## 2. X-ray Jets

X-ray jets have been discovered as transitory X-ray enhancements with apparent collimated motion (Shibata et al., 1992b, 1994a,b, 1996a, Strong et al. 1992, Shimojo et al. 1996a,b). Almost all jets are associated with

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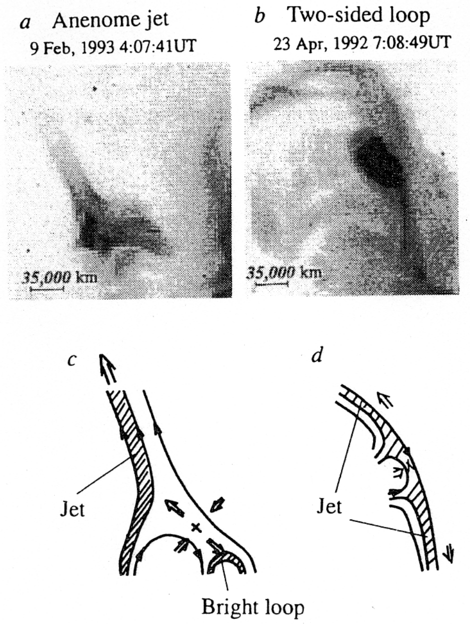

*Figure 1.* SXT images of two types of interaction of emerging flux with overlying coronal magnetic fields. (a) *Anemone-Jet* type observed on 9 Feb. 1993. (b) *Two-sided-loop* type observed on 23 Apr. 1992. Schematic illustration of (c) *Anemone-Jet* type and (d) *Two-sided-loop* type (from Yokoyama and Shibata 1995).

microflares or subflares. The length and the apparent velocity of the jets are $10^3 - 4 \times 10^5$ km and $10 - 1000$ km/s. The number of jets decreases as the length, the width, or the velocity increases. This trend is more clearly seen in the distribution of the lifetimes of the jets; the number of jets decreases as the lifetime increases from 100 sec to 10 hours, and shows a power-law distribution.

According to the preliminary analysis by Shimojo et al. (1996b), the temperature of some small jets in active regions is $4 - 6$ MK and is comparable to that of microflares at the footpoints of the jets. The estimated electron density of the jets ranges from $3 \times 10^8$ cm$^{-3}$ (for larger jets) to $5 \times 10^9$ cm$^{-3}$ (for smaller jets). The kinetic energy is estimated to be of the order of $10^{25} - 10^{28}$ erg. Shimojo et al. (1996a) found that in many jets the width of the jets is nearly *constant* or 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).

Many jets are ejected from emerging flux regions (EFRs) or unresolved X-ray bright points. Shibata et al. (1994b) examined how jets are ejected from well resolved emerging flux region, and found that jets are formed as a result of an interaction between emerging flux and pre-existing coronal magnetic field. There are basically two types of interaction, depending on the place where emerging flux appeared (Fig. 1). One is the case where emerging flux appears in coronal holes and is called the *anemone-jet* type. In this case, a jet is ejected in a vertical direction along open (vertical) coronal field. The footpoint of the jet is usually seen as an anemone-type active region. [1] The other is the case where emerging flux appears in quiet regions and is called *two-sided-loop/jet* type. In this case, two loop brightenings (or jets) occur in the horizontal direction at both sides of the emerging flux.

### 2.1. RELATION TO MICROFLARES

Shibata et al. (1996b) studied the relation between microflares and jets in some emerging flux regions. Figure 2 shows time variation of the total soft X-ray intensity of the active region NOAA 7176 from its birth on 19 May 1992 to 24 May 1992. This region appeared in a coronal hole and showed characteristics of an *anemone-jet* type. The short vertical lines in the figure show the time when the jets are ejected. It is remarkable that more than 20 jets were produced in the 5 days after the birth of the region. It is interesting to note that the emerging flux region began to decay just after ejecting several jets on 21 May, suggesting that the jets might play a role in active region decay. Detailed analysis of SXT images of this region show that all jets during these 5 days were associated with microflares (see sharp spikes in the intensity curve of Fig. 2). On the other hand, the fraction of microflares associated with jets is about 60 percent. Since the probability of detection of jets is not 100 percent because of the limited time cadence of observations, this would suggest that more microflares may be associated with jets.

