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ROLE OF PLASMOID EJECTIONS IN FLARE ENERGY RELEASE

Kazunari Shibata

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Solar Physics Division
National Astronomical Observatory
Mitaka, Tokyo 181, Japan

Solar Group of Nobeyama Radio Observatory
National Astronomical Observatory
Nobeyama, Minamisaku, Nagano 384-13, Japan

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Kazunari Shibata
National Astronomical Observatory
Mitaka, Tokyo 181, Japan

ABSTRACT

Recent *Yohkoh* observations of flares have shown various evidence of magnetic reconnection and associated plasma (possibly plasmoid) ejections. On the basis of these observations and recent numerical simulations, we discuss a unified view of the flare energy release mechanism in which plasmoid ejections play a key role to induce fast magnetic reconnection. (Note that a plasmoid is seen as a *helical* or *sheared magnetic field* in three-dimensional space.) We suggest that even small-scale flare events, such as microflares and X-ray jets, might be produced by the reconnection associated with the plasmoid (sheared field) ejection, that occurs in various current sheets, e.g., those produced by emerging flux. A *fractal current sheet* consisting of many magnetic islands (plasmoids) of various sizes is proposed to explain fast reconnection in flares.

1. INTRODUCTION

Recent numerical simulations of magnetic reconnection with high spatial resolution have revealed that nonsteady processes such as *tearing, coalescence, and ejection of plasmoids (magnetic islands)* are fundamental processes in fast magnetic reconnection at high magnetic Reynolds number (e.g., Lee and Fu 1986, Ugai 1989, Shibata et al. 1992a, Biskamp 1994, Yokoyama and Shibata 1994). Since the magnetic Reynolds number in the solar corona is extremely high $\sim 10^{13}$, a highly nonsteady, intermittent reconnection is expected to occur in the solar corona. It is hence natural to consider that the highly nonsteady and recurrent behavior of solar flares is a manifestation of the fundamental nature of fast reconnection.

Recent observations of flares with the *Yohkoh* soft X-ray telescope (SXT) and hard X-ray telescope (HXT) have revealed various evidence of reconnection (Shibata 1996), such as *cusp geometry, hot cusp loop* (e.g., Tsuneta et al. 1992, 1996, Hanaoka et al. 1994, Hiei et al. 1996), *loop top hard X-ray source (fast shock ?)* (Masuda et al. 1994, 1995), and *change in topology* associated with X-ray jets (Shibata et al. 1992b, 1994a,b).

In this article, I review *Yohkoh* observations of various mass ejections, and argue that these mass ejections are indeed the *plasmoid ejection* expected from the reconnection theory (Fig. 1). I then propose a new model of fast reconnection suitable for solar flare energy release, on the

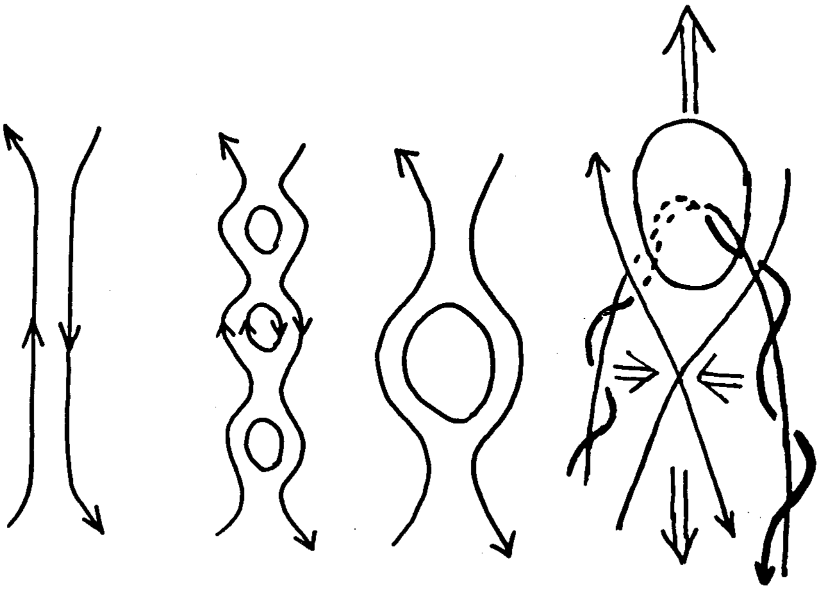

Figure 1. Current sheet formation, tearing, coalescence, plasmoid ejection, and triggered fast reconnection at high magnetic Reynolds number, which have been revealed by numerical simulations (e.g., Lee and Fu 1986, Ugai 1989, Shibata et al. 1992a, Biskamp 1994, Yokoyama and Shibata 1994). Note that in a three-dimensional space, the plasmoid would be seen as a helically twisted loop or filament. The eruptive prominence observed in Hα is a kind of plasmoid ejection.

