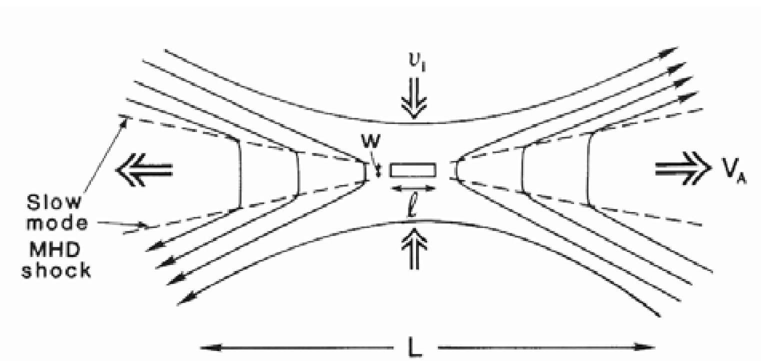
Session 4

Theoretical models of coronal mass ejections



Coronal and Stellar Mass Ejections
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Theories of Eruptive Flares

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Abstract. Recent progress of theories of eruptive flares (and CMEs) is reviewed within a framework of reconnection model with emphasis on development of basic idea and concept.

Keywords. Sun: coronal mass ejections (CMEs), magnetohydrodynamics: MHD

1. Introduction

Recent development of space solar observations have revealed various type of evidence of magnetic reconnection, not only for large scale flares and CMEs but also for small scale flares. Observations have also revealed that the association of mass ejections (plasmoids or flux rope) with these flares is much more common than previously thought, and have led to develop theories of flares and CMEs in a unified way (e.g., Shibata 1999). On the other hand, rapid development of supercomputers has developed MHD modeling of flares and CMEs greatly: we can now calculate realistic model of eruptive flares including various physical processes, such as reconnection, heat conduction, radiative cooling, and evaporation (see Shibata 2003 for a short review on this subject). Keeping these development in mind, we review recent progress of theories of eruptive flares and CMEs with emphasis on the development of basic concept and idea.

It should be noted that this paper is not a comprehensive review, and there are many important papers which are not cited in this paper. From that point of view, the reader should be referred to review papers by Priest and Forbes (2002) and Aschwanden (2002) for more complete citation and discussion of related papers.

2. Present Status of Reconnection Theory

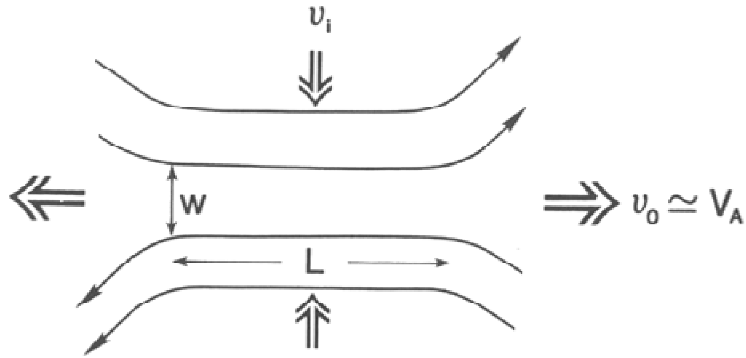
At first, we should note that basic physics of magnetic reconnection has not yet been established (e.g., Hoshino *et al.* 2001). Fundamental puzzles of magnetic reconnection are summarized as follows:

1) What determines the reconnection rate? Or, what is the condition for fast reconnection?

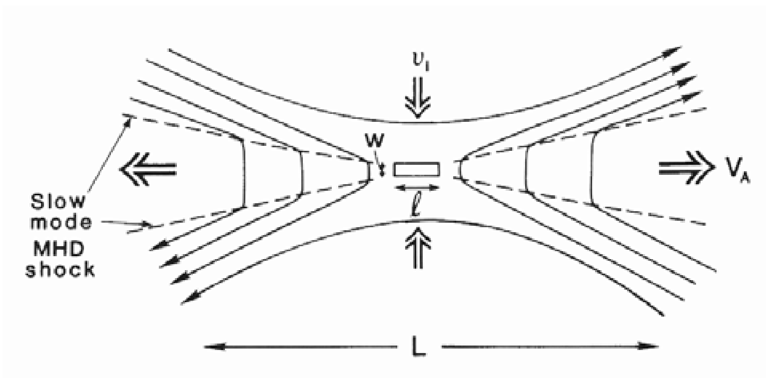
2) What is the structure of reconnection region? Sweet-Parker type or Petschek type or others?

