Magnetic Energy Storage and Release—Theory

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It is believed that magnetic energy is stored in the corona via photospheric motions in the form of force-free magnetic fields and/or electric current sheets. To produce flares, both a large storage and a fast release of magnetic free energy are needed, and they may be associated with the coexistence of a spontaneously formed electric current sheet and a highly stressed background magnetic field. The current sheet just serves as a trigger for the impulsive release of the magnetic energy stored in the high stressed field. Any fast release of magnetic energy must be accompanied with various types of MHD waves and shocks, including slow shocks and, perhaps, intermediate shocks. A realistic shock near the sun consists of several segments, which are of different types and pieced together according to certain rules, and it evolves and changes its structure while propagating outward into the interplanetary medium.

1. Introduction

It is widely believed based on observations and theoretical analyses that magnetic energy serves as a main source for coronal heating as well as various active phenomena such as solar flares, eruptive prominences, and coronal mass ejections. Therefore, the problem of magnetic energy storage and release has been so far one of the key problems on solar physics.

Recently, the development and improvement of vector magnetographs and the availability of vector field measurements have aroused great interest in force-free magnetic fields. Owing to the high conductivity of the solar atmosphere, electric currents in the corona must be concentrated in local areas or current sheets so as to effectively release their associated energy via resistive dissipation. Accordingly, there is a growing interest in electric current sheets, including their formation and stability, the involved magnetic reconnection, as well as the relationship between them and solar flares. Finally, mass ejections accompanied by impulsive release of magnetic energy will produce MHD shocks in the solar atmosphere, and the investigation of these shocks regarding their development, evolution and propagation has achieved great attention in solar-terrestrial physics. Great progress in those aspects mentioned above has been made lately and in what follows, I wish to address a few of them.

2. Force-Free Magnetic Fields and Electric Current Sheets

Since the early 1970s, an extensive study was made of force-free magnetic fields and their application to simulating coronal magnetic structures and solar flare energy build-up (e.g., see reviews by LOW, 1982, 1985). Vector magnetographs around the world now

enable us to observe all three components of the magnetic field on the photosphere. To my knowledge, the vector magnetograph at the Huairou Solar Observing Station of the Beijing Astronomical Observatory has been operating excellently providing vector field data of good quality. Meantime, a new device is presently being developed there for making simultaneous measurements of vector field at several levels of the solar atmosphere. Based on the vector field data and the force-free field approximation, scientists tried to evaluate the magnetic free energy in active regions (SAKURAI, 1987; GARY *et al.*, 1987) and the corresponding electric current morphology (HAGYARD *et al.*, 1981; DING *et al.*, 1987), and even to extrapolate the magnetic field in the upper atmosphere (SAKURAI, 1981; WU *et al.*, 1985; SAKURAI *et al.*, 1985). The present achievements are rather primitive of course, and certain obstacles have to be thrown in the way of both experiments and theories (ALY, 1989; LOW, 1989b). Further work is well worth doing, since a reliable grasp of the magnetic field and its evolution in solar active regions is obviously crucial to understanding the mechanism for preflare energy storage, flare triggering, and energy release. This will clarify previous knowledge of solar flare physics and help us to establish more quantitative models. To achieve this goal, further coordinated efforts have yet to be made in magnetic field observations and theoretical analyses. As regards to theories, it will be very instructive to devise new numerical models to extrapolate 3-dimensional structures and temporal evolution of magnetic field in the upper atmosphere in terms of vector field measurements on the photosphere or the chromosphere. Among the main requirements for such numerical models are a negligible numerical diffusivity of the magnetic field and an ability of dealing with strong discontinuities of magnetic field probably appearing in the upper atmosphere. As a first step, we may use the force-free approximation provided that the available vector field data are checked in advance to satisfy relevant necessary conditions for a force-free magnetic field (see ALY, 1984, 1989).