basis of both observations and numerical simulations, and discuss that the plasmoid ejection might be a necessary key physical process for fast reconnection. I also argue that a lack of observation of plasmoids does not necessarily mean no actual plasmoid ejection, and try to explain the reason why many flares are apparently observed *without* plasmoid ejections.

2. X-RAY PLASMOID EJECTIONS IN LDE AND IMPULSIVE FLARES – YOHKOH OBSERVATIONS –

2.1. LDE FLARES

Although no systematic study has been done for LDE (long duration event) flares until now, plasmoid ejections (or hot plasma ejections) have been found in some LDE flares with the *Yohkoh* SXT (e.g., Hudson 1994, Hiei et al. 1997). According to those studies, the velocity of hot plasma ejections was of the order of 50 – 300 km/s. Their shape was either *ovoid* (e.g., 21 February 1992 LDE flare [Hudson 1994]), *concave-outward bright* (e.g., 24 January 1992 helmet streamer event [Hiei et al. 1997]), or *helical loop* (e.g., 28 August 1992 LDE flare). Interestingly, these shapes were similar to those of some coronal mass ejections (Webb and Cliver 1995). It is also interesting to note that the acceleration of the ejections was almost simultaneous with the flare rise phase (cf. Kahler et al. 1988, Harrison 1995).

2.2. IMPULSIVE FLARES

Masuda et al. (1994, 1995) discovered a hard X-ray source well above the soft X-ray loop in some impulsive flares observed near the limb, and suggested that magnetic reconnection occurs above the soft X-ray loop. If the reconnection hypothesis similar to the CSHKP (Carmichael-Sturrock-Hirayama-Kopp-Pneuman) model is correct, the plasmoid ejection would be found high above the soft X-ray loop (Hirayama 1991) as illustrated in Figure 2. Shibata et al. (1995) searched for such plasmoid ejections in the Masuda flare on 13 Jan. 1992, and indeed discovered X-ray plasma ejections high ($\sim 10^5$ km) above the hard X-ray source.

Shibata et al. (1995) further surveyed such ejections in 8 impulsive limb flares which were

