Plasmoid-Induced-Reconnection Model of Flares

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ABSTRACT

We propose the *plasmoid-induced-reconnection model*, which is an extention of the CSHKP model but includes the following points as essential ingredients of nonsteady fast reconnection; plasmoid formation and ejections are not simple biproducts of reconnection, but play essential role to store energy (by inhibiting reconnection in preflare phase) and to induce strong inflow into reconnection region (by ejecting huge amount of plasma in impulsive phase). We found a simple analytical solution for the dynamics of a plasmoid when the plasmoid is accelerated by the momentum of a reconnection jet. The solution has a property of ***nonlinear instability*** (i.e., exponential growth in time); in this process, the plasmoid motion is closely coupled with the reconnection, and hence ***both plasmoid ejection and reconnection are equally important to cause flares.*** It is stressed that the plasmoid-induced-reconnection model naturally explains both large and small scale flares, forming a basis of a unified model of flares.

1. Introduction

Yohkoh has revealed various evidence of magnetic reconnection, such as cusps, arcades, loop top hard X-ray (HXR) sources, and so on. (e.g., Tsuneta et al. 1992, Hanaoka et al. 1994, Masuda et al. 1994, Forbes and Acton 1996). As has been predicted by some pioneers (Hirayama 1991, Moore and Roumeliotis 1992), it has also been revealed that the association of mass ejection with flares is much more common than had been thought (e.g., Shibata et al. 1995, Ohyama and Shibata 1997, 1998, Tsuneta 1997), leading to a unified view and a unified model of flares (e.g., Shibata 1996, 1997a,b).

In this paper, we discuss the plasmoid-induced-reconnection model (Shibata 1997a,b) as a basis of a unified model of flares, and examine the mechanism how a plasmoid ejection induces fast reconnection, using semi-analytical approach.

2. Plasmoid-Induced-Reconnection Model

On the basis of observations of X-ray plasmoid ejections from compact impulsive flares (Shibata et al. 1995, Ohyama and Shibata 1997), Shibata (1996, 1997a,b) proposed the *plasmoid-induced-reconnection model*, by extending the clas-

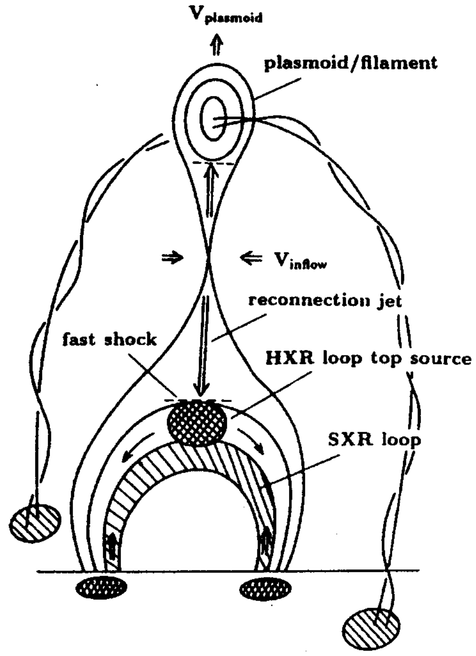

Fig. 1.— A unified model (plasmoid-indued-reconnection model) of flares (Shibata et al. 1995).

sical CSHKP model. In this model, the plasmoid ejection plays a key role to trigger fast reconnection (Fig. 1). There are basically two roles of a plasmoid in triggering fast reconnection.

First, a plasmoid can store energy by inhibiting reconnection. Only after the plasmoid is ejected out of the current sheet, the reconnection will become possible. If a larger plasmoid is ejected, a larger energy release would occur.

Second, a plasmoid can induce strong inflow into reconnection region. Let us consider the situation where a plasmoid suddenly rises at velocity $V_{plasmoid}$. Since the plasma density does not change much during the eruption process, the inflow must develop toward the X-point to compensate the mass ejected by the plasmoid. The inflow speed can be estimated from the mass conservation law (assuming incompressibility, for simplicity); $V_{inflow} \sim V_{plasmoid}L_{plasmoid}/L_{inflow}$ where $L_{plasmoid}$ and $L_{inflow}(\geq L_{plasmoid})$ 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. If the plasmoid ejection (or outflow) is inhibited by some way, the fast reconnection would soon cease (Ugai 1982).

This model naturally explains various phenomena and key physical parameters, such as (1) the Masuda's impulsive loop top HXR source as a very hot region heated by fast mode MHD shock produced by the collision of the reconnection jet with the reconnected loop (Masuda et al. 1994), (2) the total energy release rate, (3) the time scale of impulsive phase, (4) graudal loop top HXR source, and so on.