It should be noted here that these microflares are seen as *transient loop brightenings* in SXT images (Shimizu et al. 1992, Shimizu 1995). From comparison of NSO/Kitt Peak magnetogram with SXT images of many jets, Shimojo et al. (1996b) found that more than 70 percent of X-ray jets are ejected from the mixed polarity regions such as satellite spots embedded in opposite polarity regions. They also found that if the magnetic field is closed, only transient loop brightenings occur even if the magnetic polarity is mixed. This suggests that the transient loop brightenings may be physically the same as X-ray jets as illustrated in Fig. 1.

### 2.2. RELATION TO H$\alpha$ SURGES AND TYPE III BURSTS

Although there are many H$\alpha$ surges which are not associated with X-ray jets (e.g., Schmieder et al. 1995), Shibata et al. (1992b), Canfield et al. (1996a,b), Okubo et al. (1996) found some examples showing both X-ray

[1] According to Sheeley (personal communication 1995), the *anemone type active region* was already discovered by Skylab (Sheeley et al. 1975). It was called *fountain regions.*

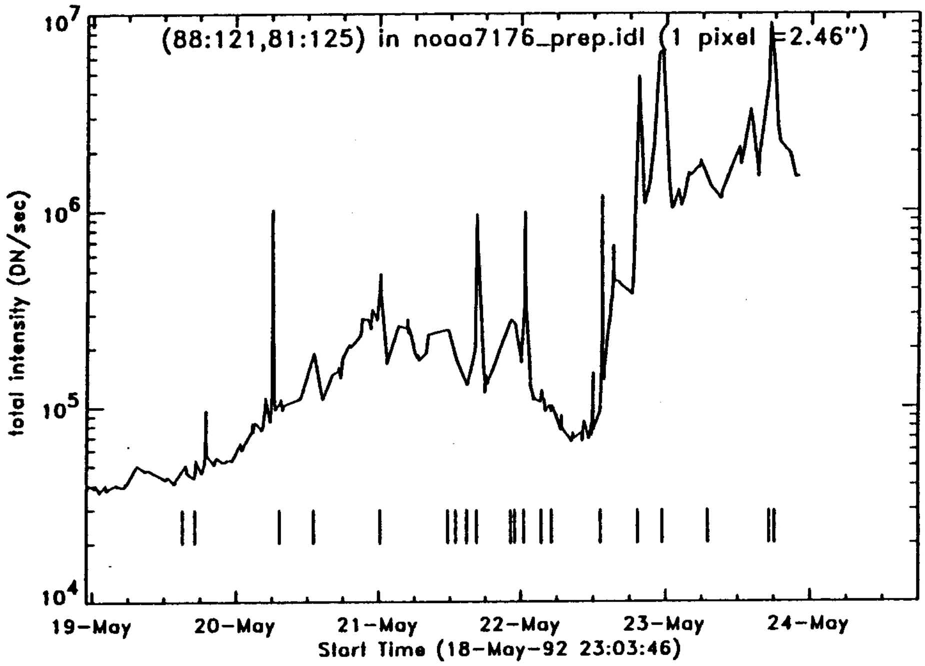

*Figure 2.* Time variation of the total soft X-ray intensity of the active region 7176 from its birth on 19 May 1992 to 24 May 1992 (Shibata et al. 1996b). This region appeared in coronal hole and and showed characteristics of *anemone-jet* type. The short vertical lines in the figure show the time when the jets are ejected.

jets and H$\alpha$ surges in the same direction. Canfield et al. (1996a,b) found several new observational signatures of magnetic reconnection in surges, that is, *converging footpoints* and *moving blue shifts.*

Kundu et al. (1995) found that a Type III burst was associated with an X-ray jet on Aug. 16 1992, and that the density derived from the X-ray jet is consistent with that derived from the Type III burst. The discovery of association with Type III bursts 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. X-ray Plasma Ejections from Impulsive Compact Loop Flares

Masuda et al. (1994, 1995) discovered hard X-ray sources well above the soft X-ray loop in some impulsive flares observed near the limb, and suggested that magnetic reconnection is occurring above the soft X-ray loop. If the reconnection hypothesis similar to the CSHKP model is correct, the plasmoid ejection would be found high above the soft X-ray loop (Hirayama 1991) as illustrated in Figure 4. 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 (around $\sim 10^5$ km) above the hard X-ray source (Figure 3).