Electric current sheets may be formed by variation of the photospheric normal magnetic flux distribution due to continuous magnetic footpoint displacements. For a magnetic field with neutral points, these neutral points readily deform into current sheets (SWEET, 1969; PRIEST and RAADU, 1975; SYROVATSKII, 1981; HU and LOW, 1982; LOW and HU, 1983; HU, 1984, 1985). Actually, as pointed out by LOW (1987), the essential ingredient is the presence of an interface separating distinct field-line topologies and that interface, usually called separatrix surface, rather than neutral point itself, is fundamental in causing the electric current sheet to form. What the photospheric displacement does is just to compress two adjacent magnetic field subregions bordered by a separatrix surface, resulting in a current sheet right on the surface (MOFFATT, 1985; LOW, 1987, 1989a; LOW and WOLFSON, 1988). Moreover, LOW and WOLFSON (1988) stressed that a current sheet may extend along the entire separatrix surface even though the footpoint displacement that induces its formation is small. Only the strength of this current sheet depends directly on the magnitude of the footpoint displacement. Since the presence of separatrices is expected in a realistic active region, the formation of electric current sheets will be a common phenomenon over the active region. For a magnetic field with the simplest topology such as a bipole, however, continuous photospheric displacements will in general lead to a smooth distribution of electric current (VAN BALLEGOOIJEN, 1985; ANTIOCHOS, 1987; ZWEIBEL and LI, 1987). Nevertheless, small-scale electric current structures are still possible to occur owing to the nonuniformity and randomness of the displacements (PARKER, 1972, 1979, 1986a, 1986b; VANBALLEGOOIJEN, 1988). What is

more, a force-free magnetic field with a continuous volume current becomes unstable if it is oversheared or overtwisted. The nonlinear development of the related instabilities may also cause current sheet formation (STRAUSS and OTANI, 1988).

In the early stage of current sheet formation, its dynamic behavior is essentially governed by the ideal MHD equations, and the interchange instability is a main threat to curved current sheets. This instability grows in the Alfvén time-scale, and may trigger and speed up magnetic reconnection across the sheet (PARKER, 1973). UCHIDA and SAKURAI (1977) discussed the interchange instability of a circular sheet tied at the photosphere, and predicted that the current sheet is stable so long as the magnetic field component B_z in the direction of the electric current deviates slightly from zero. They ignored the influence of the internal structure within the sheet on stability, but in general, such influence can not be ignored (NEWCOMB, 1960). ZHENG and HU (1990) took this influence into account and found a critical value B_c ($\sim 0.58 B_0$ for a semicircular current sheet, B_0 is the transversal component outside the sheet). The current sheet is subjected to interchange instability if $B_z < B_c$, and the wave number of the unstable mode in the z -direction, which causes the instability first, is approximately the reciprocal of the diameter of the current sheet circle. If the current sheet is attributed to a compression of two adjacent magnetic subregions, then it becomes unstable as the angle φ between the magnetic fields in the two subregions is larger than $\varphi_c = 2 \tan^{-1}(B_0/B_c) \sim 120^\circ$ (cf. Fig. 1). On the contrary, the current sheet will keep growing until it exceeds a certain limit to suffer from instabilities of other types. This shows that Uchida and Sakurai overestimated the stabilizing effect of B_z .

Fig. 1. Adjacent magnetic fields at an angle φ .

3. Reconnection across Current Sheets and Energy Release of Solar Flare

Magnetic reconnection has been recognized so far as a chief mechanism for the release of magnetic free energy, since it allows a high energy conversion rate. Extensive studies have been made on the linear growth and the nonlinear evolution of magnetic reconnection, among which the well-known Petschek mechanism seems to be generally accepted as the only workable model for fast reconnection in the solar atmosphere (PRIEST, 1981). A recent numerical simulation of magnetic reconnection across planar current sheets by LEE and FU (1986) has shown that the reconnection process depends crucially on three factors: the length of the current sheet, the reconnection rate, and the

resistivity. A steady single X line reconnection tends to transit to a unsteady multiplex X line reconnection when the sheet length is long, the reconnection rate is high, or the resistivity is small. PRIEST (1984) also addressed such a transition process, but less quantitatively than Lee and Fu, and he classified the multiple X line reconnection as “impulsive bursty reconnection.” Multiple X line reconnection models were used to explain reasonably well the flux transfer events at the dayside magnetopause (LEE and FU, 1985) and magnetospheric substorms (LEE *et al.*, 1985).

