Reconnection Models of Flares

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Abstract

Yohkoh observations of solar flares have revealed various types of evidence of magnetic reconnection, not only for large scale flares but also for small scale flares. Observations have also revealed that the association of mass ejections (plasmoids) with these flares is much more common than previously thought. On the basis of these new Yohkoh observations, we briefly (but critically) review various reconnection models of flares, and then discuss the *plasmoid-induced-reconnection model*, which is an extension of the CSHKP model but includes the following points as essential ingredients of nonsteady fast reconnection. Plasmoid formation and ejections are not simple by-products of reconnection, but play an essential role in storing energy (by inhibiting reconnection in the preflare phase) and by inducing strong inflow into reconnection region (by ejecting a huge amount of plasma in the impulsive phase). We shall also discuss how plasmoids are accelerated by global magnetic pressure and reconnection jets. 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.

Key words: Sun: flares — magnetohydrodynamics

1. Introduction

Yohkoh has revealed various types of 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). It has also been revealed that the association of mass ejection with flares is much more common than previously thought (e.g., Shibata et al. 1995, Ohyama and Shibata 1997, 1998, Tsuneta 1997, Nitta 1996), leading to a unified view and a unified model of flares (e.g., Shibata 1996, 1997a,b).

In this paper, starting from the overview of current status of basic reconnection theory, we will briefly review reconnection models of flares. Then, we discuss unified model of flares (called plasmoid-induced-reconnection model; Shibata 1997a,b), and the acceleration mechanism of plasmoids.

2. Current Status of Basic Reconnection Theory

First, it should be emphasized that even *a two dimensional theory of magnetic reconnection has not yet been established at present.* Namely, no one has yet succeeded to solve the following fundamental question: *What determines the reconnection rate ?* The reconnection rate is defined as the reconnected flux per unit time or, equivalently, electric field at the X point, or inflow speed into the X point. Some authors claimed that the driving process at the boundary determines the reconnection rate (e.g., Sato and Hayashi 1979, Priest and Forbes 1987, 1992). However, self-consistent numerical simulations show that the reconnection rate is not uniquely determined by the external boundary condition but strongly depends on the local plasma conditions such as its resistivity properties; if uniform resistivity is assumed, only Sweet-Parker reconnection is realized so that the Petschek-type fast reconnection does not occur even if the fast inflow is imposed at the boundary (e.g., Ugai 1987, Scholer 1989, Yokoyama and Shibata 1994). One may ask, then, the following question: is the reconnection rate determined solely by local plasma conditions such as microscopic physics leading to anomalous resistivity or collisionless conductivity ? The answer seems to be no, since the reconnection rate (inflow speed) cannot freely increase but is limited by the macro-scale dynamics.

We should also note that in the solar corona and flares, the microscopic plasma scale (such as the ion Larmor radius and the collisionless skin depth ($= \omega_p/c$, where ω_p is the plasma frequency and c is the speed of light), both of which

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are one of typical thickness of microscopic current sheet and are of order of 10 – 100 cm in the corona, is much smaller than the typical size of flares ($\sim 10^9$ cm). This is very different from the situation in magnetospheric substorms, where both micro and macro scales ($\sim$ 1000 km and $10^4 - 10^5$ km, respectively) are not so different. The physics of the latter dynamics is within the reach of the direct particle simulation but the dynamics of solar flares cannot be studied by the particle simulation alone. The coupling between macro-scale dynamics (magnetohydrodynamics) and micro-scale physics (electro-magnetic particle dynamics for non-Maxwellian plasma) is essential for solar flares, but is extremely difficult to solve at present.

In conclusion, even the theory of 2D MHD reconnection has not yet been established, and hence it is not surprising that the study of 3D MHD reconnection is in a very preliminary stage (e.g., see reviews by Forbes 1999). Furthermore, the full problem of magnetic reconnection with kinetic effects such as particle acceleration is far from a final resolution in the case of solar flares. This difficulty in basic reconnection theory, in turn, is a good news for observers, since the role of observations in reconnection study is quite large; there are many chances for solar observers to contribute to the development of basic reconnection theory using actual observations of magnetic reconnection occurring in the solar corona and flares.

3. Brief Review of Reconnection Models of Flares

Let us now briefly review various reconnection models of flares.