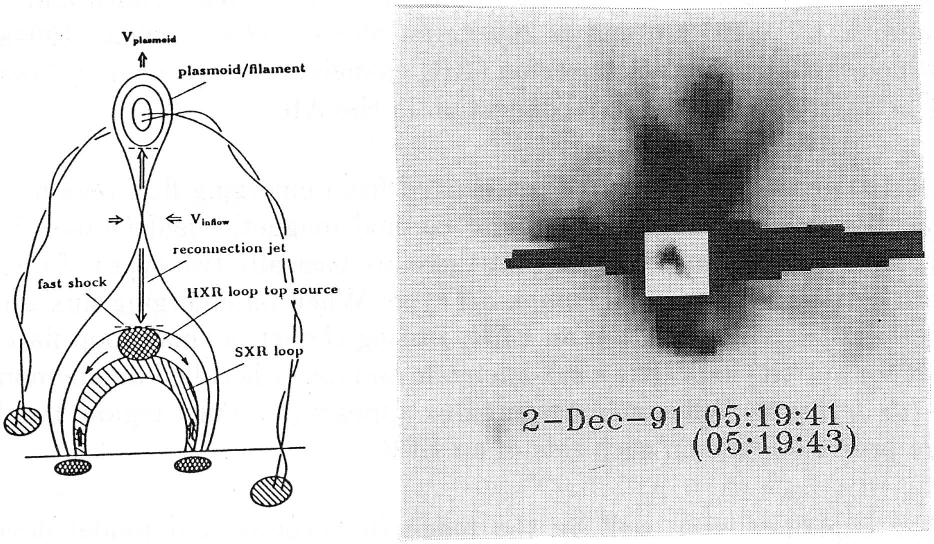

Figure 2. (a) A reconnection – plasmoid ejection model for compact loop flares. This is an extension of the CSHKP (Carmichael-Sturrock-Hirayama-Kopp-Pneuman) model of flares (Hirayama 1991, Moore and Roumeliotis 1991). The cross-hatched region at the footpoints of the soft X-ray loop shows the bright 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. (b) The SXT image of the plasmoid ejection in the 2 Dec 1991 flare. North is to the right, and west is to the top. The short exposure image of the flare loop itself taken at full resolution (2.5") is composited on the long exposure image at quarter resolution (10"). The size of the main flare loop is 1.6 x 10^4 km, and the height of the plasmoid is about 16 x 10^4 km. Note that a faint loop extending from near the plasmoid is connected to the footpoint far from the flare loop, which is similar to the model shown in (a).

selected in an unbiased manner by Masuda (1994) with the following two selection criteria: (1) The peak count rate in the HXT M2-band (33 – 53 keV) exceeds 10 cts/s/subcollimator. (2) The heliocentric longitude exceeds 80 degrees. It is remarkable that plasma ejections were found in all 8 impulsive limb flares. The ejections were seen as *loop*-like (e.g., 13 January 1992 = the Masuda flare, 4 October 1992), *blob*-like (e.g., 17 February 1992, 2 December 1991 [Fig. 2], 5 October 1992 [Ohyama and Shibata 1996]), or *jet*-like (e.g., 13 January 1992). The range of velocity of the ejections was 50 – 400 km/s. Interestingly, flares with hard X-ray sources well above (5 – 10 arcsec) the loop top showed systematically higher ejection velocities. The size of the ejections was typically (4 – 10) $\times 10^4$ km. The soft X-ray intensity of the ejections was 10^{-4} – 10^{-2} of the peak soft X-ray intensity in the bright soft X-ray loop. The strong acceleration of the ejections occurred nearly simultaneously with the hard X-ray impulsive peaks (Ohyama and Shibata 1996).

Ohyama and Shibata (1996) analyzed the temperature and emission measure distribution of the blob-like X-ray plasma ejection (hereafter referred to as a *plasmoid*) in the 5 October 92 flare, and found the following. The temperature of the plasmoid was $\sim 6 - 13$ MK, the electron density was $\sim 8 - 15 \times 10^9$ cm^{-3}. The temperature of the plasmoid was lower than that of the region between the plasmoid and the flare loop, consistent with the reconnection model. The thermal and kinetic energy of the plasmoid was an order of magnitude smaller than the thermal energy of the soft X-ray flare loop; e.g., $E_{kin} \leq 10^{28}$ erg $\ll E_{th}(flare) \sim 10^{30}$ erg in the case of the 5 October 1992 flare. This indicates that the kinetic energy of the plasmoid ejection cannot be a source of the flare energy.

3. X-RAY JETS – PLASMOID EJECTIONS IN MICROFLARES ?

Yohkoh/SXT has revealed that X-ray jets (Shibata et al. 1992b, 1994a, Strong et al. 1992) are often ejected from microflares (Shimizu et al. 1992). Here X-ray jets are defined as transitory

X-ray enhancements with an apparent collimated motion (Shibata et al. 1992b). Shimojo et al. (1996) studied statistical properties of jets, and found that the average length and (apparent) velocity of jets were $\simeq 1.7 \times 10^5$ km and $\simeq 200$ km/s. Shibata *et al.* (1992b, 1994a,b) found several cases in which the footpoint active region (AR) changed its shape or morphology during a jet, which may be indirect evidence of reconnection in the AR.

Shibata *et al.* (1994b) noted that jets are often ejected from emerging flux regions (EFRs) as a result of interaction between emerging flux and coronal magnetic field (some of which are clearly seen in the SXT full Sun movie), and that there are basically two types of interaction of emerging flux with coronal fields: (1) *Anemone-Jet* type: When an emerging flux appears in a coronal hole, a vertical jet is ejected from an EFR. During the jet, a small loop flare occurs in the EFR. An EFR (or an AR) looks like a sea-anemone and hence is called an anemone-AR. (2) *Two-Sided-Loop (or Jet)* type: When an emerging flux appears in a quiet region, two horizontal jets (or loops) are produced, one on each side of an EFR.