While current sheet models have been plausible and successful in many fields like magnetospheric physics, they encounter certain uncertainties when applied to solar flares. Such a situation is largely due to the deficiency of detailed observations. It seems that solar flares are hardly elucidated only by current sheets induced by photospheric displacements. Photospheric motions are usually slow and it takes one or more days to build up a sufficient amount of magnetic energy in the corona for a solar flare (WU and HU, 1981; WU *et al.*, 1984). If such amount of energy were stored in the form of current sheets, it would be unimaginable that the associated current sheets could keep developing stably. Perhaps a more reasonable application of the current sheet model is to small flares (HEYVAERTS *et al.*, 1977) or coronal heating (PARKER, 1987). Therefore, the only choice is to seek for certain instabilities in the corona which force the magnetic field there to form current sheets abruptly and then to reconnect rapidly across the sheets, so that a large amount of magnetic energy ($\sim 10^{23}$ – 10^{25} J) can be released in a short period ($\sim 10^3$ – 10^4 s). Obviously, only with the coronal magnetic field highly stressed in advance is it possible to make the above-mentioned scenario workable. KOPP and PNEUMANN (1976) argued in their two-ribbon flare model that the ascending prominence associated with the flare might open the overlying closed magnetic field to form a vertical current sheet, but it remained unclear what caused the prominence eruption. However, one point we can be sure of is that the kinetic energy of the eruptive prominence should be acquired from the underlying magnetic field, which possesses sufficient free energy. It is here, then, that we have returned at last to the original conclusion: a highly stressed coronal magnetic field is a necessary condition for causing big flares.

Any flare models must be tested by observations whereas new observations or better interpretations of the previous data will provide additional clues for establishing and modifying theoretical models. Recently, MACHADO *et al.* (1988a, 1988b) made careful investigation of the SMM and ground-based observations and concluded that a flare is characterized by an interaction among a set of bipoles (i.e. loops). Most ($\sim 90\%$) of the total energy in the impulsive phase is released inside one or more highly stressed bipoles whereas only a small fraction ($\sim 10\%$) of the total energy conversion occurs at the interaction site between the bipoles. Nearly potential bipoles have no internal energy release, and only receive energy injected from the interaction site. They conjectured that a current sheet forms right at the interaction site, and the magnetic reconnection there triggers the main flare energy release within the highly stressed bipoles. The picture drawn above by Machado *et al.* seems to be consistent with the following conclusion made by LIVI *et al.* (1989): Flares begin at or near opposite polarity magnetic features that are cancelling and that cancellation is a necessary condition for the occurrence of flares. By interpreting cancellation as a result of magnetic reconnection, reconnection across a current sheet may be identified as a necessary condition for flares too. It has yet to be ascertained whether the cancelling magnetic features have one-to-one correspondence to the interaction sites between bipoles for flares. Taking the Machado *et al.*'s

scenario for granted, it happens to be in accordance with the following suggestion by LOW and WOLFSON (1988): The formation of current sheets may be expected to initiate flares when it takes place in a magnetic field that has been highly stressed with a storage of substantial free energy. On the other hand, if these current sheets form in a magnetic field with little free energy, their resistive dissipation leads to only a minor heating of the coronal plasma. Meanwhile, the fact that a current sheet may extend along the entire separatrix surface enlightens us on the problem how the energy release inside the highly stressed bipole is triggered and sustained to the end. We would like to give a possible picture qualitatively as follows. The separatrix current sheet induced by the interaction between loops and the reconnection over the interaction site serves as a trigger, which leads to a relaxation of the magnetic field near the surface of the highly stressed loop. As a result, a new current sheet ensues in between the relaxed field and the internal highly stressed field (cf. Fig. 2), and the reconnection continues inwards until the relaxation of the entire loop is complete. It will be interesting to follow the dynamical process of the reconnection with a time-dependent hydromagnetic code and to study its consequences with the flare in mind.

Fig. 2. A new current sheet formed between the relaxed field (shown with no twist) and the highly stressed field (shown twisted).

4. Development and Evolution on Hybrid MHD Shocks

Quite an amount of the released magnetic energy associated with various solar active phenomena is converted into thermal and kinetic energy of the coronal plasma, bringing about various kinds of mass ejecta. MHD shocks may form as a supersonic mass ejection sweeps through the corona. These shock waves will heat the plasma and accelerate energetic particles, and so, give rise to some specific radiation features and exert significant influence on the solar-terrestrial environment. Therefore, the study of MHD shocks has been an attractive part of solar-terrestrial physics.