3) How much fraction of energy goes to nonthermal particles?

Hence, now is the stage that laboratory, space, and solar plasma physicists are collaborating to solve this basic physics. It should be emphasized that solar physicists have a lot of chances to contribute to solving this basic physics of reconnection, using excellent imaging data of solar flares and flare-like phenomena.



(a) Sweet-Parker reconnection



(b) Petschek reconnection

Figure 1. Reconnection models

Furthermore, we have following key questions on the origin of flares and CMEs.

4) How is energy stored? Is it the shearing motion or emergence of twisted flux tube?

5) What is the triggering mechanism for flares/CMEs?

6) What is the role of magnetic helicity in flares/CMEs?

As for the role of magnetic helicity, the reader should refer to Kusano (2005) and Hu (2005).

3. The Standard Model

The standard model of eruptive flares has been developed by the following pioneering researchers : Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp-Pneuman

(1976). Hence the standard model is often called CSHKP model. Here we note the brief history how the term 'CSHKP' model appeared. At first, US people called the standard model 'Kopp-Pneuman' model in 80's. Since this was not fair, Shibata (1991) proposed to change it to 'SHKP' model, respecting pioneering work by Sturrock (1966) and Hirayama (1974). At that time, Sturrock himself was fair, and added 'C' just in front of 'SHKP' in 1992, noting the real pioneering work by Carmichael. Svestka and Cliver (1992) also used the term 'CSHKP' model in the same proceedings book.

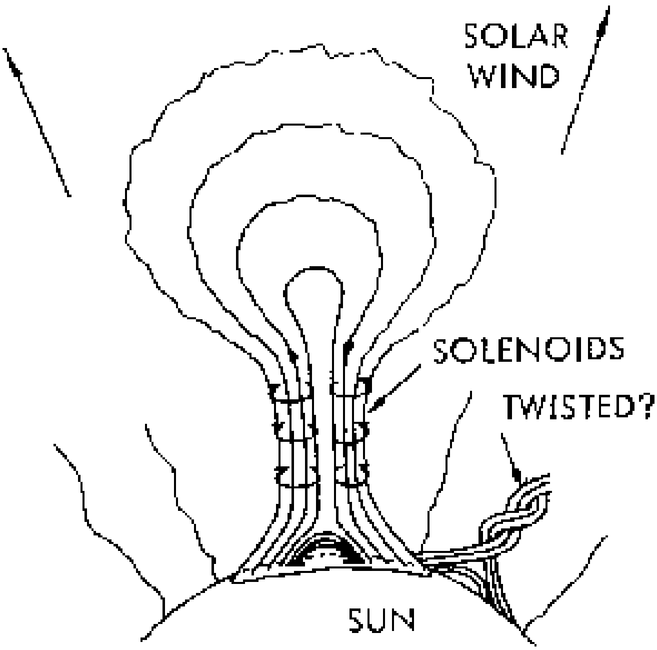


Figure 2. Carmichael (1964)

The standard model of eruptive flares has evolved significantly after 1976, especially because of development of understanding basic physics of reconnection region, as summarized in a nice review paper by Priest and Forbes (2002). Kopp and Pneuman (1976) considered that after reconnection of open field line, the solar wind along open field line collide to form shock inside the reconnected closed field, which heat the coronal plasma to flare temperature. However, Cargill and Priest (1982) correctly pointed out that we should consider the role of slow mode shock associated with Petschek type reconnection. Forbes and Priest (1984) noted the formation of fast shock (termination shock) due to reconnection jet above the reconnected loop, and Forbes and Malherbe (1986) pointed out that the slow shock is dissociated to isothermal slow shock and conduction front in solar flare condition.