3.1. Classical Two Ribbon Flare Model (CSHKP Model)

The most commonly quoted reconnection model for flares is the so-called *CSHKP model* (Carmichael 1964, Sturrock 1966, Hirayama 1974, Kopp-Pneuman 1976). This term was first introduced by Sturrock (1991), as describing that "The eruption of a filament (or of an "extended filament") distorts the overlying magnetic field configuration in such a way as to produce a current sheet." It has been argued that magnetic field lines in this current sheet successively reconnect to form apparently growing flare loops and separating H α ribbons at their footpoints (see also Svestka and Cliver 1992 for a historical review). This model is also called *classical two ribbon flare model* (see also many models for extension of this model such as Cargill and Priest 1983, Forbes and Priest 1984, Cliver et al. 1986, Martens and Kuin 1989, Moore and Roumeliotis 1992). It should be noted here that actual processes considered in these four pioneering papers are different. For example, Carmichael (1964) and Kopp and Pneuman (1976) thought that the solar wind opens a closed loop to form vertical current sheet, while Sturrock (1966) considered that an excess of gas pressure in the closed field region will produce a cusp and then drive field lines out of cusp, forming a current sheet. On the other hand, Hirayama (1974) proposed that prominence eruption plays an important role in triggering magnetic reconnection. The common point in the four pioneering papers is only that *magnetic reconnection occurs in a vertical current sheet above a closed loop.* There is no agreement on the mechanism of current sheet formation in these four papers. Hence, in a narrower sense, the CSHKP model refers to only the magnetic reconnection occurring in a vertical current sheet above a closed loop. In a wider sense, the CSHKP model may include the *filament eruption* or related *global eruptive MHD instability* as a key process for triggering fast reconnection (e.g., Pneuman 1981, Priest 1981).

This is an important point, and if we forget this, we will not be able to discuss the comparison between the CSHKP model and observations. Indeed it is not the Kopp-Pneuman model but this CSHKP model in a narrow sense that Yohkoh established on the basis of discovery of beautiful cusps in LDE flares (e.g., Tsuneta et al. 1992, 1996, Hiei et al. 1994, Forbes and Acton 1996, and see also the reviews by Hudson and Ryan 1996, Shibata 1996, Kosugi and Shibata 1996). This was a great step and a landmark in the flare research since before Yohkoh there were many researchers who were skeptical about the reconnection model even in the case of LDE flares.

It should also be mentioned that on the basis of the CSHKP model in a wider sense, Shibata et al. (1995) searched for X-ray plasma ejections above 8 impulsive compact-loop flares observed at the limb, and indeed found that all these flares were associated with X-ray plasma ejections high above the soft X-ray loop, as originally predicted by Hirayama (1991).

3.2. Current Sheet Formation Models

3.2.1. Converging Flux Model

Noting that the CSHKP model in a narrower sense (i.e., reconnection in a vertical current sheet above a loop) has been established by Yohkoh observations (at least phenomenologically), we will move on to the next question: What is the mechanism of the current sheet formation ?

Sweet (1958) considered the approach of two bipoles toward each other (i.e., quadrupole), which creates a current sheet between them. Uchida (1981, 1996) has criticized the CSHKP (or standard) model, by arguing that the CSHKP model has a problem about the formation of current sheet, and instead proposed a quadrupole model. However, this criticism is not justified, since there is no agreed opinion about the current sheet formation mechanism in the CSHKP model as we discussed above. It is better to say that Uchida's model is not an alternative model but is an extension of the CSHKP model, if he admits the fast reconnection as a basic energy release mechanism. [1] Uchida (1981, 1996) proposed that the current sheet should be formed between two approaching bipoles, as discussed by Sweet (1958). Priest et al. (1994) and Parnel et al. (1994) developed this model and called the *converging flux model*.

It should be also noted that there is one good point in Uchida's idea on the role of a dark filament. He considered that the dark filament inhibits the collapse of a current sheet and stores the energy. Using the modern word, we can say that a plasmoid (or a helical flux rope in 3D space) inhibits the collapse of the current sheet. (It is interesting to see that Hirayama (1974) also considered similar idea.) This could be an important process as we discuss later (see section 4).

3.2.2. Emerging Flux Model

A current sheet is also formed between emerging flux and pre-existing flux. This model is called the *emerging flux model* (Heyvaerts, Priest, Rust 1977, Forbes and Priest 1984, Shibata et al. 1992, Yokoyama and Shibata 1995). Shibata et al. (1992) and Yokoyama and Shibata (1995, 1996) found that even this kind of small scale reconnection is accompanied by the formation and ejection of plasmoids. Hence, apart from the formation process of current sheet, the basic structure and dynamics occurring in the current sheet in the emerging flux model are quite similar to those in the current sheet in the converging flux model (or quadrupole model).