The solar atmosphere and the interplanetary medium, characterized by various nonuniform structures, provide a specific environment for the development and evolution of MHD shocks. The Alfvén speed is larger than the sound speed in some region like the proximity of the sun, or vice versa in the other. MHD shocks developed there are not only of single type, but also of hybrid type, in which a MHD shock consists of several segments of different types. Furthermore, such a hybrid shock may partly or completely change its properties as it is propagating out ward away from the sun.

It is believed that both the fast and slow shocks exist in nature, but less attention has been paid to the slow shock than its fast counterpart. As for the intermediate shock, the matter is even worse since it has been long considered as nonevolutional or unstable (see ANDERSON, 1963). In addition, shock research has been limited to shocks of single type or shock systems consisting of several separate single-type shocks, without touching upon

the hybrid shocks as well as their temporal evolution.

Such a situation, however, has been changed to some extent recently. First of all, observational evidences have been found for the existence of slow shocks in interplanetary space (CHAO and OLBERT, 1970; BURLAGA and CHAO, 1971; RICHTER *et al.*, 1985a, 1985b; HUNDHAUSEN *et al.*, 1987; RICHTER, 1988), and this has stimulated great enthusiasm for the investigation of slow shocks. Based on observations of coronal mass ejections (CMEs), HUNDHAUSEN *et al.* (1987) suggested that slow shocks of concave-upward shapes may form for most CME events. To quantify such a suggestion, HU *et al.* (1990), STEINOLFSON and HUNDHAUSEN (1989) took a unipole open field and a uniform field as the background, respectively, and carried out numerical simulations of the dynamical formation of slow shocks ahead of supersonic but subAlfvénic mass ejections. The slow shock obtained in their numerical models is characterized by a limited transversal extent and a slightly flattened shape, as well as a coexisting fast mode wave, which deflects the background magnetic field so as to create a rarefaction ahead of the slow shock and a compression in the flank. If the background field is replaced by an open one with a neutral current sheet in its middle (STEINOLFSON and HUNDHAUSEN, 1990b; HU and ZHENG, 1991), the resulting slow shock turned out to be concave-upward, in agreement with the suggestion of HUNDHAUSEN *et al.* (1987).

Next, since WU (1987, 1988) showed by numerical solutions of resistive MHD equations that at least some of the intermediate shocks are admissible and can be formed through nonlinear steepening for a continuous wave, one has started reconsidering intermediate shocks with great interest. There are and will be certainly disputes on this subject though (see LEE *et al.*, 1989). Nevertheless, intermediate shocks should be allowable at least as a time-dependent process. The first attempt was made by STEINOLFSON and HUNDHAUSEN (1990a) at a numerical modelling of the intermediate shock formation for a 2-dimensional time-dependent case. It was shown that an intermediate shock forms as a mass ejection with speed slightly higher than the Alfvén speed is sweeping through a uniform background plasma with the ratio of thermal pressure to magnetic pressure less than 1. This shock proceeds the ejective mass, and it is joined by a switch-on shock to a fast shock located at the flank. In their opinion, the formation and the stability of the intermediate shock are attributed to the cross-flow interactions peculiar to multi-dimensional flows.

RICHTER (1988) noticed that slow shocks were scarcely observed over the last few years in interplanetary space beyond 0.3 AU, whereas they might occur frequently closer to the sun. This shows that slow shocks formed near the sun may have probably changed their properties before propagating deep into the interplanetary space. To explain this, WHANG (1987) assumed a shock system consisting of a slow shock, a fast shock, and a rotational discontinuity, which intersect along a closed transition line. As the system moves outward from the sun, the area enclosed by the transition line expands, the fast shock grows stronger, and the slow shock diminishes, and the entire shock system evolves into a forward fast shock. It remains unclear in his analysis, however, how the assumed shock system is formed at the very beginning, and what the dynamical mechanism is for the transition.

As a matter of fact, it seems more acceptable that a slow shock changes its properties so as to directly become a shock of other types. Before moving on to discuss the transition process, it is worthwhile pausing for a while to examine the jumps of the tangential component of the magnetic field across shocks of various types. This