These features are explained very well by the magnetic reconnection model developed by Yokoyama and Shibata (1994, 1995, 1996). They performed two-dimensional MHD numerical simulation of reconnection between emeriging flux and the coronal field, extending the previous simulations by Shibata *et al.* (1992a). As discussed in the Introduction, their results show that the nonsteady processes, such as *tearing*, *coalescence*, and *ejection of the islands (or plasmoids)*, occur in the small-scale current sheet formed between emerging flux and the overlying coronal field. The physics of ejection of islands (or plasmoids) is quite similar to that seen in the larger eruptive flares.

Yokoyama and Shibata (1995) found that a cool jet is also produced at the same time when a hot jet is ejected. They interpreted the hot jet as corresponding to the X-ray jet found by *Yohkoh* and the cool jet as corresponding to Hα surges. Indeed, Canfield et al. (1996) found 8 cases in which both Hα surges and X-ray jets are ejected nearly simultaneously in the same direction (see also Okubo et al. 1996). One of the most interesting common features found by Canfield et al. for these surges was the *spinning motion of the surges*, which suggests an unwinding of the magnetic twist after the reconnection between a twisted flux tube and an untwisted one. Such an unwinding motion is often seen in Hα filament eruption.

Consequently, we may say that the relationship between X-ray jets and Hα surges is, in some sense, similar to that between X-ray plasmoid ejections and Hα filament eruption, and hence we suggest that X-ray jets and Hα surges correspond to hot and cool plasmoids, respectively.

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) ? One answer has already been given by numerical simulations of Yokoyama and Shibata (1995, 1996); a blob-like plasmoid ejected from the current sheet soon collides with the ambient magnetic fields. The magnetic island confining the plasmoid then reconnects with the ambient fields, and finally disappears (Fig. 3). 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 (Shibata and Uchida 1986).

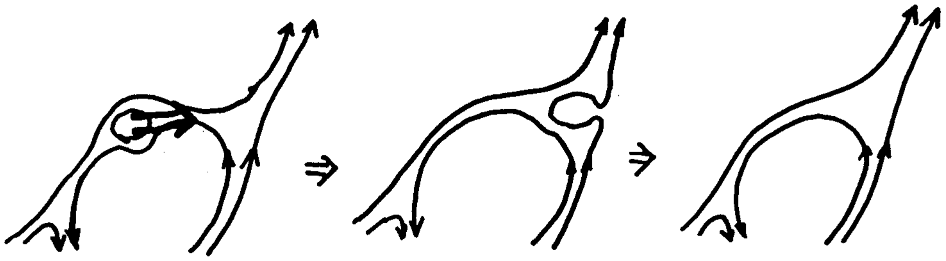

Figure 3. **Why are plasmoid ejections not always observed ? This is because a plasmoid (magnetic island) reconnects with ambient magnetic fields, and soon disappears. The lifetime of the plasmoid (or loop) ejection is very short, only of order of $t \sim L/V_{plasmoid} \sim 10 - 100$ sec in microflares.**

This explains why we usually do not observe plasmoid-like (or loop-like) mass ejections in smaller flares (e.g., microflares). That is, in smaller flares, the current sheet length is short, so that a plasmoid (a magnetic island) soon collides with an ambient magnetic field to reconnect with it and disappear. Hence the lifetime of the plasmoid (or loop-like) ejection is very short, of the order of $t \sim L/V_{plasmoid} \sim 10 - 100$ sec.

4. ROLE OF PLASMOID EJECTIONS IN FAST RECONNECTION

4.1. CURRENT SHEET COLLAPSE INDUCED BY PLASMOID EJECTION

Yohkoh observations have revealed various evidence of magnetic reconnections in flares, and also that the plasmoid ejections are much more common in flares than had been thought. What is a role of plasmoid ejections ?