It may be argued that one important difference between the emerging flux model and converging flux model is the orientation of the current sheet; the current sheet is horizontal in the emerging flux model while it is vertical in the converging flux model. However, the orientation of the current sheet strongly depends on the local magnetic field strength and configuration, so that even in the emerging flux model it is possible to have a nearly vertical current sheet (e.g., Yokoyama and Shibata 1995, 1996).

3.2.3. Sheared or Converging Arcade Model

The previous two models (converging flux or emerging flux models) are basically based on quadrupole or triple-pole models. However, there are also possibilities that the current sheet can be created in a bipole (or an arcade in 3D space). Forbes (1990) proposed that approaching footpoint in arcades forms a current sheet, while Choe and Lee (1996) found that even a single sheared arcade eventually leads to the formation of a current sheet as a result of a resistive MHD instability which occurs when the aspect ratio of a sheared arcade (h/w) exceeds $5 - 10$ (h is the height and w is the distance between two footpoints of the arcade). (Note that if there is no resistivity, the sheared arcade tends to be an infinitely long current sheet, as Aly (1991) and Sturrock (1991) conjectured. Hence the current sheet can be formed long before the Aly-Sturrock state is reached. Hence, there is no basic difficulty resulting from the Aly-Sturrock theorem.)

On the other hand, Mikic et al. (1988), Biskamp and Welter (1989), and Kusano et al. (1995) studied the evolution of multiple sheared arcades, and showed that the system becomes unstable because of a resistive MHD instability to form a current sheet (see also Magara et al. 1997). It was found that multiple arcades have a larger growth rate than in a single arcades (Choe and Lee 1996). Hence the multiplciity of bipoles is favorable for the formation of a current sheet (and the resulting reconnection). It should be noted that all these numerical simulations show that fast reconnection is necessary to create the fast ejection of plasmoids. In other words, the coronal mass ejection (possibly corresponding to plasmoids) cannot occur if there is no fast reconnection. If we identify fast reconnection as flares, this means that CME cannot occur without flares !

Finally we should remember that a shearing flow at the photospheric footpoint of the arcades is simply an assumption. What is the origin of hypothetical shear flow ? Is the shear flow really a surface convection flow or

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1 Uchida (1981) originally proposed that the interchange instability plays a fundamental role in explosive energy release in the impulsive phase, and that the magnetic reconnection occurs slowly in the decay phase in an interleaved current sheet. This is fundamentally different from the standard view of flares in which *fast reconnection* is believed to occur. Although his idea is interesting, there is no evidence of the interchange instability in actual current sheets observed in the solar corona, magnetosphere, and laboratory experiment. It is also theoretically difficult to expect that the interchange instability occurs in a vertical current sheet and it is even difficult to expect that the instability grows significantly in the nonlinear stage; the interchange instability usually plays a role of mixing the plasma rather than creating an explosive flow (e.g., Tajima and Shibata 1997).

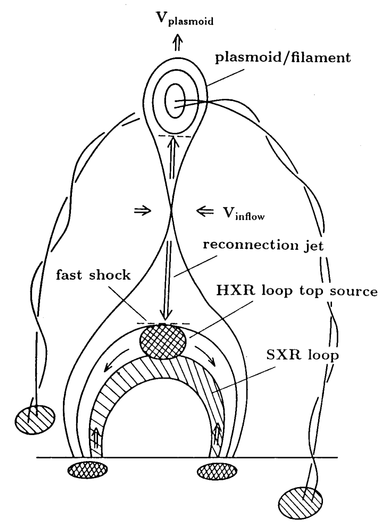

Fig. 1.. A Unified Model of Flares: Plasmoid-Driven Reconnection Model.

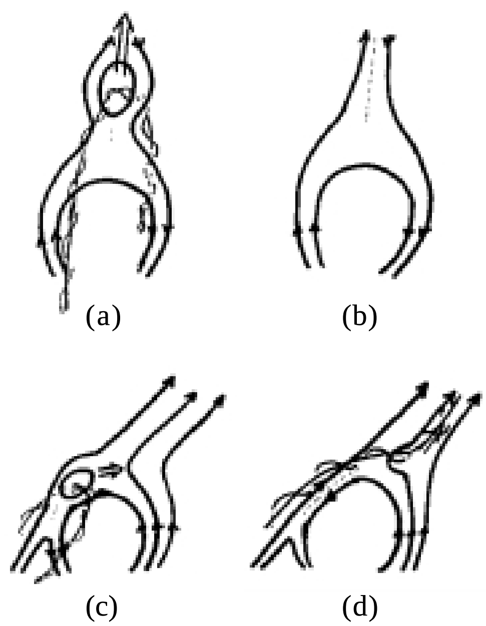

Fig. 2.. Further Unified model of flares, microflares, and X-ray jets.

a result of the emergence of a twisted flux tube ? To answer this question will be an important subject in future observations.