Yokoyama and Shibata (1997) carried out for the first time the self-consistent MHD simulation of reconnection including heat conduction, and confirmed that the adiabatic slow shock is dissociated to isothermal slow shock and conduction front as predicted by Forbes and Malherbe (1986). This is very important to understand the structure of cusp-shaped flares observed by Yohkoh (Tsuneta *et al.* 1992). Yokoyama and Shibata (1998, 2001) succeeded to perform 2D MHD simulation of reconnection with heat conduction

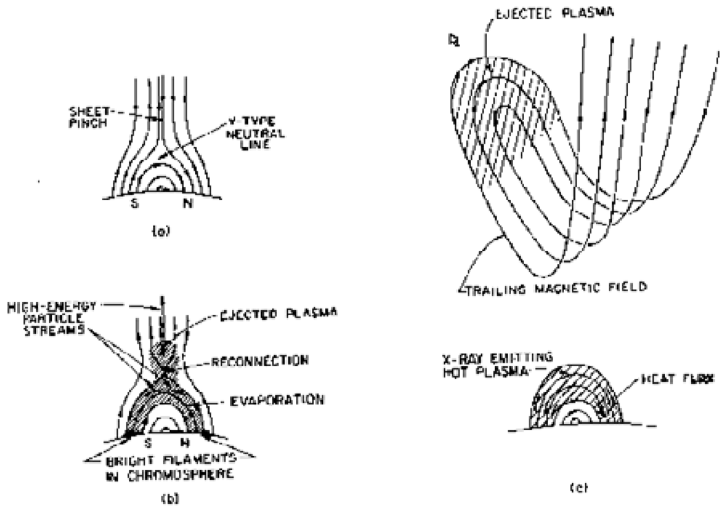


Figure 3. Sturrock (1966)

and chromospheric evaporation, and this is the most advanced model of eruptive flares. Yokoyama and Shibata (1998, 2001) further discovered the following scaling law for flare temperature:

$$T \sim 10^7 K (B/50G)^{6/7} (L/10^9 cm)^{2/7} (n_0/10^9 cm^{-3})^{-1/7} \tag{3.1}$$

where B is the magnetic field strength, L is the reconnected loop length, and n_0 is the preflare electron density. This enabled the further unification of solar and stellar flares (Shibata and Yokoyama 1999, 2002).

4. Aly-Sturrock Theorem

It has often been discussed that the Aly-Sturrock conjecture (Aly 1984, 1991, Sturrock 1991) is a difficulty for modeling of eruptive flares and CMEs. Is this a real difficulty? We briefly outline a history of this conjecture.

Barnes and Sturrock (1972) calculated nonlinear evolution of force free field, and obtained the result that the energy stored in the nonlinear force free field is greater than that of the open field. At first, this result was thought to be consistent with observations, because the closed force-free field with energy higher than the open field can easily evolve to open field, and then magnetic reconnection occur in such open field current sheet to produce flares. More than 10 years later, however, Aly (1984) presented a conjecture 'the energy of any smooth force free field occupying a 'half coronal space' should be smaller than the energy of the so-called open field having the same flux distribution on the plane photospheric boundary'. Yang, Sturrock & Antiochos (1986) recalculated the Barnes-Sturrock problem, and reached the conclusion that 'Our new results differ from the earlier results of Barnes and Sturrock and we conclude that the earlier article was in error.' Furthermore, using the analytical approach, Sturrock (1991) showed 'the Aly conjecture is valid'. This is why the conjecture was called the Aly-Sturrock conjecture, and people began to think that the conjecture is not consistent with standard model (CSHKP model) of eruptive flares, since people thought the "open" vertical current sheet is necessary for the standard model whereas it is not easy to have such "open" vertical current sheet on the basis of the Aly-Sturrock conjecture.

However, it should be noted that the Aly-Sturrock conjecture is based on very simplified assumptions, such as force free (gas pressure and gravity can be neglected), Cartesian geometry, and that all magnetic field lines are connected to the boundary. So there are many ways out of this dilemma as follows.