Observations show that the kinetic energy of plasmoid ejections is not sufficient to account for the total energy of flares. On the other hand, it has been revealed that the strong acceleration of the plasmoid ejection occurs during the rise or impulsive phase of flares. Does this suggest that the plasmoid ejection is simply a biproduct of the impulsive energy release in the fast reconnection ? In this regard, we have to remember that many observations of flares associated with Hα prominence eruption show that the prominence eruption (plasmoid ejection) begins well before the impulsive phase of flares, though the velocity is small before the impulsive phase. This is also true for some X-ray plasma ejections. We suggest that the plasmoid ejection plays the role of a trigger for fast reconnection; the ejection of a plasmoid helps faster reconnection and associated impulsive energy release, while the released energy helps further acceleration of the plasmoid and resulting faster reconnection, and vice versa.

Is this kind of process physically possible ? Let us consider a current sheet with a plasmoid (magnetic island) inside it (Fig. 1). Apparently, the plasmoid inhibits the reconnection. Only after the plasmoid has been ejected out of the current sheet, will the reconnection become possible. Once the reconnection has begun, the released energy helps the acceleration of the plasmoid. If the plasmoid speed increases, then the speed of the inflow into the neutral point will also be increased. Since the inflow speed determines the reconnection rate, this means that the ultimate origin of fast reconnection is the fast ejection of the plasmoid.

This process can be understood as a collapse of a current sheet after the ejection of a plasmoid

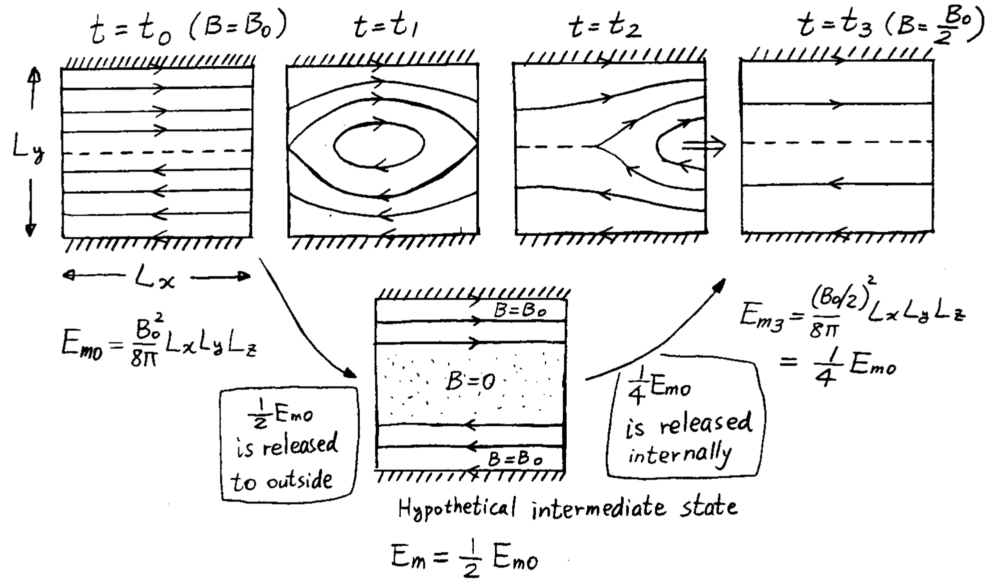

Figure 4. Detailed processes during the collapse of a current sheet accompanied by the ejection of a plasmoid. It is assumed here that a half of initial magnetic flux is reconnected to form a plasmoid ($t = t_1$). After the ejection of the plasmoid ($t = t_2$), the current sheet collapse occurs; i.e., the remaining magnetic flux expands to compress the current sheet. At the final stage ($t = t_3$), magnetic field strength decreases to a half of the initial value, and the magnetic energy in the box (E_{m3}) is one forth of the initial magnetic energy ($E_{m3} = E_{m0}/4$, where E_{m0} is the initial magnetic energy contained in the box). This process and the effect of the collapse of the current sheet is more easily understood if we consider a hypothetical intermediate state between the ejection of the plasmoid and the collapse; i.e., the state in which a half of the initial magnetic flux is removed out but the remaining flux has not yet expanded. After this hypothetical state, the remaining flux expands to fill the box. This process (i.e., the current sheet collapse) releases *one forth of the initial magnetic energy.* It is interesting to note that this is an ideal MHD process. Hence even if the reconnection is inhibited after the ejection of the plasmoid, we can expect that one forth of the initial magnetic energy is released by the collapse of the current sheet.