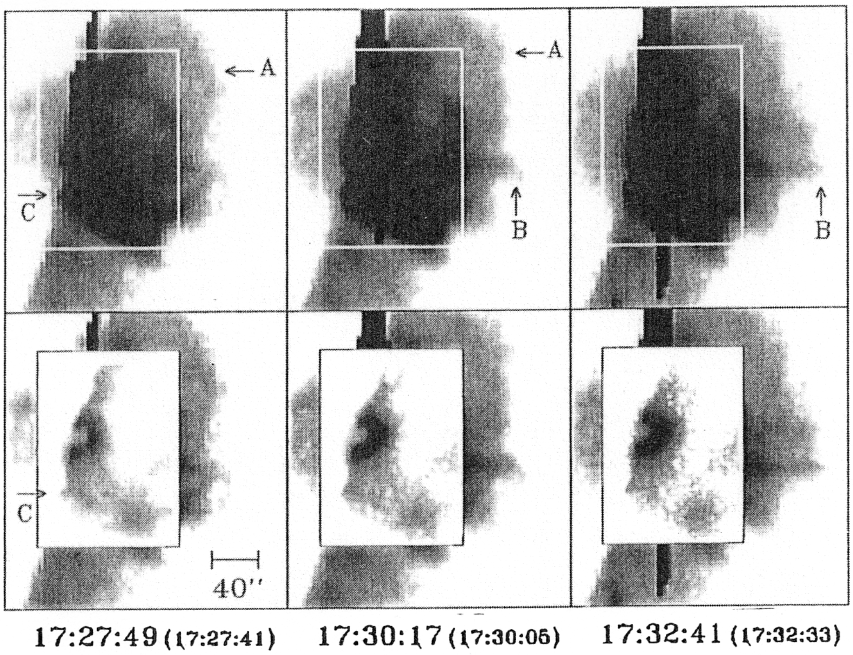

*Figure 3.* Soft X-ray (negative) images of X-ray plasma ejections found in the Masuda flare on 13 Jan. 1992 (Shibata et al. 1995). The upper three shows long-exposure images at 5 arcsec spatial resolution, and the bottom shows short-exposure images at 2.5 arcsec resolution (at nearly the same time) composited on the long-exposure images. The time in the brackets denotes the exact time when the short-exposure images are taken. 40 arcsec correspond to about 29000 km. A careful examination of the long-exposure images revealed at least two very faint erupting features high ($4 \times 10^4 - 8 \times 10^4$ km) above the soft X-ray loop. They are indicated by the arrows A and B; the ejection A seems to be loop-like, and the ejection B looks more like a jet. The velocity of these ejections is about 100 – 150 km/s. The onset of both ejections are nearly simultaneous with the hard X-ray impulsive peak.

Shibata et al. (1995) further surveyed such ejections in 8 impulsive limb flares which were selected in an unbiased manner by Masuda (1995) 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 seen were loop-like, blob-like, or jet-like. It was further found that the range of velocity of the ejections is 50 – 400 km/s. Interestingly, flares with hard X-ray sources well above (5 – 10 arcsec) the loop top show systematically higher ejection velocities. The size of the ejections is typically $(4 - 10) \times 10^4$ km. The soft X-ray intensity of the ejections is $10^{-4} - 10^{-2}$ of the peak soft X-ray intensity in the bright soft X-ray loop. The strong acceleration of the ejections occurs nearly simultaneously with the hard X-ray impulsive peaks (Ohyama and Shibata 1996).

Ohyama and Shibata (1996) analyzed the temperature and emission measure distribution of X-ray plasma ejections in some cases showing bright