4. Unified Model (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, 1998), Shibata (1996, 1997a,b) proposed the *plasmoid-induced-reconnection model*, by extending the classical CSHKP model. In this model, the plasmoid ejection plays a key role in triggering 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 from the current

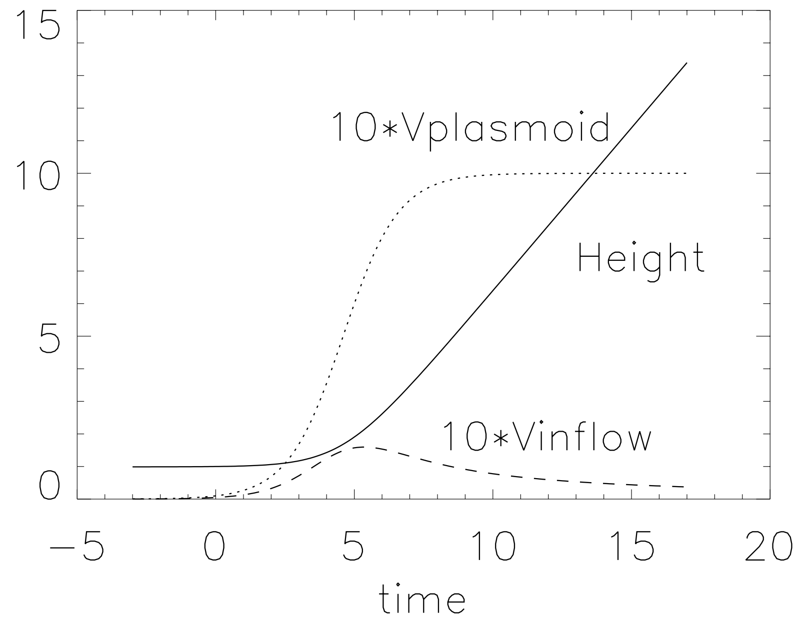

Fig. 3.. Plasmoid velocity (Vplasmoid), its height, and inflow velocity (Vinflow) as a function of time, predicted by the analytical model described in the text. Note that the unit of time is $1/\omega$. This figure may be compared with observation shown in Fig. 2.

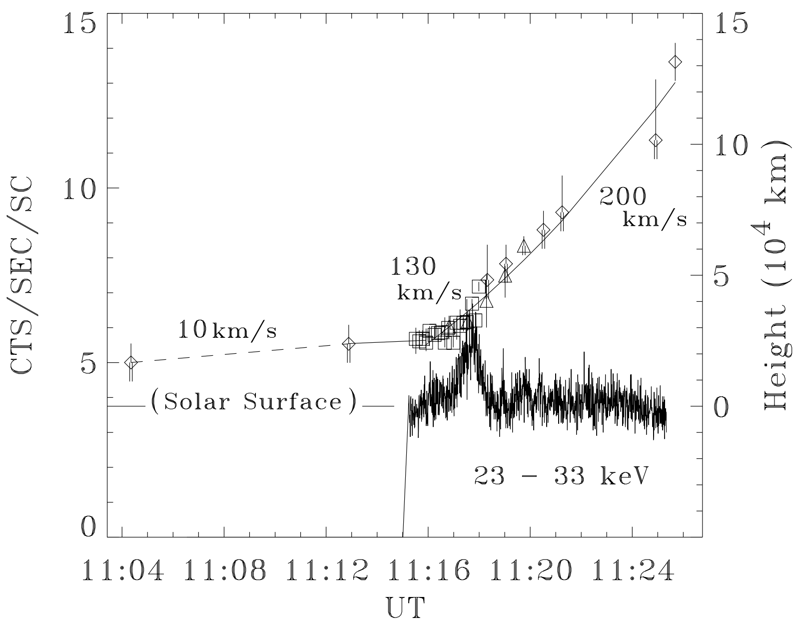

Fig. 4.. Observed relationship between plasmoid height and hard X-ray intensity (Ohyama and Shibata 1997). Since hard X-ray intensity is a measure of energy release rate ($\sim B^2 V_i L^2/4\pi$), this figure could represent the relationship between plasmoid height and inflow speed (V_i).

sheet is reconnection possible. If a larger plasmoid is ejected, a larger energy release will occur.