component retains its sign across both fast and slow shocks, increasing in magnitude across fast shocks and decreasing in magnitude across slow shocks. In contrast, it changes sign across an intermediate shock, and its magnitude may either increase or decrease. What we described above may be summarized in Fig. 3, where the solid lines with arrow represent the magnetic field lines upstream (B_1) and downstream (B_2), and the dashed lines denote the shock fronts. Three particular fronts are drawn in this figure: two are perpendicular to B_1 and B_2 , respectively, and the third is the bisector of the angle between the two. These three lines correspond to the switch-on (ON), switch-off (OFF), and Alfvén (A) shock, respectively. Taking these particular lines as the boundaries, one may differentiate slow (S), intermediate (I_a and I_b), and fast (F) shocks, according to the shock front orientation, as shown in Fig. 3. As we can see, the distinguishing feature of intermediate shocks is that the magnetic field lines upstream and downstream lie in the same side of the shock front normal. As far as the magnetic field strength is concerned, $B_1 = B_2$ for the Alfvén shock $B_1 > B_2$ for I_a , and $B_1 < B_2$ for I_b .

Fig. 3. Refraction of magnetic field lines across shocks of various types.

Coming back to the problem of shock transition, it should be emphasized that, during the formation and evolution of a shock, the direction of magnetic field lines both upstream and downstream must change continuously. In other words, the shock front orientation relative to B_1 and B_2 should change continuously with space and time. Accordingly, we suggest that both the linkage and the transition between different types of shocks will generally follow the rule:

$$S \leftrightarrow \text{OFF} \leftrightarrow I_a \leftrightarrow A \leftrightarrow I_b \leftrightarrow \text{ON} \leftrightarrow F.$$

For instance, a slow shock can not be linked directly with a fast shock to form hybrid shocks. Also, it is generally impossible for a shock to evolve from a slow shock directly into a fast shock.

Recently, we have tested the above-mentioned scenario in terms of a numerical example concerning the dynamical evolution of slow shocks near the sun (HU *et al.*, 1991). Two cases were treated by taking an open magnetic field with (case A) or without neutral current sheet (case B) as the background. The initial coronal plasma is assumed isothermal, with the sound speed ~ 135 km/s. The Alfvén speed is approximately 1000 km/s on the solar surface, and it decreases and approaches the sound speed at $20 R_\odot$ (solar radius). An appropriate magnetic flux eruption is introduced on the base, resulting in a nearly uniform supersonic mass ejection (250–300 km/s). In the early stage, a slow shock occurs ahead of the ejective mass, and the whole picture is similar to that obtained by HU *et al.* (1990). As the slow shock reaches $10 R_\odot$, where its Alfvén number

approaches 1, the transition takes place. Both cases show that the slow shock grows stronger and moves faster before the transition. The slow shock is then transformed into an intermediate shock via a switch-off shock rather than into a fast shock. At the same time, the leading edge of the compression region of fast wave steepens into fast shock, whereas the location connecting the original slow shock and the compression region of fast wave steepens into an intermediate shock. The final configuration of the shock is schematically shown in Fig. 4(a), which is analogous to that given by STEINOLFSON and HUNDHAUSEN (1990a). For case A, the segment of intermediate shock is preserved and the shock as a whole maintains the configuration shown in Fig. 4(a). For case B, however, the intermediate shock will become a fast shock via a switch-on shock. Such transition starts from the symmetrical axis and gradually spreads to both sides, and the resulting hybrid shock has a structure of F-ON-I-ON-F, shown schematically in Fig. 4(b). As the hybrid shock continues moving, the two switch-on shocks come closer, the intermediate shock becomes narrower and disappears at last, and consequently, the entire shock evolves from a hybrid shock into a fast bow shock. The about result shows that the intermediate shock may form in a particular location during a time-dependent process and keep existing in the proximity of neutral current sheets. We hope that this conclusion might stimulate space experimentalists in finding observational evidences for the presence of intermediate shocks somewhere in the interplanetary space, for instance, in the proximity of sector structures of the interplanetary magnetic field.

Fig. 4. Hybrid shock configuration in an open magnetic field (a) with neutral current sheet in the symmetrical axis (Case A) and (b) without that sheet (Case B).

Although there is much that we do not yet know or understand about the intermediate shock, it is my conviction that such shock should be a member of the whole shock family in its own right. It suffices to look at the role played by the intermediate shock in the spatial connection and the temporal evolution of slow and fast shocks. Here, it will be instructive to recall the comment made by GRAD (1960) thirty years ago, while the switch-on shocks were considered as unstable. He said, "The 'switch-on' shocks must turn out to be stable or the whole structure of MHD shock theory is worthless. One must have 'switch-on' shocks to solve problems." Nowadays, can we make a similar comment on the intermediate shocks?

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