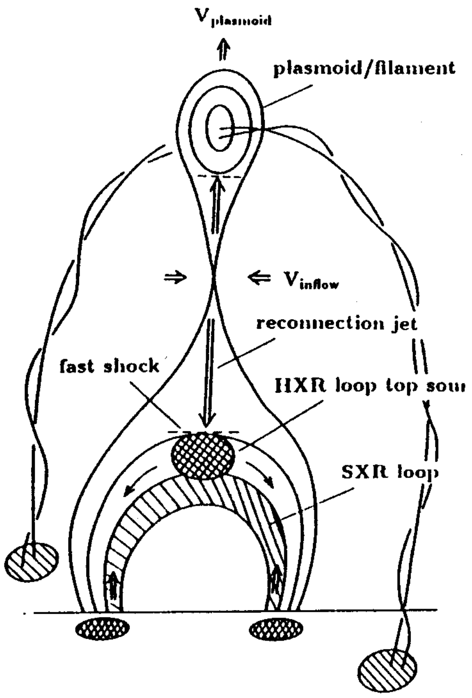

*Figure 4.* A reconnection – plasmoid ejection model for compact loop flares. This is an extension of the CSHKP (Carmichael-Sturrock-Hirayama- Kopp-Pneuman) model of flares (Hirayama 1991, Moore and Roumeliotis 1991). Note that plasmas confined by a closed field (in two dimensions) or by a helically twisted flux tube (in three dimensions) are called *plasmoids*. The cool ($\sim 10^4$ K) plasmas associated with the twisted flux tube is the *filament* or *prominence*. Hot ($> 10^6$ K) plasma ejections are expected to be associated with the twisted tube or expanding loop high above the reconnected (soft X-ray) loop. 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.

blob-like ejections (often referred to as *plasmoids*), and found the following. The temperature of the plasmoids is $\sim 6 - 13$ MK, the electron density is $\leq 1.5 \times 10^{10}$ cm$^{-3}$. The temperature of the plasmoids is less than that of the flare loop. The thermal and kinetic energy of the plasmoid is an order of magnitude smaller than the thermal energy of the soft X-ray flare loop.

## 4. Modeling and Interpretation

Yokoyama and Shibata (1995, 1996a,b, Yokoyama 1995) successfully modeled the two types of reconnection of emerging flux with overlying preexisting magnetic fields (Fig. 1) and the associated formation of X-ray jets and H$\alpha$ surges in each case, by extending the previous numerical simulations (Shibata et al. 1992a). In these models, the reconnection produces not only hot/cool jets but also hot loops (Fig. 1). The latter would correspond to *transient loop brightenings* (Shimizu et al. 1992) and hence a part of the *microflare* process.

These numerical simulations showed that the reconnection proceeds with the formation and ejection of magnetic islands (plasmoids). In the Yokoyama and Shibata model, cool gas confined by magnetic islands eventually become a cool jet (H$\alpha$ surge), and hot gas surrounding an island become a hot jet (X-ray jet). This may be in some sense similar to the X-ray plasma ejection observed in impulsive flares (see Fig. 4 for a model). In fact, Ohyama and Shibata (1996) found that the temperature of the X-ray plasma ejection (plasmoid) is cooler inside than outside. (It should be noted here that the loop-like X-ray plasma ejection such as in Fig. 3 would correspond to a side view of the plasmoid ejection as shown in Fig. 4.) A model for impulsive flares accompanied by the plasmoid ejections has been developed by Magara et al. (1995) (see also Ugai 1989).

Traditionally, the emerging flux model and the CSHKP model have been developed independently to explain *compact loop flares* and *eruptive flares* separately (e.g., Priest 1981). However, the new observations have revealed various common phenomena such as ejection of hot plasmas in various flares (Table I). It is now not easy to classify flares into two classes. In fact, statistical studies show no essential differences between larger flares and microflares (e.g., Shimizu 1995). On the other hand, recent numerical simulations showed also some common physical processes, such as an ejection of plasmoids, in both the emerging flux model and the CSHKP model. Hence, I would like to propose that the flare phenomenon should be understood in a unified scheme in which the ejection of plasmoids plays a key role in triggering fast reconnection.

TABLE 1. Unified View of Various Mass Ejections from Flares

| Hot Mass Ejections | Cool Mass Ejections | Flares |
|---|---|---|
| X-ray jets | H$\alpha$ surges | microflares |
| X-ray plasma ejections | sprays or H$\alpha$ filament eruptions | impulsive flares |
| CME | H$\alpha$ filament eruptions | LDE flares or giant arcades |

## 5. Conclusions

Conclusions are summarized in the following.

(1) Both *X-ray jets* and *transient loop brightenings* are part of microflares. In open field regions, X-ray jets and loop brighenings are formed, whereas in closed field regions, only loop brightenings occur.

(2) Various observational signatures of reconnection have been found in X-ray jets and H$\alpha$ surges. These are successfully modeled by Yokoyama (1995) and Yokoyama and Shibata (1995, 1996a,b).

(3) Discovery of X-ray plasma ejections in impulsive flares gives us further evidence of reconnection (in addition to the Masuda's loop top HXR source) and leads to a unified view of mass ejections in flares (Table I).

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