Furthermore, Shibata (1996, 1997a,b) proposed that the plasmoid-induced-reconnection model is also applicable to smaller flares, such as microflares and X-ray jets (Yokoyama and Shibata 1994, 1996). The key point is that the plasmoid formation and ejection is a scale invariant process and so it can occur even in a very small flare. The apparent difference in morphology between plasmoid ejections and X-ray jets is simply due to the fact that the length of the current sheet is short in smaller flares so that the plasmoid soon collide with the ambient field and reconnects with it to disappear. (Fig. 2). 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). 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.

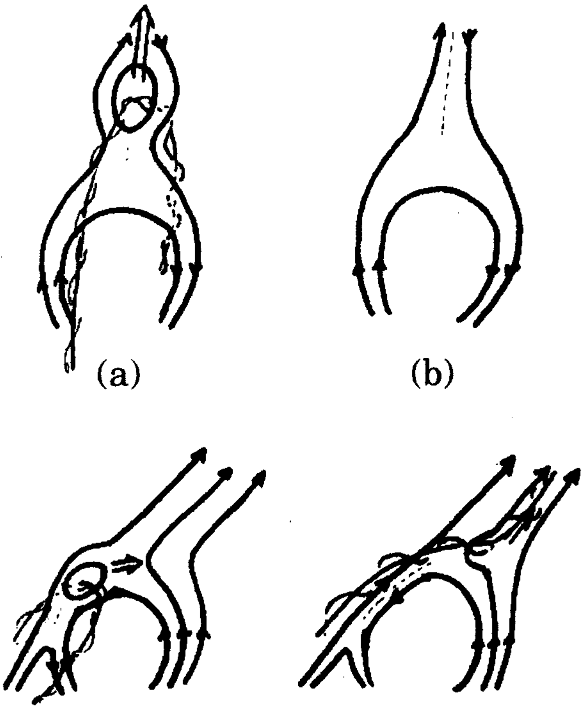

Fig. 2.— Application of the unified model (plasmoid-induced-reconnection model) to large flares [(a) and (b)] and small flares [(c) and (d)] (Shibata 1997a).

3. Plasmoid Acceleration

In the previous section, we simply assumed that a plasmoid is suddenly accelerated just before impulsive phase of flares. In this section, we shall consider possible acceleration mechanisms of a plasmoid.

We consider the situation that the reconnection just begins and creates a plasmoid with a length of L_p and a width of W_p. Since the reconnection generates a jet with the Alfven speed V_A from a reconnection point (an X-point), the reconnection jet collides with the plasmoid and accelerate it. Then the plasmoid speed increases, and induce faster inflow into the reconnection point, leading to faster reconnection and larger energy release rate. This, in turn, accelerates the plasmoid again, eventually leading to a kind of nonlinear instability for the plasmoid ejection and the associated reconnection.

Let us estimate the plasmoid velocity in this process, by assuming that the plasmoid is accelerated solely by the momentum of the reconnection jet. We also assume that the plasmoid density ρ_p and the the ambient plasma density ρ are constant with time, for simplicity, and also that the mass added to the plasmoid by the reconnection jet is much smaller than the total mass of the plasmoid.

Equating the momentum addition by the reconnection with the change of momentum of the plasmoid, we have

$$\rho_p L_p W_p \frac{dV_p}{dt} = \rho V_i L_r V_A = \rho V_p W_p V_A \qquad (1)$$

where we use the mass conservation relation for the inflow and the outflow, $V_p W_p = V_i L_r$. Physically, this means that the inflow is induced by the outflow (plasmoid ejection). This is the reason why this reconnection is called ***plasmoid-induced-reconnection***.

The equation (1) is easily solved to yield the solution

$$V_p = V_0 \exp(\omega t) \qquad (2)$$

where V_0 is the initial velocity of the plasmoid, and $\omega = \frac{\rho V_A}{\rho_p L_p}$. Thus, the plasmoid velocity increases exponentially with time, and the "growth time" $(1/\omega)$ is basically of order of Alfven time. The inflow speed becomes

$$V_i = \frac{W_p}{L_r} V_p = \frac{W_p V_0 \exp(\omega t)}{L_r(0) + \frac{V_0}{\omega}(\exp(\omega t) - 1)} \qquad (3)$$

If W_p is constant, the inflow speed increases exponentially with time in the initial phase, but tends to be constant ($\simeq \omega W_p$) in the later phase.