- True opening of field line is not necessary for reconnection and mass ejections (Aly 1991).
- Non-force free (e.g., gas pressure, gravitational) (Sturrock 1991).
- Initially partly open, partly closed field (Sturrock 1991).
- Cylindrical axisymmetric geometry with spherical boundary (Lynden-Bell and Boily 1994).
- Resistive process (Mikic and Linker 1994).
- Quadrupole magnetic field (e.g., Biskamp and Welter 1989, Antiochos *et al.* 1999, and many).
- Two bipole sources (Choe and Cheng 2002).

Break out model by Antiochos *et al.* (1999) has been thought to be the promising way out of the dilemma. However, we should remember that there are many flare models with quadrupolar or multipolar magnetic field (e.g., Biskamp and Welter 1989, Uchida *et al.* 1999, Chen and Shibata 2000; also classical emerging flux model by Heyvaerts *et al.* 1977, Sweet (1958)'s model all belong to this category), and it is not fair that only break out model is discussed.

Why multipolar flux system is favorable? The reason is simple. If the magnetic field is bipolar, large energy is necessary for plasma to escape from closed bipolar flux system since plasma has to stretch many field lines. If the flux system is multipolar, small energy is enough for plasma to escape from the closed field region, since the number of field lines that plasma has to stretch is much smaller than that for bipolar flux system.

5. Current Sheet Formation (Energy Storage) Model

Traditionally, the following models have been considered to be applied to small scale flares or non-eruptive flares: converging flux model (Sweet 1958, Uchida *et al.* 1999, Priest *et al.* 1994), emerging flux model (Heyvaerts *et al.* 1977, Forbes-Priest 1984, Shibata *et al.* 1992, Yokoyama-Shibata 1995), sheared or converging arcade model (Mikic *et al.* 1988, Biskamp and Welter 1989, Forbes 1990, Kusano *et al.* 1995, Choe and Lee 1996, Magara *et al.* 1997, Hu 2000, Choe-Cheng 2001). However, there is no essential difference between small and large scale flares. It is also theoretically possible to unify these models and the standard model for eruptive flares, since the plasmoid (flux rope in 3D) is easily created in the current sheet (Shibata 1997).

Hence Shibata (1998, 1999) proposed the unified model, which he call plasmoid-induced reconnection model, in which plasmoids play following two roles 1) to store energy by inhibiting reconnection, 2) to induce inflow after ejection of plasmoids. In this model, fast reconnection occur as a result of strong inflow induced by plasmoid ejections. However, in order to create plasmoids, reconnection is necessary, and even after that, plasmoids are accelerated by energy release through reconnection, whereas the plasmoid ejection induces strong inflow and reconnection, which then accelerate plasmoids even further, vice versa. Hence both plasmoid ejection and magnetic reconnection are strongly coupled and form a kind of nonlinear instability (Shibata and Tanuma 2001). It is also noted that the current sheet tend to show many plasmoids with different sizes, i.e., fractal structure. Observed fractal-like hard X-ray and microwave emissions (Benz and Aschwanden 1992) (a,b): giant arcades, LDE/impulsive flares, CMEs

(c,d): impulsive flares, microflares, jets

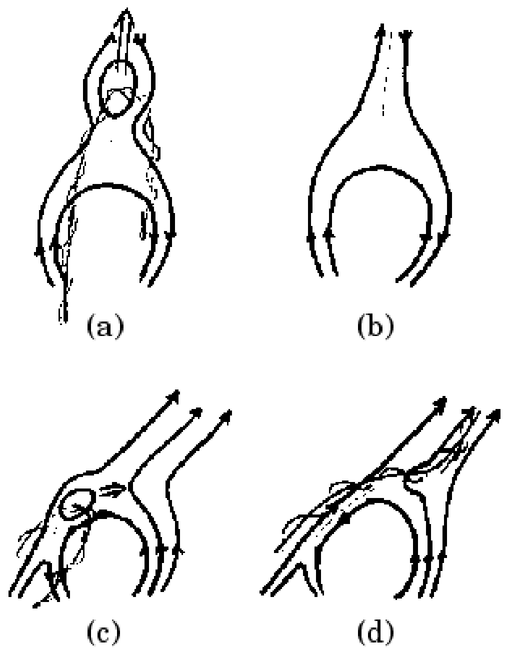


Figure 4. Unified model (Shibata 1999)

may be a result of such fractal-like reconnection induced by various plasmoid ejections with different size.