(see Fig. 4). One important point is that the collapse itself is an ideal MHD process and the energy released during the collapse is non-negligible; indeed it amounts to one fourth of the magnetic energy stored in the original current sheet in the case of a simple model illustrated in Figure 4. In this case, once a large plasmoid has been ejected, at least one fourth of the magnetic energy contained around the plasmoid will be released even if the reconnection is inhibited after the ejection. Actually, the strong inflow due to the collapse induces fast impulsive reconnection, followed by a slow reconnection phase corresponding to the growth phase of plasmoid, and vice versa, leading to intermittent fast reconnection (and plasmoid ejection). Each cycle (ejection of a plasmoid and triggered fast reconnection) may correspond to a different impulsive HXR/microwave peak in a flare with multiple peaks.

4.2. FRACTAL CURRENT SHEET

It should be noted here that we have not yet reached a definite answer on the origin of resistivity necessary for reconnection. Since the ion Larmor radius in the corona is $\sim$ 100 cm, the current sheet width has to be of the order of $\sim$ 100 cm (!) in order to excite anomalous resistivity. This is a very unlikely situation because the flare size is $\sim 10^9$ cm, and hence the length of the current sheet is expected to be of the order of 10^9 cm. Is it possible to have such a long, thin current sheet with a large aspect ratio, 10^9cm/100cm $\sim 10^7$? This is a fundamental puzzle in the solar flare problem.

This puzzle might be solved if we consider nonsteady processes (in the current sheet) discussed in the Introduction, i.e., tearing, coalescence, and ejection of islands. Those processes are highly

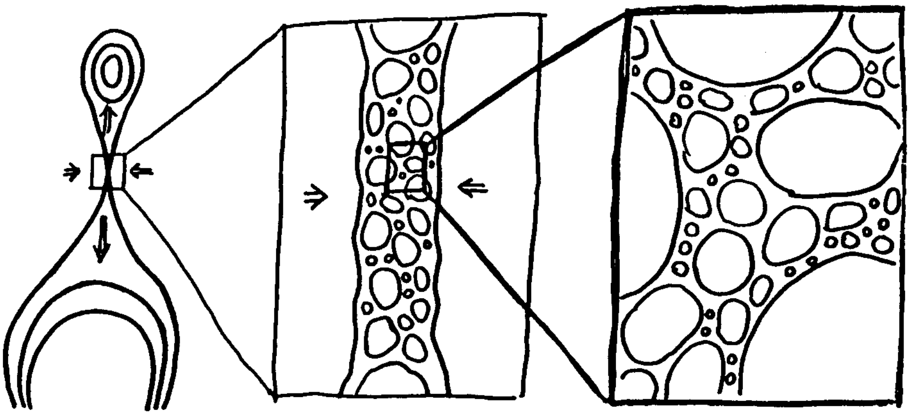

Figure 5. Fractal Current Sheet (Tajima and Shibata 1997).

nonsteady and intermittent (Biskamp 1994), and produce turbulent and fractal structures in the current sheet (Fig. 5; Tajima and Shibata 1997). Hence a macroscopic current sheet may have a fractal structure with a size ranging from the ion Larmor radius ($\sim$ 100 cm) to the current sheet length ($\sim 10^9$ cm), enabling succesive reconnection on the Alfven time scale. This may be the real nature of anomalous resistivity.

5. CONCLUSIONS

1. *Yohkoh* SXT found X-ray plasmoid ejections in both LDE flares and impulsive flares. The rate of association was higher than that of Hα prominence eruption with flares.
2. In both LDE and impulsive flares, the velocity of plasmoids was typically 50 – 400 km/s. This is much smaller than the Alfven speed in the corona. One possible reason for this low velocity of plasmoids may be their high density (Magara et al. 1996).
3. Strong acceleration of plasmoids occurred during the rise or impulsive phase of flares.
4. In the case of microflares, some of the X-ray jets may be hot plasmoid ejections, and Hα surges may be cool plasmoid ejections.
5. One important reason why plasmoids are not always observed in flares is their *short life time* due to reconnection with ambient fields.
6. Plasmoid ejections can trigger fast reconnection, by collapsing the current sheet after their ejection.
7. Plasmoids (magnetic islands or current filaments) have a *fractal nature*, and thus can create very small-scale current filaments. This enables the onset of anomalous resistivity either due to kinetic effects or due to macroscopic MHD turbulence.

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