Second, a plasmoid can induce strong inflow into the 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 in some way, the fast reconnection would soon cease (Ugai 1982).

This model naturally explains various phenomena and key physical parameters, such as (1) Masuda's impulsive loop top HXR source as a very hot region heated by the fast mode MHD shock produced by the collision of the reconnection jet with the reconnected loop (Masuda et al. 1994, 1995), (2) the total energy release rate, (3) the time scale of impulsive phase, (4) gradual 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. 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.

5. 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.

5.1. Acceleration by Reconnection Jet

We consider the situation where 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 Alfvén speed V_A from a reconnection point (an X-point), the reconnection jet collides with the plasmoid and accelerates it. Then the plasmoid speed increases, and induces 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

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

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

$$V_p = V_0 \exp(\omega t) \tag{2}$$

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 Alfvén time. The inflow speed becomes

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

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

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

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 Alfvén speed V_A as time goes on. The inflow speed becomes

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

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,

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

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 Fig. 3, which reminds us of the 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 $\propto V_i B^2/(4\pi)$).

5.2. Acceleration by Magnetic Pressure

The plasmoid can be accelerated by magnetic pressure in the ambient medium. This mechanism is often called *diamagnetic expulsion* or *melon seed mechanism* (Parker 1957, Schluter 1957, Pikelner 1969, Uchida 1969, Cargil and Pneuman 1984, Pneuman and Cargil 1985). Let us estimate the plasmoid speed accelerated by this mechanism.

The equation of motion for a plasmoid may be written as

$$\rho_p \frac{dV_p}{dt} = -\frac{d}{dz}\frac{B^2}{8\pi} \tag{16}$$

where z is the distance measured from the initial position of the plasmoid.

Note that the actual configuration of the plasmoid is three dimensional, so that we have to take into account various 3D effects such as line tying of foot points of the 3D flux rope (plasmoid) on the solar surface, complicated multi-dimensional dynamics around the plasmoid, and so on. We should keep in mind this idealization in the following calculation. Nevertheless, such a calculation (the use of equation (16) with prescribed ambient magnetic field $B(z)$) is useful to grasp some key physics underlying in the plasmoid dynamics.

We shall consider the simple case for magnetic field distribution in the ambient medium: $B \propto 1/z^2$. The example of this magnetic field is a unipolar radial field (potential field). Assuming ρ_p = constant, we find the solution

$$V_p = V_{A0}(1 - \frac{z_0^2}{z^2})^{1/2} = V_{A0}(1 + \frac{t_{A0}^2}{t^2})^{-1/2} \tag{5}$$

where $t_{A0} = z_0/V_{A0}$, $V_{A0} = B_0/(4\pi\rho_p)^{1/2}$ is the Alfvén speed at $z = z_0$, B_0 is the field strength at $z = z_0$, and z_0 is the initial position of the plasmoid. The plasmoid speed tends to be constant (V_{A0}) as time goes on. The acceleration time is comparable to the Alfvén time for characteristic size z_0.

6. 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 Alfvén speed, and the acceleration time is of order of the Alfvén time $\rho_p L_p/(\rho V_A)$. 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 the impulsive phase of solar flares.

On the other hand, the plasmoid can be accelerated by the magnetic pressure in the global field configuration (diamagnetic expulsion or the melon seed mechanism). The terminal speed attained by the magnetic pressure acceleration is of order of the Alfvén speed at the initial position of the plasmoid, and thus comparable to that by reconnection jet acceleration. The only difference between two mechanisms is the acceleration time or the characteristic size.

According to numerical simulation of reconnection in a sheared arcade (Choe and Lee 1996), the plasmoid speed remained slow if uniform resistivity (leading to slow reconnection) is assumed, whereas fast plasmoid ejection becomes possible if anomalous resistivity (leading to fast reconnection) is assumed. In fact, the reconnection jet in the fast reconnection can accelerate a plasmoid self-consistently as we discussed in section 5.1. Hence the reconnection dynamics is coupled with the plasmoid dynamics, and the fast reconnection is necessary to produce fast plasmoid ejections (Forbes 1990, Magara et al. 1997). If we identify fast reconnection as flares and fast plasmoid ejection as CMEs, this means that CMEs cannot occur without flares.

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