6. Two-step Reconnection Model as Triggering Model

Chen and Shibata (2000) presented an MHD simulation model of eruptive flares and CMEs on the basis of idea from observational data analysis on the triggering of filament eruption by emerging flux (Feynmann and Martin 1995). In this model, small scale reconnection (cancellation) associated with emerging flux triggers large scale reconnection in the X-point high above or far from the emerging flux region. In this sense, it can be classified as two-step reconnection model (Wang and Shi 1993). The magnetic helicity annihilation model by Kusano *et al.* (2003), the break out model by Antiochos *et al.* (1999) and the tether cutting model by Moore & Roumeliotis (1992) also belongs to this model.

More recently, Shiota *et al.* (2003) extended the Chen-Shibata model and compared the model with Yohkoh observations of Y-shaped ejections above giant arcades (helmet streamer), finding the signature of slow and fast mode MHD shocks.

7. Remaining Questions

Finally, we list several key remaining questions in the following:

1) What is the condition of fast reconnection? Is it related to plasmoid ejections?

2) What is the energy storage and trigger mechanisms? Are they related to emerging flux?

3) Where are reconnection jet, inflow, and MHD shocks? Though there are several new findings on this subject (e.g., Yokoyama *et al.* 2001, Shiota *et al.* 2003), the Doppler shift observations of these phenomena are remained as important subjects for Solar B which will be launched in 2006.

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Discussion

SCHWENN: Please comment on non-reconnection CME model

SHIBATA: As for this, I had an interesting discussion with B. C. Low. He claims that there is a regime where a CME can occur without reconnection, and such CMEs can be accelerated by magnetic buoyancy after draining mass from the prominence due to gravity. I think even in such case, reconnection is necessary to drain mass from the prominence. Hence I do not believe that many CMEs belong to a non-reconnection model. Only a small fraction of CMEs may belong to a non-reconnection model, if the CME is similar to a slowly rising arch filament observed in an emerging flux region. But in this case there is no explosive energy release nor rapid mass motion.

KAHLER: What does it mean that reconnection is fractal - size structure or energy releases? what is the evidence that reconnection is not only structured but also fractal?

SHIBATA: Here I used the word fractal from two points of view: spatial structure and temporal variation. As a result, the energy release shows also fractal: the occurrence frequency vs released energy would show power law distribution. We have proposed that the current sheet consist of a number of plasmoids (flux rope) which have difference sizes with power law distribution (fractal) (Tajima and Shibata 1997, Shibata and Tanuma 2001). These plasmoids collide each other or expelled from the current sheet, both of which induce intermittent reconnection. Since the released energy and time scale are determined by the size of plasmoid, the energy spectrum and the power spectrum of time variability would also show power law distribution (fractal). There are indirect evidence for this, i.e., time variability of radio microwave emissions and hard X-ray emissions (e.g., Benz and Aschwanden 1992), both of which show power law spectrum for time variation of the intensities of these emissions.

GOPALSWAMY: Most filament eruptions are accompanied by mass down flows? How does this down flows fit in your eruption scenario?

SHIBATA: Once the eruption of plasmoid (flux rope) occurs, the core of flux rope (prominence) would expand like Omega shape. So gravity acts along the rising Omega (helical) loop, enabling mass draining. So such observations fit our eruption scenario.

STERLING: You said that the important point about break out is the reconnection in the corona. But isn't it also important that the coronal reconnection be slow initially, and then fast? Without the initial slow reconnection, you would not have a stress buildup between the two flux system followed by explosive eruption. Therefore I think that the important point is that the reconnection rate in the corona be slow at first, and then fast. I think that the key is for the reconnection to be inhibited initially. This is a basic point for many astrophysical circumstances.

SHIBATA: Yes I agree with you about the importance of inhibiting reconnection. Without inhibiting reconnection, it would be difficult to store energy in the corona and also difficult to get explosive energy release. At present, we do not know how we can have slow reconnection initially and then get fast reconnection later. There is no established answer about this question, which is of course a key basic question of the reconnection physics.