As time goes on, the mass added to the plasmoid by the jet increases and eventually becomes non-negligible compared with the initial mass. In this case, we obtain the solution

$$V_p = \frac{V_A \exp(\omega t)}{\exp(\omega t) - 1 + V_A/V_0} \qquad (4)$$

Hence the plasmoid speed is saturated at around $t = t_c \simeq \frac{1}{\omega} \ln(V_A/V_0)$ and hereafter tends to the Alfven speed V_A as time goes on. The inflow speed becomes

$$V_i = \frac{W_p V_p}{L_r}$$

$$= W_p \frac{V_A \exp(\omega t)/(\exp(\omega t) + a)}{(V_A/\omega)\ln[(\exp(\omega t) + a)/(1 + a)] + L_r(0)} \qquad (5)$$

where $a = V_A/V_0 - 1$. If W_p is constant in time, the inflow speed gradually decreases in proportion to $1/t$ after t_c. On the other hand, if W_p increases with time in proportion to t after t_c, the inflow speed becomes constant,

$$V_i = \omega W_p(t = 0) = \frac{\rho V_A}{\rho_p L_p} W_p(t = 0) \qquad (6)$$

In this case, the reconnection becomes steady, and the shape of the reconnection jet and plasmoid becomes self-similar in time and space.

A typical solution for W_p = constant is shown in Figure 3, which reminds us of observed relation between plasmoid height vs. hard X-ray intensity (Fig. 4; Ohyama and Shibata 1997). It is noted here that the hard X-ray intensity is a measure of the total energy release rate in a flare whereas the inflow speed is related to the total energy release rate ($\propto$ poynting flux $\propto V_i B^2/(4\pi)$).

4. Discussion

We have seen that the plasmoid can be accelerated by the local reconnection even if there is no global acceleration of the plasmoid by the magnetic pressure. The acceleration of the plasmoid is strongly coupled with the reconnection dynamics, leading to the nonlinear instability. The maximum velocity of the plasmoid is the Alfven speed, and the acceleration time is of order of the Alfven time

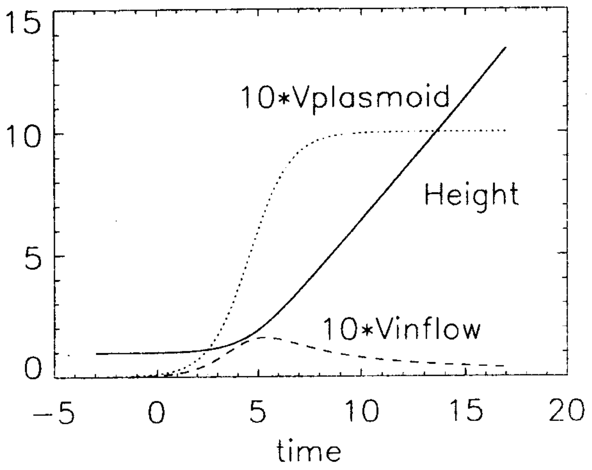

Fig. 3.— Plasmoid velocity (Vplasmoid), its height, and inflow velocity (Vinflow) as a function of time, predicted by the analytical model described in the text. Note that the unit of time is $1/\omega$. This figure may be compared with observation shown in Fig. 2.

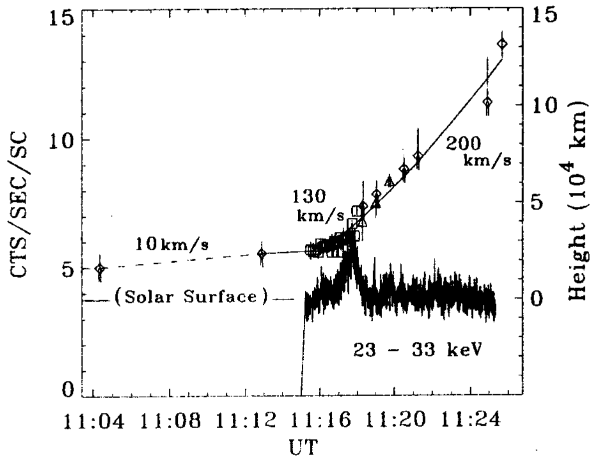

Fig. 4.— Observed relationship between plasmoid height and hard X-ray intensity (Ohyama and Shibata 1997). Since hard X-ray intensity is a measure of energy release rate ($\sim B^2 V_i L^2/4\pi$), this figure could represent the relationship between plasmoid height and inflow speed (V_i).

$\rho_p L_p/(\rho V_A)$. This nonlinear dynamics determines the maximum reconnection rate uniquely (if the resistivity increases in accordance with dynamics); the maximum inflow speed is $W_p \rho V_A/(\rho_p L_p)$. Actual dynamics would be nonsteady bursty reconnection due both to microscopic and macroscopic mechanisms, which would correspond to impulsive phase of solar flares.

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